Harry Ozier-Lafontaine
Magalie Lesueur-Jannoyer *Editors*

Sustainable Agriculture Reviews 14

Agroecology and Global Change

Springer

Sustainable Agriculture Reviews

Volume 14

Series Editor
Eric Lichtfouse

For further volumes:
http://www.springer.com/series/8380

*Other Books by Dr. Eric Lichtfouse**

Sustainable Agriculture
Sustainable Agriculture, Volume 2
Organic Farming, Pest Control and Remediation of Soil Pollutants
Climate Change, Intercropping, Pest Control and Beneficial Microorganisms
Sociology, Organic Farming, Climate Change and Soil Science
Genetic Engineering, Biofertilisation, Soil Quality and Organic farming
Biodiversity, Biofuels, Agroforestry and Conservation Agriculture
Alternative Systems, Biotechnology, Drought Stress and Ecological Fertilisation
Genetics, Biofuels and Local Farming Systems
Agroecology and Strategies for Climate Change
Organic Fertilisation, Soil Quality and Human Health
Environmental Chemistry. Green Chemistry and Pollutants in Ecosystems
Farming for Food and Water Security
Environmental Chemistry for a Sustainable World
Volume 1. Nanotechnology and Health Risk
Environmental Chemistry for a Sustainable World
Volume 2. Remediation of Air and Water Pollution
Rédiger pour être publié ! Conseils pratiques pour les scientifiques

Call for review articles
Authors wishing to publish a review article in *Sustainable Agriculture Reviews or Environmental Chemistry for a Sustainable World* should contact the Editor.
E-mail: Eric.Lichtfouse@dijon.inra.fr

*Eric Lichtfouse is Chief Editor and founder of impact-factor journals and book series. He is giving conferences, lectures and workshops on scientific writing and communication in Europe and the USA. He has founded publication assistance services to help authors, institutes and universities. For further information see LinkedIn, ResearchID and Google Scholar Citations.

Harry Ozier-Lafontaine
Magalie Lesueur-Jannoyer
Editors

Sustainable Agriculture Reviews 14

Agroecology and Global Change

Springer

Editors
Harry Ozier-Lafontaine
INRA, UR1321, ASTRO Agrosystèmes Tropicaux
Petit-Bourg, France

Magalie Lesueur-Jannoyer
HortSys Research Unit
CIRAD
Caribbean Agroenvironmental Campus
Le Lamentin, Martinique, France

ISSN 2210-4410 ISSN 2210-4429 (electronic)
ISBN 978-3-319-06015-6 ISBN 978-3-319-06016-3 (eBook)
DOI 10.1007/978-3-319-06016-3
Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014942694

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

I like farmers because they are not learned enough for wrong thinking

Montesquieu

Farming is a profession of hope

Brian Brett

Farmer Thinking

The global food demand will sharply increase in 2050 to feed an estimated population of nine billion. At that time, agricultural extension will not be possible anymore because production has already reached sustainable limits in many parts of the world due to environmental degradation and climate change. Worse, in the name of immediate profits industrial agriculture is actually producing contaminated food and water, increasing atmospheric CO_2 by burning soil carbon, and decreasing soil fertility in the long term. Industrial agriculture has also deepened the social gap between the farmers from the countryside and the customers from the cities, leading to many food security issues. As cleverly foreseen by Montesquieu, we should never have ignored farmer thinking. The actual challenge of agriculture is therefore to be sustainable and ecological and to produce safe food.

On field discussions on a seeder adapted to direct sowing in tropical wet areas. © 2013 Magalie Lesueur Jannoyer

Agroecology

Agroecology is a scientific discipline that uses ecological theory to study, design, manage, and assess agricultural systems that are productive but also resource conserving, according to Altieri (http://nature.berkeley.edu/~miguel-alt/what_is_agroecology.html; Altieri 2012; Altieri and Nicholls 2012; Altieri et al. 2012). The main agroecological goals are thus to feed the world without degrading natural resources and to sustain productivity by optimizing ecological processes. These overall principles are developed for decision makers in the FAO Save and Grow reports for sustainable intensification of smallholder crop production (Food and Agriculture Organization 2011) and in the ONU special contribution of Olivier de Shutter (De Shutter 2011, 2012). The future of agriculture depends on how effectively we understand and manage both social and ecological factors. The science of agroecology involves by nature the study of the whole agrosystem. As a consequence, investigations must be multidisciplinary with contributions from all disciplines relevant to the farming system, such as biological, physical, and social sciences. The major breakthrough versus industrial agriculture is that agroecology does not rely solely on technical knowledge. Farmers and human networks are indeed considered central players of the system. As a consequence, the classical top-down directives are not efficient anymore. Alternatively, bottom-up, participatory, and codesign studies will lead to sustainable innovations that will be accepted by farmers and the public.

Cover crop trials in banana cropping systems. © 2013 Magalie Lesueur Jannoyer

Family Farming

2014 is the International Year of Family Farming. Most farmers worldwide practice family farming, which yields nearly 70 % of the global agricultural production. Family farming is a very good topic for agroecological investigations, because most of the time family farming involves the use of biological regulations in diversified production systems instead of monoculture and chemical solutions. Family farming also provides local knowledge and know-how accumulated over centuries. Family farming is also a good case for agroecological studies, because it involves interactions at various scales and organization levels, from individuals to communities and territories landscapes.

This book shows applications of agroecological principles. The overall finding is that farming diversification and mixed cropping systems lead to both ecological intensification of agriculture and to the mitigation of global change. Chapter 1 by Angeon et al. explains the design of agroecology with a focus on the connection of life with economic and social sciences to build sustainable systems. Chapter 2 by Preston and Rodríguez reviews the recycling of farm products into feed, food and fuel. Chapter 3 by Ratnadass and Barzman reviews advances for crop protection. Chapter 4 by Alexandre et al. focusses on animal science, which is usually overlooked in agroecology. Chapter 5 by Clermont-Dauphin et al. explains how to manage soil biodiversity to design new cropping systems. Chapter 6 by Boval et al. reviews alternatives for grasslands intensification in tropical areas. Chapter 7 by Valet and Ozier-Lafontaine reviews traditional farmer intercropping systems for free ecosystem services, with a focus on participatory and codesign research. Chapters 8 by Chave et al. reviews advances in biocontrol for soil pests. Chapter 9 by

Mixed cropping system: the example of the creole garden in the Caribbean. © 2013 Harry Ozier-Lafontaine

Archimède et al. reviews the potential of local tropical resources for livestock nutrition. Chapter 10 by Le Henaff and Cebesi highlights the need to remove language barriers for agroecological education. Chapter 11 by El Ramady et al. presents an exhaustive review of soil quality and plant nutrition. Chapter 12 by El Ramady et al. presents the advanced concept of micro-farms.

Petit-Bourg, Guadeloupe — Harry Ozier-Lafontaine
Le Lamentin, Martinique — Magalie Lesueur Jannoyer
Dijon, France — Eric Lichtfouse

References

Altieri MA http://nature.berkeley.edu/~miguel-alt/what_is_agroecology.html

Altieri MA (2012) Convergence or divide in the movement for sustainable and just agriculture. Sust Agric Rev 9:1–9. doi:10.1007/978-94-007-4113-3_1

Altieri MA, Nicholls CI (2012) Agroecology scaling up for food sovereignty and resiliency. Sust Agric Rev 11:1–29. doi:10.1007/978-94-007-5449-2_1

Altieri MA, Funes-Monzote FR, Petersen P (2012) Agroecologically efficient agricultural systems for smallholder farmers: contributions to food sovereignty. Agron Sust Dev 32:1–13. doi:10.1007/s13593-011-0065-6

De Shutter O (2011) Agroecology and the right to food. http://www.srfood.org/en/report-agroecology-and-the-right-to-food

De Shutter O (2012) Agroecology, a tool for the realization of the right to food. Sust Agric Rev 8:1–16. doi:10.1007/978-94-007-1905-7_1

Food and Agriculture Organization, "Save and Grow" initiative (2011) www.fao.org/ag/save-and-grow

Acknowledgments

This book was initiated in 2012 during the summer school entitled Functional Traits and Sustainable Mixed Cropping System Design organized by the INRA and the CIRAD in Martinique. The main issue was the application of agroecology in tropical areas. We thanks all the contributors and school attendees who improved our vision and who helped widen the field application of agroecology.

Contents

Agroecology Theory, Controversy and Governance

Valérie Angeon, Harry Ozier-Lafontaine, Magalie Lesueur-Jannoyer, and Arnaud Larade

Abstract Industrial agriculture has clearly reached its limits. Industrial agriculture is not able anymore to satisfy the basic needs of the growing worldwide population while ensuring the conditions of reproduction of natural assets. New production models have to be designed to protect and reclame polluted and degraded agricultural areas. Agroecology is considered as a promising way to achieve ecologically-intensive agrosystems, since the seminal contribution of Altieri in 1995. Nevertheless agroecology has not fully emerged as a scientific discipline yet. Agroecology is more that a traditional scientific discipline because agroecology breaks the frontiers between biophysical sciences and social sciences. This chapter reviews the roots and evolution of agroecology in the first section. Here we propose a mathematical theory of viability to handle uncertainty and complexity within agrosystems. This theory allows to define a kern of viability in which the agrosystem stay viable

V. Angeon (✉)
Ceregmia Research Unit, Université des Antilles et de la Guyane (French West Indies and Guiana University), Caribbean Agroenvironmental Campus, Petit Morne, 97232 Le Lamentin, Martinique, France

INRA, UR143, Unité de Recherche en Zootechnie, F-97170 Petit-Bourg, France
e-mail: Valerie.Angeon@martinique.univ-ag.fr

H. Ozier-Lafontaine
INRA, UR1321, ASTRO Agrosystèmes Tropicaux, F-97170 Petit-Bourg, France
e-mail: Harry.ozier-lafontaine@antilles.inra.fr

M. Lesueur-Jannoyer
HortSys Research Unit, CIRAD,
Caribbean Agroenvironmental Campus, Petit Morne,
97232 Le Lamentin, Martinique, France
e-mail: magalie.jannoyer@cirad.fr

A. Larade
AgroParisTech, UMR Metafort, 9, Avenue Blaise Pascal,
CS 70054, 63178 Aubière Cedex, France
e-mail: arnaud.larade@agroparistech.fr

H. Ozier-Lafontaine and M. Lesueur-Jannoyer (eds.), *Sustainable Agriculture Reviews 14: Agroecology and Global Change*, Sustainable Agriculture Reviews 14,
DOI 10.1007/978-3-319-06016-3_1,

in the long term (section "Scientific stakes: New frontiers"). However, agroecological innovations create new uncertainties and controversies that must be solved. Some solutions can be found individually while other solutions must by co-constructed using innovative collective actions and hydrid forums (Callon et al. 2001, section "Scientific controversy and uncertainty"). Such collective knowledge makes agroecology as the starting point of a representative democracy by setting up adaptive governance on territories (section "How to manage agrosystems in the context of global changes?").

Keywords Agroecology • Agrosystems • Social and ecological systems • Panarchy • Viability • Adaptive governance • Strategic management

Introduction

The competitive quest for economic growth based on the use or even the depletion of natural resources is under suspicion since the 1970s. The Meadows report was one of the first major contributions of the last century that brought on the political agenda the question of sustainable growth. The most important challenge to be risen in the twentieth century consists in feeding an increasing population with scarce resources. This Malthusian and pessimistic viewpoint explaining the gap existing between the exponential needs of the population and the slow evolution of raw resources is nowadays shared and taken into consideration. As a matter of fact, there is strong interest in paying attention to alternative ways of consumption but also production. In this perspective, the new turn driven by agroecology principles is central and is worth being under scrutiny.

The popularity of agroecology comes from Altieri (1995) though pioneer works (Bensin 1928) had set up the concept. In his seminal article, Altieri (1995) describes agroecology as a science, a practice, a movement. As a science, it pushes back the frontiers of common knowledge and founds new paradigms: this science of natural resource management addresses the basis for the conception of performing ecologically, biodiverse, resilient, sustainable and socially just agrosystems (Altieri et al. 2012). As a practice, agroecology aims at furnishing guide of action, techniques, innovations – rooted in societal features (propensity to collective action, quality of coordination) – that support the ecological management of natural resources. As a movement, agroecology corresponds to societal aspirations that contest the intensification and the standardization of production and consumption systems. This movement pleads for ethical values, responsible development for sustainable future and raises agroecology as a consistent topic that should be debated across academics and stakeholders whether they are farmers, decision-makers or civil society.

Almost 20 years later Altieri's key contribution, what are the new challenges faced by agroecology? How should agroecology evolve? In this introductory chapter, we wonder about the frontiers agroecology must stretch to successfully set up the third agricultural revolution. We argue that one of the main challenges agroecology has to face to consists in strengthening its scientific maturity and its credential as a discipline. This scientific reawakening implies new directions that may abolish the traditional boundaries existing between science and practice, between the academic sphere and the civil society. Such a stance invites to conceive in a more holistic approach science, practice and action by substituting to the top-down principle of knowledge transfer, collective learning processes.

In this article, we seek to appraisal the consistency of agroecology as a scientific discipline, paying attention to the foundations of its research program and to the front of science it attempts to renew. We then explore the general framework of agroecology, considering what it brings in terms of theoretical soundness, methodological robustness and empirical results.

To fulfill this ambition, our reasoning unfolds in three steps. In section "Scientific stakes: New frontiers", we design the theoretical frame of this integrative discipline as a science for action. Nevertheless, the accumulation process of information, knowledge and innovation is far from being complete. It becomes evident that the agrotechnological advances are not yet stabilized and that their impacts are not either well known. This opens spaces for scientific controversy and incertitude. This context of scientific incertitude is a strong feature of the end of the last century which impacts societal norms of action as debated in section "Scientific controversy and uncertainty". We then discuss in section "How to manage agrosystems in the context of global changes?" in what extent governance processes are likely to sustainably manage agrosystems under uncertainties.

Scientific Stakes: New Frontiers

The transition, from an agroindustrial model to a model based on diversification and ecological intensification for a better satisfaction of the local food demand and the production of ecosystem services, is henceforth inescapable (Griffon 2006). Alternative solutions have been studied by the agronomic research for decades, just as original initiatives have been taken by producers in the prospect of innovative system design. This funds the historical development of agroecology.

Rooted in crop physiology, ecology, zoology, agroecology is an integrative science which main challenge is probably to be erected as a full discipline. This implies that it is not anymore considered as a patchwork of approaches but builds its own research program. In this section, the case for considering agroecology as a distinctive scientific discipline with a coherent scientific corpus is examined. We then pay attention to the developments on the panarchical framework which conceptualizes the interaction between humans and their environment (Gunderson and Holling 2002).

Panarchy: The Theoretical Roots of Agroecology

In the field of systemic ecology (Capra 2003), the objective of the Panarchy is to develop a conceptual framework to describe the dynamics of change of social and ecological systems (Fig. 1). It brings together the environmental, economic and

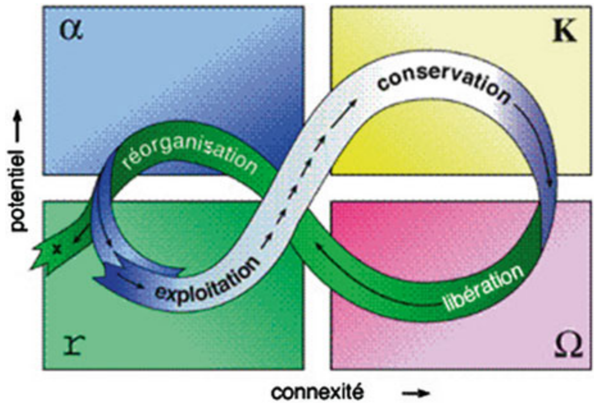


Fig. 1 Representation of the four ecosystem functions (r, K, Ω, α) and the action flow that makes link between them. The cycle reflects changes within two dimensions, (1)Y axis: the inherent potential of biomass and nutrient resources accumulation; (2) X axis: the degree of connectivity (connectence) among control variables. *Arrows* show the flow speed in the cycle. Along time, system structures and functions are changing because of the internal dynamics and external influences, resulting in four specific stages, described by Holling for the ecological system dynamic: a growth stage (r) with slow biomass and nutrients accumulation; a conservation stage (K): the system becomes more and more interconnected, less flexible and more vulnerable; a stage of limited resources liberation (Ω), after disturbance; a reorganization phase (α), then leading to another phase of growth in a new cycle, with a phase r similar or different from the previous one

social concerns, and conditions of change and stability, and takes into account the complex interactions between different areas and different scales (Gunderson and Holling 2002). This consideration is thoroughly compatible with the notion of social and ecological systems.

Following Anderies' et al. (2004, p. 3) definition, *"a social and ecological system is an ecological system intricately linked with and affected by one or more social systems. An ecological system can loosely be defined as an interdependent system of organisms or biological units. 'Social' simply means "tending to form cooperative and interdependent relationships with others of one's kind" (Merriam-Webster Online Dictionary 2004). Broadly speaking, social systems can be thought of as interdependent systems of organisms. Thus, both social and ecological systems contain units that interact interdependently and each may contain interactive subsystems as well. We use the term "social and ecological system" to refer to the subset of social systems in which some of the interdependent relationships among humans are mediated through interactions with biophysical and non-human biological units".*

The numerous interactions between social and ecological systems augment the complexity of the overall social and ecological system, involving multiple levels and scales of uncertainty. In addition to natural determinants of uncertainty, relational, spatial, jurisdictional etc. uncertainties appear as core features of the societal matrix in which social and ecological systems evolve.

This concept allows that natural ecosystems are disturbed and managed. It carries four main axioms including the double and seemingly contradictory characteristic of all complex systems, namely stability and change:

1. The change is neither continuous nor progressive, nor always chaotic, but controlled by interactions between fast and slow variables.
2. Different scales concentrate resources and potential in different ways, and non-linear processes reorganize resources between the different levels.
3. Ecosystems do not have one but multiple equilibrium. They are associated with processes that maintain stability in terms of biogeochemical cycles and productivity, as well as destabilizing processes that stimulate diversity, resilience and opportunism.
4. Management systems should take into account these dynamic characteristics of ecosystems and flexibility, adaptation and experience at levels consistent with the scale of ecosystem functions and their critical levels.

Nevertheless, if this conceptual framework helps to tackle the complexity of structures and relations that are inherent to the analysis of social and ecological systems, it does not provide any concrete tools to guide action and decision-making. The need of instruments for governing social and ecological systems and managing their long run evolution is crucial especially in the context of global changes. We mean by global change all the combined effects of the globalization of socio-economic exchanges (Young et al. 2006), the dynamics of population (mobility and migration), the evolution of societal and cultural changes (Giddens 1999; Bajoit 2006), of food requirements and modernization of agriculture, the potential rise of environmental crises (global warming, extreme natural hazards, etc.), the impacts of human activities on ecosystems and natural resources (depletion of fossil fuels, access to water, pressure on fisheries, loss of biodiversity, etc.). Numerous studies lead by the IPCC (2007, 2013) come to the conclusion that the natural capacity of social and ecological systems to adapt to shocks is overcome, a fact that reaffirms the importance of human intervention to promote their viability.

In the following sub-section, we give some highlights on the viability theory. This theoretical frame defines for any system the set of initial states for which exists at least one future evolution and the rules of decisions that warrant this viability.

Exploring the Conditions of Viability of Social and Ecological Systems

The viability theory has its roots in "Le hasard et la nécessité " (Monod 1970) and has been translated in mathematics (Aubin 2010; Saint-Pierre 1994, 1997). It enables a form of application of the principles of Panarchy in a dynamic process. It describes the behavior of controlled evolutionary systems in which the evolution of the state of the system is governed by a differential equation set describing diverse variables.

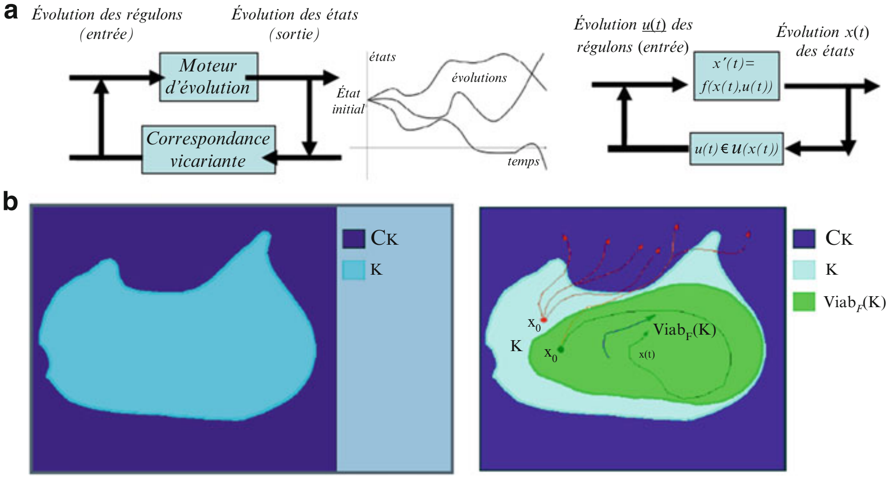


Fig. 2 (**a**) Retroactions. On the *left*, an input/output system composed of two *boxes*, the *first box* takes the regulon inputs and provides states as outputs, that interact themselves with regulons, constraining regulons to obey to constrains depending on states (through what it is called a vicariant correspondence). On the *right*, the mathematical translation of this evolutionary example (Aubin 2010). (**b**) Framework of an environment and its viability kernel. On the *left*, any subset K, but including its boundaries (closed subset). On the *right*, its viability kernel. From the viability kernel, one evolution at least is viable in this set. From the viability kernel complementary set, all evolutions leave the environment in a limited time (Aubin 2010)

According to their roles, these variables have a specific name (Aubin 2010):

– Coefficient, if the variable remains constant;
– Command or control, if there is an identified actor driving the evolution of this variable, as automations, robotics or financial markets;
– Regulon, when the drivers of the evolution of this variable are not known or when these drivers are abstractions. States, economic agents, individuals, metabolisms, markets are some examples of regulon;
– Tyche, referenced as chance in the Greek mythology, when no information is given on the drivers nor on their effect. These variables are called tychastic.

The main question remains in the knowledge of the set of initial states from which there is at least one viable evolution in the environment. This set is called the viability kernel. Beyond knowledge of the viability kernel, which guarantees the existence of viable or persistent changes, we must drive them and provide decision rules that will help to ensure the sustainable evolution of a system. It goes through a feedback, which associates each state to the regulon to be used to maintain sustainable development in the environment (Fig. 2a). The viability theory is based on a collection of mathematical theorems characterizing the viability kernels in various ways, exploring their properties and focusing on their applications in various fields (Fig. 2b). The tools of classical analysis familiar to mathematicians and mathematics users are not suited to the study of such problems (Saint Pierre 1994, 1997).

The viability theory consists in a rigorous analytical framework to formalize the evolution of systems under uncertainty. It determines the “right” decisions that strengthens the robustness of social and ecological systems and helps *a contrario* to identify those that have to be indisputably avoided. Based on an algorithm, the viability theory provides numerical applications that lead to operational decision rules. Despite its systemic vision, its compatibility with a holistic approach of social and ecological systems, and its empirical application, with the production and use of specific indicators, this conceptual frame requires strong capacities to aggregate all the variables that depict a system, with no capacity to more than four variables.

The necessity to adjust the real complexity of the problems, set down to the dimensionality of the models, is of first importance to validate the built model and to make it operational. Few attempts have been made to give applied consistency to the viability theory. The expected results from the research program coordinated by Ozier-Lafontaine and Angeon (2012–2016) on “viability and adaptive governance of tropical island agrosystems” aims at modeling some possible agricultural futures according to the evolution of global changes and their consequences by calibrating the variables in consultation with stakeholders (Angeon et al. 2013). Such implemented, the viability theory is used to help the stakeholders to specify the objectives to reach, the levels to respect in matters of sustainability and the means to achieve them. It can then be apprehended as a tool that is likely to improve partnership and reflexive processes in the context of complexity and uncertainty raised by global changes.

The mathematical theory of viability gives a robust conceptualization of sustainable social and ecological systems focusing on internal driving forces that guarantee to what extent the system remains resilient. It provides satisfying tools for action and decision-making processes to successfully manage natural or anthropized systems whatever the foreseeable impacts or uncertainties it is submitted to. Otherwise, it measures the gap existing between the future trajectory of a system and its initial state. There is clear evidence that the uncertainty context in which social and ecological systems are managed depends not only on external factors such as natural hazards, global markets, but also on internal determinants depending on societal contexts and cognitive norms that shape stakeholders’ behaviour. Agroecology as scientific outputs faces controversies. As a practice, it is confronted with experimental and non controlled results.

Scientific Controversy and Uncertainty

The rationale for agroecology is the need to develop sustainable systems of food production. This requires that knowledge must be effectively delivered to the people who are in a position to take appropriate action. In a context of scientific uncertainty, the place and the role of experts become less and less credible. The legitimacy of action is not all the more left to scientists. This opens new spaces for new categories of stakeholders in decision-making processes.

Photo 1 Multi roots species within the same plot (yams, sweet potatoes, taro) inside a biodiverse landscape. When practical knowledge contributes to manage biodiversity and productivity

The Blindness of Science

Since the third agricultural revolution and its technological package around transgenesis, scientists are not anymore the unique owners of knowledge and truth. At the end of the last twentieth century, many controversies have discredited scientific research, a fact that still persists today (Callon et al. 2001). The impacts of genetically modified organisms on biodiversity and human health are one of the subjects that have attracted the most debate and argument over the last decades. As a result, scientific uncertainty on these concerns made experts losing their propensity to advise the regulator. The lack of objective knowledge opens space for new categories of actors as long as they remain mobilized to assert their rights to participate in the debate though the quality of the information they base on is disputable. This situation highlights the limits, or maybe the failures, of the system of representative democracy.

Agroecology has so far received little criticisms on the accuracy of its objectives (sustainable agriculture, better interactions between plants, animals, humans and the environment). The main criticisms are related to the irenic nature of its ambition to feed the world with alternative farming systems whose yields and productivity will obviously be lower than those obtained in conventional systems (Kassie et al. 2009). In this section, we show that the scientific fundaments of agroecology are also subject to the law of uncertainty and can lead to results opposite to those expected (Batary et al. 2011). We illustrate this point with two examples: cover plants and ecological corridors (Photo 1).

Photo 2 Mixing *Citrus* and beans, managing productivity and treasury

Getting Results Opposite to Those Expected: Some Examples

Emergent Properties Versus Resilience in Intercropping Systems

Agroecological systems, as well as conventional systems are not immune to emerging phenomena. Finding a solution to a constraint can generate new ones, sometimes more damaging. Many examples in the literature demonstrate facts relating to the emergence of new diseases related to changes in micro-climatic conditions more favorable to the expression of new pathogens such as fungi or bacteria, or related to changes in bio-physicochemical properties of soils such as acidification. The design of innovative systems will therefore seek to promote synergies at different levels in order to compensate for their weaknesses. Care should be taken to mobilize several functions with a holistic approach in the fight against particular pests or in facilitating the bioavailability of soil resources (Brussaard et al. 2010) (Photos 2, 3, and 4).

Ecological Corridors

The notion of ecological infrastructure or corridor is promoted by the European Union in its strategy for the biodiversity until 2020. The target 2 consists in maintaining and in enhancing the ecosystems and their services by the establishment of a green infrastructure and the restoration of at least 15 % of degraded ecosystems (EU 2011). At the international level, the notion of ecological corridors was introduced by the International Union for Conservation of Nature in its World Conservation Strategy published in 1980. More recently, one of the Aïchi Objectives (from the Nagoya conference, Convention on Biologic Diversity in October 2010) re-asserts

Photo 3 Producing in same plot exploring two different spheres: roots spheres with Cassava and atmosphere by Maize

Photo 4 Closing the biochemical cycles with integrated (goat) breeding

the need to create representative ecological networks at the Earth scale. It emphasizes, on one hand, the relations between nature and society and, on the other hand, the landscape scales (Debray 2011). The ecological network aims at ensuring the connections between habitats of natural species by maintaining or creating corridors, between biodiversity tanks participating in the physical connectivity of

Photo 5 Taro roots culture within a swamp forest of *Pterocarpus officinalis*

elements of the landscape (Baudry and Burel 1999; Vimal 2010). The role of agricultural activities by the use of agroecological practices is then underlined as they rely on local knowledge crop management practices which better fit to local conditions and lead to the conservation and regeneration of the natural resources.

Despite this large political consensus around the notion of ecological corridors, infrastructures and networks, its scientific roots are controversial. Firstly, the effectiveness of ecological corridors is not always proven and can deeply reduce the population viability: augmentation of diseases transmission, propagation of catastrophic disturbances for adjacent landowners, development of exotic species, etc. The structural conception of the functionality of ecological corridors is incriminated. Secondly, the basis of ecological networks relies on a great simplification of complex mechanisms: continuity at a large spatial scale cannot properly take into account the multiple spatial interactions that emerge at lower scales.

These two examples illustrate that there is no general answer to the question: "does agroecology systematically prevent social and ecological systems from vulnerability?" Decision-making processes in a context of risk and uncertainty is even more a complex problem when stakeholders are embedded in their normative visions.

A Changing Institutional Context: New Players in the Innovation Arena

New players, with no more stabilized information than others on the environmental topics they feel concerned with, are welcomed to the decision-making table. This implies to take into account the different stakeholders' voices in a meaningful way.

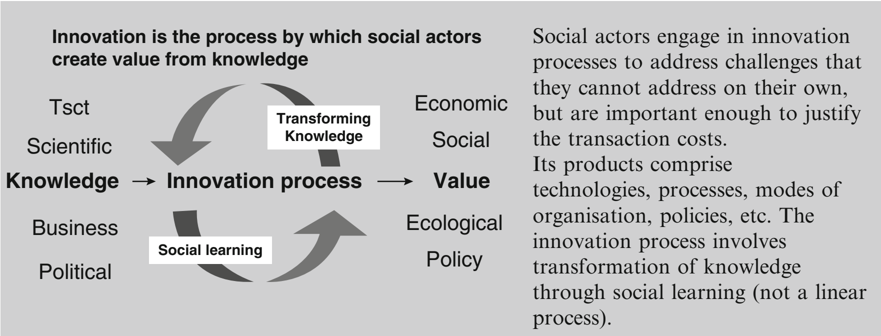


Fig. 3 Agricultural Innovation Systems (*AIS*): schematization of the innovation process (World Bank 2006)

The participation of the plurality of actors is favored by two main contemporary factors. Firstly, it is inherent to the evolution of public policies referential that encourages the implementation of governance principle to facilitate collective decision-making procedures. The actors are thus involved in deliberative processes that engage their shared responsibility. Secondly, the extension of the sphere of actors is also permitted in the ongoing context of uncertainty which has been reinforced with the transgenic revolution. Discrediting scientific knowledge, the place and the role of experts, uncertainty and complexity of living systems create new decision spaces that are occupied by epistemic communities. These communities called by Callon et al. (2001) "hybrid forums" discuss or legitimize socially the agro-technical choices. These socio-technical controversies shape the basis of a "dialogic democracy" that contributes to the redefinition of the social pact to ratify.

These actors are marked by their normative visions or interests that are sometimes (or often) divergent. The challenge to be raised is then to define: how to guide collective decision-making process? What forms of governance to invent? What institutional arrangements to instigate? The answers to these questions are central for implementing innovation dynamics.

Innovation is a central issue in agroecology. The question of how to enable agricultural innovation for development is now discussed and researched more and better understood than ever before. From Hall (2009), innovation is the process of creating and putting into use combinations of knowledge from many different sources (Fig. 3):

- This knowledge may be brand-new, but usually it results in new combinations of existing knowledge.
- To be termed innovation, the use of this knowledge has to be novel to the farmer or the firm, neighbors and competitors, but not necessarily new globally.
- Invention, on the other hand, is the creation of new knowledge, new to the world, usually by research organizations, but also by artisans and others.

Whatever the type of innovation, the farmer can rarely alone develop its innovations. It is obvious that the demand for innovation in agricultural systems is supported by

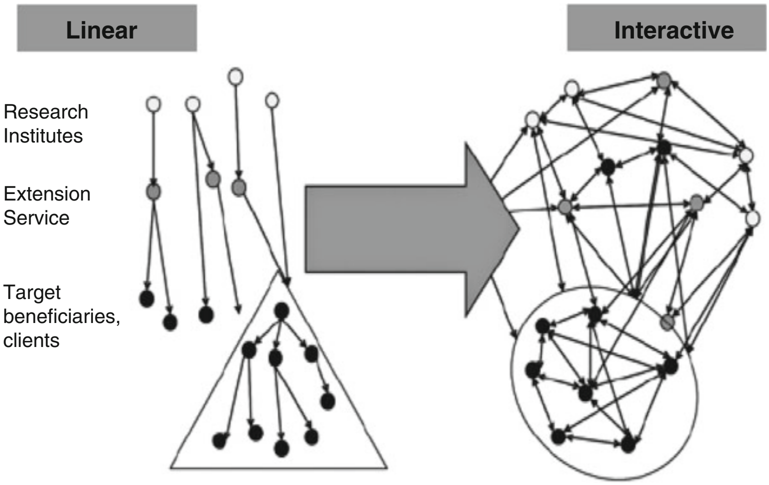


Fig. 4 Towards a changing vision: from the 'top down' approach to a participative approach of innovation (World Bank 2007)

many actors (Fig. 4), not just by farmers. Studies on innovation show that the ability to innovate is often linked (i) to collective action and sharing of knowledge between actors, (ii) to incentives and available resources that were invested in collaboration actions and (iii) to the creation of an enabling environment for the production of ideas and innovations by different actors (World Bank 2006). This challenges our ability to advance together (Ozier-Lafontaine et al. 2011):

– technologies, i.e. principles underpinned by ecological intensification;
– institutions vs. socio-economic expectations, to identify the institutional constraints to solve: laws, regulations, traditions, customs, beliefs, societal norms and nuances;
– policies, which, if they are appropriate, timely and relevant, may promote and facilitate the generation, sharing and using of knowledge for innovation;
– the various public and private organizations that must innovate in the services they provide; the priority is to increase investments in agricultural science and technology, research and extension, education and agricultural training, farmers organizations and other local institutions and thus contribute to widely spread the knowledge and innovation. The role of the inter-branch associations, professional training and technical institutes is particularly important.

According to Funes-Monzote (2009), when innovation is applied to the design of ecologically intensive agricultural systems, four levels of innovation can be observed and crossed (Fig. 5).

– **Level 1:** innovation optimizes agricultural practices; this results in marginal changes in the agroecosystem, usually focusing more on the decision rules for the application of practices than of their technical modification. Here are mainly mobilized the classical concepts of agronomy.

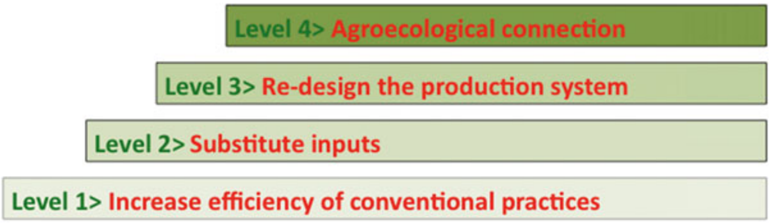


Fig. 5 Innovation levels for ecological intensification of production systems (Adapted from Hill; Gliessman)

- **Level 2:** new objectives or constraints, such as no use of chemical inputs, are applied to the system, implying a larger change in involved practices. The concepts of agronomy and ecology are used at the scale of the field plot.
- **Level 3:** a more systemic approach is applied at the field plot scale and to the main crop. The overall functioning of the agroecosystem is revisited and deeper changes are emerging, such as integration and management of biodiversity through new species, as example. The concepts of agronomy and functional ecology are mobilized at field scale.
- **Level 4:** more radical changes are being considered within the farming system and the agroecosystem by integrating functional diversity and associations of different productions at different scales, leading to a global management of ecological processes. Systems from this approach are usually out compared to conventional systems. The concepts of systemic agronomy and ecology are assembled at different scales from field plot and its immediate environment to farm and landscape.

The development of agroecological practices requires their appropriation by those who are able to take accurate decision for consistent action. This is likely to occur in the implementation of governance processes.

The theory of viability permits to move apart some non viable conditions. Within the kern of viability, some uncertainties and controversies related to the proposed innovations have to be dealt, not only by individuals but also in collective. They can be discussed and debated within hybrid forums that enable to manage agrosystems and their innovations. How to operationalize those hybrid forums? (Photos 6 and 7)

How to Manage Agrosystems in the Context of Global Changes?

Studies on the sustainability of agricultural systems show that innovation in agriculture passes through a reconciliation with the functioning of natural systems (IAD 2011) consisting in strengthening the resilience of agricultural systems through the management of the diversity of crops, livestock, of the soil ecology and of the agro-ecosystems global diversity, from the field to the landscape (de Schutter 2011). This process of ecological intensification and design of innovative agricultural systems, less dependent

Photos 6 and 7 (to the *left*: clump of trees) and (to the *right*: a pond): Some fixed landscape components in grassland; welcoming some ecological processes actors producing some ecological services useful for agriculture

on chemical inputs, is supported by professionals and citizens concerned about their health and environmental conservation. In such a context, which form of governance is likely to increase the propensity of stakeholders to address this challenge in agroecology? Is adaptive governance adequate?

To answer these questions, we first make a literature review about adaptive governance. Showing the limits of this contribution, we suggest a more strategic approach.

Adaptive Governance: A Review

Adaptive governance aims at developing new governance forms to manage social and ecological systems. The term derives from adaptive management defined as "a systematic process for improving management policies and practices by learning from the outcomes of management strategies that have already been implemented" (Pahl-Wostl et al. 2007, p. 4). To expand the focus from adaptive management of ecosystems to broader social contexts, Dietz et al. (2003) refers to the concept of adaptive governance. They mean "creating the conditions for ordered rule and collective action or institutions of social coordination." Governance is then the structures and processes by which people in societies make decisions and share power (Folke et al. 2005).

As reminded in section "Scientific stakes: New frontiers", social and ecological systems are characterized by complexity and unpredictability. They are exhibited to abrupt or continued changes that have unpredictable consequences. The viability of such systems strongly depends on social decisions. For example: what kind of agriculture does the society want to preserve? In what extent? By which means: the conservation of some biodiversity elements, some ecological functions, the evolution or adaptive capacities of the whole agrosystem? At what scale? These objectives are not pre-determined. They have to be defined by stakeholders committed in collective negotiations ("hybrid forums" as say Callon et al. 2001). This is why the results of the decision-making process are likely to change over time and round tables. Social and ecological systems are exhibited to external shocks (such as natural hazards) which intensity is more or less high. Will these shocks impact the structure of these systems occurring simple adaptation or transformation (Pahl-Wostl 2009)?

Several works also point out that the resilience of social and ecological systems can be conceived by the notion of scales (Cash et al. 2006; Termeer et al. 2010; Berkes 2006; Angeon and Caron 2009). In addition to spatial and temporal scales, jurisdictional, institutional, networks, management and knowledge scales have to be considered. Scales are continuously moving. These changes make more complex environmental management problems as there are cross-scales and cross-level interactions on the same scale. For instance, mismatch between the environmental scale and the social organization scale can generate a disruption of some functions of the social and ecological systems. Consistent responses lead to remodel the social scale, to change or create new institutions in order to settle the problem. Similarly, cross-level interactions threaten the resilience of social and ecological systems. Typically, a cross-level issue on the time scale occurs when short term solutions can aggregate in long term problems. On the institutional scale, a cross-level issue could be solved by creating better links between the different levels and not by assuming exclusive top-down or bottom-up interactions (Berkes 2006).

In this perspective, management issue for social and ecological systems to be resilient deals with "scale challenges". Such a stance implies that the actors managing the social and ecological systems are aware of the importance of cross-scale and cross-level interactions, especially the dynamics between spatial and temporal ones. As Termeer et al. (2010) underlines, adaptive governance "takes the challenge of enhancing the capacity to create the right cross-scale and cross-level links at the right time, around the right issues.". Adaptive governance assumes the search of match between scales and levels of scales, for instance, concerning the agroecologic issue, between the scientific knowledge and the traditional knowledge. This approach admits that there is no single, correct or best characterization of scale problems and that these concerns result from negotiation, in other words, no decision is imposed by a group of actors or corresponds to their preferences for a specific scale or level.

Adaptive governance and management can be seen as based on three pillars: enhancing the information flow through cross-scales and cross-levels (such as forum-type prescriptions), improving social innovation for transformative processes (such as network-type prescriptions) and promoting learning processes (such as agroecological, social, institutional apprenticeship). Adaptive governance assumes social relations characterized by cooperation, collaboration and coordination; matching closely with the idealogic/historical bases of agroecology (cf. section "Introduction" §1). However, solutions and prescriptions to assume conflicting social relations are rare or weakly developed.

On another hand, adaptive governance focuses on social and ecological systems so, it remains possible to create societal artifacts as far as they may control and guide the performances of social and ecological systems. This is a condition within which the social and ecological system could be resilient but based on non-viable agrosystems.

Improving Adaptive Governance for Managing Agrosystems

The agroecological approach, which gathers agronomy and ecology at different scales, strengthens the classical methods of research but also opens new channels, including the integration of the knowledge on the ecological functioning of the agroecosystem and the knowledge of producers, mobilizing new methods of generation and analysis of data (participatory action research and comparative approach). We may consider in a balanced way the two ecological and social components of agrosystems and prevent than societal features encompass environmental concerns. To reach this objective, adaptive governance process may integrate a strategic conceptual framework. We suggest to rely on the strategic environmental management analysis (Mermet et al. 2005) which gives some methodological prerequisites to consistently implement governance processes towards an effective integration of environmental stakes.

This conceptual framework is based on four principles.

1. The analysis of the system of action must imperatively rely on the definition of the ecological object to take into account and of the aims to be pursued.
2. A social diagnosis of the stakeholders committed in the management of the environmental object must be done. It is useful to determine the whole human actions set that strongly influence the properties of the environmental object. This is what the authors call “effective management”.
3. The third principle is to focus on the actors who initiate appropriate changes for the effective management of the ecological object. They are identified as “environmental strategic actors” who operate the “intentional management” (Mermet 2011). These actors play an effective role as agent of change in favor of environment.
4. The last principle is to replace this environmental strategic analysis in a dynamic perspective as social and ecological systems change over time especially through the structuring outcomes of conflicts in which the preoccupations of the environmental strategic actors are partly integrated. This theory of action assumes conflicts as vectors of change.

Strategic environmental management analysis does not propose all answers a priori. It can be implemented where it is possible to meet some environmental strategic actors. Is it the case in all societies?

As an orthogonal proposition to the third agricultural revolution, and considering agroecology as an “ecologization of agricultural practices and public policies”, it “tends to question in a transversal way the whole space of public and private actions” (Mzoughi and Napoléone 2013). In that sense, the political side of agroecology calls for governance proposals. We have identified the levers of adaptive governance as its limits that can be by-passed by a more strategic perspective (Photos 8 and 9).

Photo 8 A Guadeloupe endemic specie *Melanerpes herminieri*; needs forest connectivity to adapt to global changes and to survive within the Earth

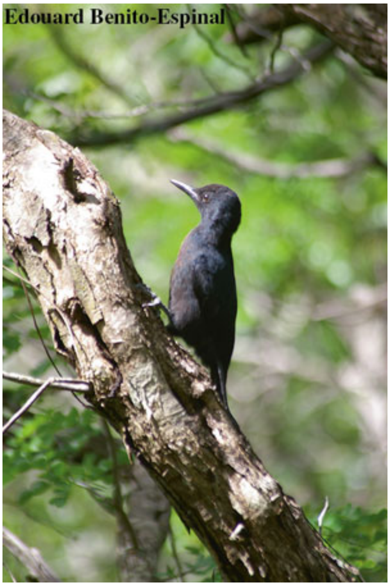


Photo 9 spontaneous flora (*Crotalaria*) as producer of useful metabolites in the soil

Conclusion

First we have reminded the roots and the wide range of agroecology assuming its principles able to face the challenge of producing more to feed exponential needs while preserving natural resources (Section "Introduction"). Integrating such innovations calls to deal with more uncertainties and complexity, what could be done

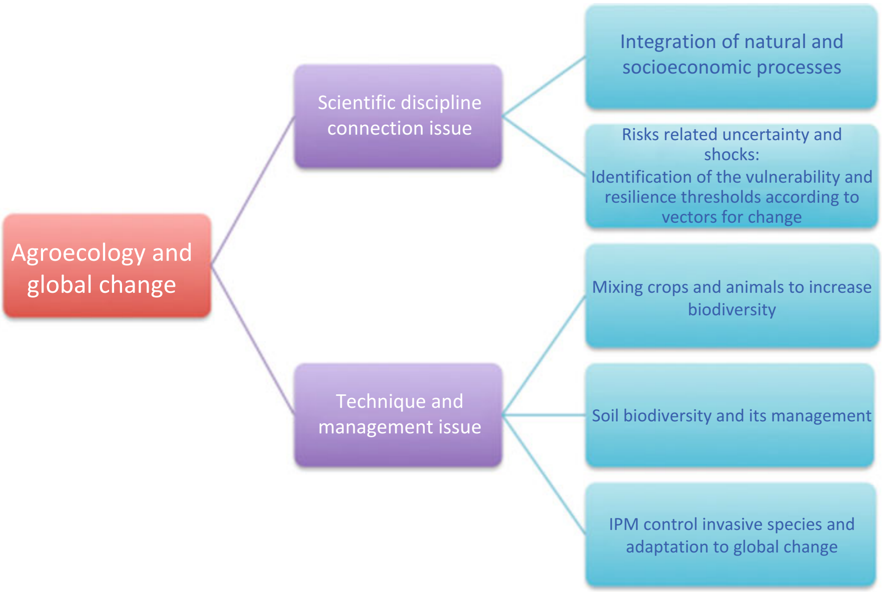


Fig. 6 The main challenges for agroecology versus global change

using the mathematical theory of viability to define a kern of viability (section "Scientific stakes: New frontiers"). Despite the fact the kern of viability is defined, some others uncertainties and controversies remain. They challenge individuals as collectives (section "Scientific controversy and uncertainty") calling for the definition and the implementation of new governance paradigms. Adaptive governance completed by strategic perspectives are identified to match some of the challenges (section "How to manage agrosystems in the context of global changes?") on rural territories. That way, agroecology is not simply a technical and agricultural innovation but could be seen as a starting point for social innovation, enhancing (or reinforcing) the representative democracy. Our findings are relevant with some results supported by other authors.

Agriculture, considered as a structuring agent of rural areas, development of societies and natural resource management, faces the challenge of producing more and better with less (de Schutter 2010; FAO 2011). The acceleration of global change defines a new specification for agricultural research, campaigning for a new research policy. The challenge is to reduce the vulnerability of our production systems and agricultural sectors, while strengthening the provision of ecosystem services. Such reflection invites to understand farming systemically, i.e., in connection with the physical productive supports, environmental and social contexts in which it fits, and cannot be registered outside the sustainability paradigm.

In their article Tomich et al. (2011) point two major challenges for the future, the first relating to disciplinary connections, and second, technological and management of agro-ecological processes (Fig. 6).

Related to the issue of disciplinary connection "*the integrative study of the ecology of the entire food system, encompassing ecological, economic and social dimensions*" (Francis et al. 2003) sets the need of articulation of the natural sciences (agronomy, ecology and environment) and social sciences (sociology, political and management sciences, economics and geography), required to drive the agroecological approaches with a view to innovation and sustainability.

From a conceptual point of view, the theory of panarchy and viability theory were presented as support of the research action process to promote. The perspective of these concepts emulates a controversy about how to do science for sustainability. Making science for impact will require an interdisciplinary effort and a perspective of research differing from the top-down classical model, to enroll in a participatory co-construction of innovation, supported by current Systems of Agricultural Innovation (World Bank 2006, 2007).

References

Altieri MA (1995) Agroecology: the science of sustainable agriculture. Westview Press, Boulder

Altieri MA, Nicholls C, Funes F (2012) The scaling up of agroecology: spreading the hope for food sovereignty and resiliency, a contribution to discussions at Rio+20 on issues at the interface of hunger, agriculture, environment and social justice. SOCLA's Rio+20 position paper, 20 p

Anderies J, Janssen MA, Ostrom E (2004) A framework to analyze the robustness of social-ecological systems from an institutional perspective. Ecol Soc 9(1):18

Angeon V, Caron A (2009) Quel rôle joue la proximité dans l'émergence et la pérennité de modes de gestion durable des ressources naturelles? Nat Sci Soc 17:361–372

Angeon V, Bates S, Chia E, Diman JL, Fanchone A, Ozier-Lafontaine H, Saint-Pierre P (2013) Détermination des contraintes de viabilité des exploitations agricoles: application aux Antilles françaises, 50ème colloque de l'Association de Science Régionale de Langue Française, Mons, Belgique, 8–11 juillet 2013

Aubin JP (2010) La mort du devin, l'émergence du démiurge. Essai sur la contingence, la viabilité et l'inertie des systèmes, Beauchesne, Paris, 604 p. EAN/ISBN: 9782701015040

Bajoit G (2006) Le changement social – approches sociologiques des sociétés occidentales contemporaines. Armand Colin, Paris

Batáry P, Báldi A, Kleijn D, Tscharntke T (2011) Landscape-moderated biodiversity effects of agri-environmental management: a meta-analysis. Proc R Soc B 278(1713):1894–1902. doi:10.1098/rspb.2010.1923, 22

Baudry J, Burel F (1999) Ecologie du paysage. Concepts, méthodes et applications. Editions Tec&Doc/Lavoisier, Paris, 360 p

Bensin BM (1928) Agroecological characteristics description and classification of the local corn varieties chorotypes

Berkes F (2006) From community-based resource management to complex systems: the scale issue and marine commons. Ecol Soc 11(1):15p

Brussaard L, Caron P, Campbell B, Lipper L, Mainka S, Rabbinge R, Babin D, Pulleman M (2010) Reconciling biodiversity conservation and food security: scientific challenges for a new agriculture. Curr Opin Environ Sustain 2:34–42. doi:10.1016/j.cosust.2010.03.007

Callon M, Lascoumes P, Barthe Y (2001) Agir dans un monde incertain. Essai sur la démocratie technique. Le Seuil (La couleur des idées), Paris

Capra F (2003) La toile de la vie: une nouvelle interprétation scientifique des systèmes vivants. Paris, Le Rocher, 370 p

Cash DW, Adger WN, Berkes F, Garden P, Lebel L, Olsson P, Pritchard L, Young O (2006) Scale and cross-scale dynamics: governance and information in a multilevel world. Ecol Soc 11(2):8

de Schutter O (2010) Rapport du Rapporteur spécial sur le droit à l'alimentation, Nations Unies, décembre 2010

de Schutter O (2011) Agroécologie et droit à l'alimentation. Rapport Présenté à La 16ème Session Du Conseil Des Droits De l'Homme De l'ONU, New York, Etats-Unis, ONU

Debray A (2011) La notion de réseau écologique en France: construction scientifique, appropriation par les politiques publiques et traduction territoriale. Vertigo – la revue électronique en sciences de l'environnement, Débats et perspectives, (en ligne). doi:10.4000/vertigo.10687

Dietz T, Ostrom E, Stern PC (2003) The struggle to govern the commons. Science 302(5652):1907–1912. doi:10.1126/science.1091015

European Union (2011) La biodiversité, notre assurance-vie et notre capital naturel – Stratégie de l'UE à l'horizon 2020, Communication de la commission au parlement européen, au conseil, au comité économique et social européens et au comité des régions, Bruxelles, COM(2011) 244 final, 3 mai 2011, 17 p

Folke C, Hahn T, Olsson P, Norberg J (2005) Adaptive governance of social-ecological systems. Ann Rev Environ Res 30:441–473

Food and Agriculture Organization of the United Nations (2011) Save and grow. A policymaker's guide to the sustainable intensification of smallholder crop production. FAO, Rome, 102 p. ISBN 978-92-5-106871-7. http://www.fao.org/ag/save-and-grow/

Francis C, Lieblein G, Gliessman S, Breland TA, Creamer N, Harwood L, Salomonsson L, Helenius J, Rickerl D, Salvador R, Wiedenhoeft M, Simmons S, Allen P, Altieri M, Flora C, Poincelot R (2003) Agroecology: the ecology of food systems. J Sust Agr 22(3):99–118

Funes Monzote FR (2009) Agricultura con futuro. La alternativa agroecologica para Cuba. Estacion experimental Indio Hathuey. Universidad de Matanzas, Cuba

Giddens A (1999) Runaway world: how globalization is reshaping our lives. Profile, London, 104 p

Griffon M (2006) Nourrir la planète. Pour une révolution doublement verte. Odile Jacob, Paris, 456p

Gunderson LH, Holling CS (2002) Panarchy: understanding transformations in human and natural systems. Island Press, Washington, DC

Hall AJ (2009) Challenges to strengthening agricultural innovation systems: where do we go from here? Farmer First revisited. Scones and Thompson, London

IAD (2011) L'agriculture de 2050 commence maintenant. Produit par L'Institut de L'Agriculture Durable, 47 p

IPCC (2007) Fourth assessment report (IPCC AR4). Intergovernmental Panel on Climate Change, Geneva

IPCC (2013) Climate change. The physical science basis, Working group I contribution to the Fifth Assessment Report, Cambridge University Press, Cambridge, UK/New York, NY, USA

Kassie M, Zikhali P, Pender J, Köhlin G (2009) Sustainable agricultural practices and agricultural productivity in Ethiopia: does agroecology matter? Environment for Development, April 2009, DP-09-12, 43 p

Mermet L (2011) Strategic environmental management analysis: addressing the blind spots of collaborative approaches. IDDRI, Coll pour le débat, n°5, 34 p

Mermet L, Leroy M, Narcy JB, Poux X (2005) L'analyse Stratégique de la gestion environnementale: un cadre théorique pour penser l'efficacité en matière d'environnement. Nat Sci Soc 13:127–137

Monod J (1970) Le hasard et la nécessité. Essai sur la philosophie naturelle de la biologie moderne. Edition du Seuil, Paris, 197p

Mzoughi N, Napoléone C (2013) L'écologisation, une voie pour reconditionner les modèles agricoles et dépasser leur simple évolution incrémentale. Nat Sci Soc 21:161–165. doi:http://dx.doi.org/10.1051/nss/2013092

Ozier-Lafontaine H, Angeon V (2012) Viability and adaptive governance of tropical island Agrosystems. French National Research Agency, Antilles françaises, March, 43 p

Ozier-Lafontaine H, Boval M, Alexandre G, Chave M, Grandisson M (2011) Vers l'émergence de nouveaux systèmes agricoles durables pour la satisfaction des besoins alimentaires aux Antilles-Guyane. Innov Agrono 16:135–152

Pahl-Wostl C (2009) A conceptual framework for analyzing adaptive capacity and multi-level learning processes in resource governance regimes. Global Environ Change 19:354–365

Pahl-Wostl C, Craps M, Dewulf A, Mostert E, Tabara D, Taillieu T (2007) Social learning and water resources management. Ecol Soc 12(2):22p

Saint-Pierre P (1994) Approximation of the viability kernel. Appl Math Optim 29:187–209

Saint-Pierre P (1997) Le calcul du noyau de viabilité, outil d'analyse des modèles dynamiques de systèmes contraints. In Blasco F (ed) Tendances nouvelles en modélisation pour l'environnement: Journées du Programme Environnement, vie et sociétés du CNRS [Paris, 1996]. Elsevier, Paris/Amsterdam/Oxford

Termeer C, Dewulf A, van Lieshout M (2010) Disentangling scale approaches in governance research: comparing monocentric, multilevel and adaptive governance. Ecol Soc 15:15

Tomich TP, Brodt S, Ferris H, Galt R, Horwath WR, Kebreab E, Leveau JHJ, Liptzin D, Lubell M, Merel P, Michelmore R, Rosenstock T, Scow K, Six J, Williams N, Yang L (2011) Agroecology: a review from a global-change perspective. Annu Rev Environ Resour 36:193–222. doi:10.1146/annurev-environ-012110-121302

Vimal R (2010) Des aires protégées aux réseaux écologiques: science, technique et participation pour penser collectivement la durabilité des territoires, Thèse en biologie des populations et écologie, Université de Montpellier II, décembre 2010

World Bank (2006) Enhancing agricultural innovation: how to go beyond the strengthening of research systems. Economic Sector Work report, Washington, DC

World Bank (2007) Améliorer l'innovation agricole: Comment aller au-delà du renforcement des systèmes de recherche. Banque Mondiale, Washington, DC

Young OR, Berkhout F, Gallopin GC, Janssen MA, Ostrom E, van der Leeuw S (2006) The globalization of socio-ecological systems: an agenda for scientific research. Glob Environ Chang 16:304–331

Food and Energy Production from Biomass in an Integrated Farming System

Reg Preston and Lylian Rodríguez

Abstract This chapter describes experiences in a small farm in the Colombian foothills, in which the aim was to demonstrate – and at the same time to research – the major components of the strategy that should underpin all future farming systems: namely the need to "decarbonize" the system, by reducing emissions of greenhouse gases, generating electricity locally from natural resources, making maximum use of solar energy and ensuring there is no conflict between use of available resources for both food and fuel production. The inevitable decline in the production of oil (peak oil), which will have negative effects on all features of contemporary lifestyles, is viewed from the positive standpoint of the opportunities that will be created for more sustainable farming systems when solar energy, via the production of biomass, will be the basis of the required needs for food, feed and fuel energy.

It is argued that in such a scenario, small scale integrated family farms, will have comparative advantages – economic, social and environmental – in a world in the decline phase of the oil age and increasing dependence on solar energy. Transport is the major end user of fossil fuel, thus as the supply of this resource diminishes and the price increases, there will be advantages in decentralization and localization of both production and processing of the immediate products of photosynthesis which are of low bulk density and therefore expensive to transport. An analysis of the alternative technologies for production of fuel energy from biomass, as a component of a farming system, leads to the conclusion that gasification is the most appropriate

R. Preston (✉)
Center for Research and Technology Transfer, Nong Lam University,
Linh Trung Ward, Thu Duc District, Ho Chi Minh City, Vietnam
e-mail: preston@lrrd.org

L. Rodríguez
Finca TOSOLY, AP 23, Socorro, Colombia
e-mail: lylianr@utafoundation.org

H. Ozier-Lafontaine and M. Lesueur-Jannoyer (eds.), *Sustainable Agriculture Reviews 14: Agroecology and Global Change*, Sustainable Agriculture Reviews 14,
DOI 10.1007/978-3-319-06016-3_2,

route. The advantages of this process are that: the feedstock is the fibrous parts of plants which are not viable sources of food or feed. The energy used to drive the process is derived from the combustion of the feedstock and there is minimal input of external sources of energy, (mainly for the construction of the gasifier and associated machinery). The products of gasification are a combustible gas and a carbon-rich residue (biochar). The gas can be used to drive an internal combustion engine linked to an alternator producing electricity; while the biochar when returned to the soil can be a sink for sequestering carbon and a means of improving soil fertility.

The role of livestock in the farming system is emphasized as the means of optimizing the use of highly productive perennial crops such as sugar cane and multi-purpose trees. Sugar cane is easily separated into energy-rich juice which can replace cereal grains in feeding of pigs and residual bagasse which is one of the feed-stocks of the gasifier. Forage trees are the natural feed resources for goats which selectively consume the leaves, leaving the fibrous stems as another feedstock for gasification. Sugar cane juice contains no fibre and almost no protein which creates opportunities for use of vegetative sources of protein such as the foliage of perennial plants, among which Taro (*Colocacia esculenta)* and New Cocoyam (*Xanthosoma sagittifolium*) have been found to have many advantages. It is concluded that integrated, small scale, farming systems based around multi-purpose crops and livestock, can provide food, feed and fuel energy with no conflict among these end uses. Gasification of fibrous crop residues produces electricity and a soil conditioner (biochar) that is also a sink for sequestration of atmospheric carbon. Bio-digestion of all liquid wastes produces a gaseous fuel for cooking with alternative use as a complement to the gaseous fuel from the gasifier. The system delivers real benefits for the environment as a negative carbon footprint through carbon sequestration and improvements in soil fertility.

Keywords Biochar • Biodigesters • Biomass • Carbon footprint • Carbon sequestration • Cattle • Climate change • Electricity • Energy • Feedstock • Fossil fuel • Gasification • Global warming • Goats • Greenhouse gas emissions • Livestock • Pigs • Soil fertility • Sustainable farming systems

Energy as the Stimulus to Development – And Economic Recession

The components of the world crises – economic recession, global warming and resource depletion (especially fossil fuels) – presently facing humanity are closely inter-related. The gaseous emissions from the burning of fossil fuels are the major contributor to global warming; the apparently inexhaustible supply of fossil fuels facilitated the exponential growth of the world population during the past century and, more recently, the unsustainable indebtedness in the developed countries, which led to the economic recession of 2008–2009.

In the past century, the needs for energy, and indirectly for food, of the expanding world population were provided by cheap oil. The inevitable process of adaptation to increasing cost and declining supplies of oil, will almost certainly change the future life style of the majority of the world's population. On the positive side it will provide greater opportunities for small scale farmers as there will be comparative advantages – economic, social and environmental – for the utilization of biomass for food, feed and fuel production, in a world in the decline phase of the oil age. This is because over 70 % of fossil fuel is used for transport. As the supply diminishes and the price increases, transport will be the sector most affected. Most forms of biomass are of low bulk density. Thus, there will also be comparative advantages for decentralization and localization of both production and processing of this resource.

For the future, the only long term alternative to fossil fuel (as exo-somatic energy – that is energy not derived from digested food – muscle power) is solar energy, utilized either directly as a source of heat, or indirectly in solar-voltaic panels, as wind, movements of waves and tides, or in biomass produced by photosynthesis. Solar energy will also have to be relied on to produce food, in what must surely have to be small-farm systems in rural areas, to support the largely urbanized population, The green revolution which dramatically increased food supplies during the last 40 years was a "fossil energy" revolution as it was energy in the form of oil and natural gas which facilitated production of fertilizers, especially nitrogen, pesticides and herbicides, and the mechanization and irrigation that permitted multiple cropping.

Another "energy" revolution is possible but it will be based on making greater use of the energy derived daily from the sun. It must produce both energy and food and have an EROEI (Energy Return on Energy Invested) of at least 5 (Hall et al. 2008, 2009). It will also need the support of human energy and increased numbers of people working in rural areas.

There are few difficult decisions about producing food by photosynthesis. By contrast, the ideas proposed for redirecting energy from the sun into potential energy to replace that of fossil fuels are many. Rapier (2009) describes many of these proposals as *Renewable Fuel Pretenders* arguing that their proponents believe they have a solution but that it will never develop into a feasible technology because the proponents "have no experience at scaling up technologies". In this category he lists cellulosic ethanol, hydrogen and diesel oil from algae.

It is surprising that gasification of biomass, as a means of producing a combustible gas, has received so little attention – perhaps because it is not a new technology. It is one of the purposes of this chapter to demonstrate that it holds real prospects of being applicable at the small, dispersed farm level, provided it is developed as a component of a mixed, integrated farming system.

Gasification is a process for deriving a combustible gas by burning fibrous biomass in a restricted current of air. The process is a combination of partial oxidation of the biomass with the production of carbon which at a high temperature (600–900 °C) acts as a reducing agent to break down water and carbon dioxide (from the air) to hydrogen and carbon monoxide, both of which are combustible gases. In the gasification process, some of the carbon from the biomass combines with the mineral fraction to produce biochar (Lehmann and Joseph 2009), which promises to have multiple uses in the farming system (Rodríguez et al. 2009c; Preston 2014).

The advantages of gasification are that:

- the feedstock is the fibrous part of plants which are not viable sources of food or feed;
- the energy used to drive the process is derived from the combustion of the feedstock;
- there is minimal input of fossil fuel (mainly for the construction of the gasifier and associated machinery);
- the process can be de-centralized as units can be constructed with capacities between 4 and 500 KW.

Food, Feed and Energy from Biomass

Several writers (eg; Brown 2007; Falvey 2008) have challenged the morality of converting food into liquid fuel, in a world where one third of the population is already malnourished with certain prospects that this proportion will increase as the world population marches on to the eight to nine billion predicted before the mid-point of this century. Second generation ethanol from cellulosic biomass is also not the answer, as apart from the doubtful economics of the process, the major proposed feed-stocks – Switch grass and Miscanthus – provide no food component.

This conflict can be avoided by using gasification to produce the fuel energy, as the feedstock can be the cellulosic component of the plant, leaving the more digestible protein and carbohydrate components as the source of food/feed. The most useful end products of gasification are electricity and biochar, thus electrification of most road transport systems is a necessary corollary. Utilization of biochar will be facilitated by locating the gasification process within the farm producing the biomass.

Sugar Cane, Protein-Rich Forages and Pigs

The choice of sugar cane as the pivotal crop in the farming system is justified by its high yield and efficient use of solar energy, and the ease of separating the 100 % digestible sugar cane juice from the structural fibre (bagassse). Because the juice contains no fibre, it is the perfect medium for facilitating the incorporation in diets for pigs of protein-rich vegetative sources such as the edible leaves of trees, shrubs and vegetables, the levels of which in cereal-based diets are constrained by their moderately high levels of fibre. Research has been done with several protein-rich forages, including the leaves of cassava and mulberry, the vines of sweet potato, the leaves and stems of water spinach and more recently the leaves and stems of Taro (Preston 2006). In his review of these different forages, Preston (2006) came to the conclusion that the Colocacia, Alocacia and Xanthosoma members of the Araceae family offered the greatest potential as vegetative protein sources in pig diets because of their high yield, ease of cultivation (many species grow wild in ponds and in the forests [Peng Buntha et al. 2008; Ngo Huu Toan and Preston 2007]), ease of conservation by ensiling (Rodríguez and Preston 2009a), and the apparent relatively high energy value of the stems complementing the protein in the leaves.

The choice of pigs as the main livestock component in an integrated farming system is justified by several factors: ease of marketing the meat, low investment (compared with cattle), and the fact that pig excreta is the preferred feedstock in anaerobic biodigesters.

Feed and Energy from Forage Trees and Goats

The advantages offered by sugar cane as a combined source of feed for pigs and gasifier feedstock have already been discussed. A similar synergism applies to the use of forage trees as the protein source for goats. The browsing habit of this species facilitates the separation of the leaves, which become the protein component of the diet, while the residual stems are easily processed as feedstock for the gasifier.

In the TOSOLY farming system, the chosen trees species are Mulberry (*Morus alba*) and Tithonia (*Tithonia diversifolia*). Mulberry leaves have been extensively studied as a protein source for ruminants, mainly goats (Yao et al. 2000; Theng Kouch et al. 2003; Nguyen Xuan Ba et al. 2005; Pathoummalangsy Khamparn and Preston 2008). The conclusion of Pathoummalangsy Khamparn and Preston (2008) was that Mulberry leaves almost certainly were rich in "bypass" protein in view of the marked increases they induced in the growth rate of goats.

The multi-purpose role of sugar cane is apparent in the fact that for pig feeding and gasification, only the stalk is used. The growing point and leaves are thus available as a potential energy-feed resource for ruminants.

Integrated Farming Systems

In a recent paper, on the "Post Carbon Institute" web site, Heinberg and Bomford (2009) stated that

> "The only way to avert a food crisis resulting from oil and natural gas price hikes and supply disruptions while also reversing agriculture's contribution to climate change is to proactively and methodically remove fossil fuels from the food system". Their proposals in relation to farming systems were that:
>
> "Farmers should move toward regenerative fertility systems that build humus and sequester carbon in soils, thus contributing to solving climate change rather than exacerbating it. More of the renewable energy that will power society can and must be generated on farms. Wind and biomass production, in particular, can provide farmers with added income while also powering farm operations".
>
> In the same report they referred to papers indicating that, compared with large farms, "smaller farms have greater biodiversity (Hole et al. 2005), more emphasis on soil-building (D'Souza and Ikerd 1996) and greater land-use efficiency (Rosset 1999)".

In a review of the investment opportunities in agriculture to increase food production in a resource-depleted world (Kahn and Zaks 2009), the point was made that “Alternative approaches are being researched and tested in development such as the reemergence of small, self-sufficient organic farms, characterized as local, multi-crop, energy and water efficient, low-carbon, socially just, and self-sustaining”.

The TOSOLY Farm in Santander, Colombia

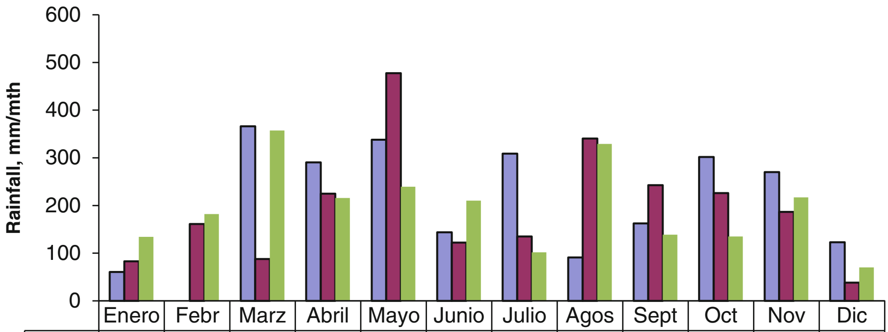
The Farming System

The TOSOLY farm is situated in the Colombia foothills, in the Department “Santander Sur”, 20 km from the town of Socorro (Map 1).

The region is characterized by relatively uniform rainfall (Fig. 1) and soils that are acidic (pH 4.0–4.50).

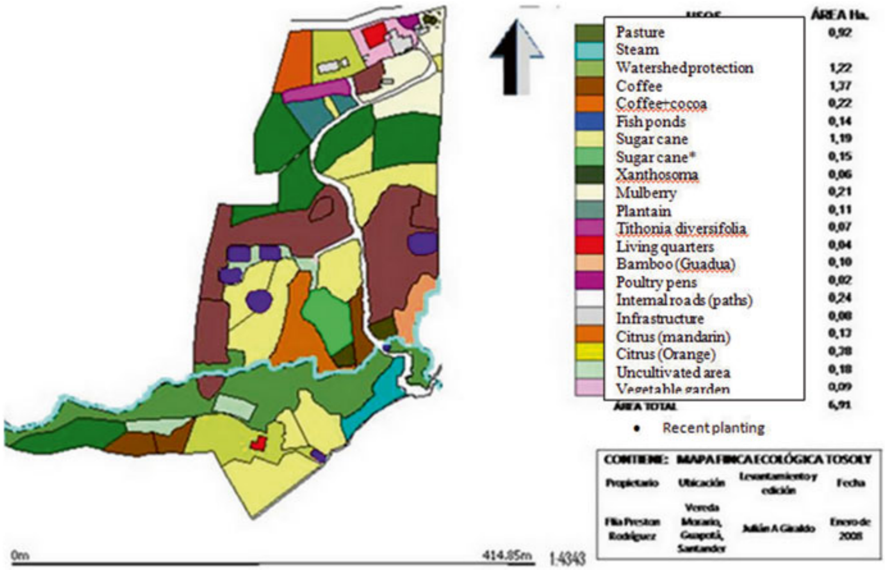
The farm is situated at 1,500 msl and occupies an area of 7 ha on a hillside with overall slope of 20 % (difference in height of 60 m over a distance of 350 m). Traditionally the soils in the region have been, and continue to be, exploited for

Map 1 Location of the TOSOLY farm



	Enero	Febr	Marz	Abril	Mayo	Junio	Julio	Agos	Sept	Oct	Nov	Dic
2007	60	0	366	290	338	144	309	91	162	302	270	123
2008	83	161	88	225	477	122	135	340	243	226	187	38
2009	134	182	357	216	239	210	102	329	139	135	217	70

Fig. 1 Monthly rainfall in TOSOLY farm during 2007–2009



Map 2 Distribution of the cropping areas in TOSOLY farm

shade "Arabica" coffee and small scale production of "Panela" from sugar cane. In order to promote biodiversity, the crops on the farm are replicated in different areas (Map 2). The principal crop is sugar cane (Photo 1), presently occupying 1.34 ha but projected to increase to 2 ha as the pasture areas are gradually displaced with more productive crops.

Tree crops include coffee, cocoa, and forage trees (chiefly mulberry [*Morus alb*a] (Photo 2), and "Boton de oro" [*Tithonia diversifolia*] (Photo 3), forage plants (New Cocoyam [*Xanthosoma Sagittifolium*] (Photo 4) and Water spinach [*Ipomoea*

Photo 1 Sugar cane is distributed in different areas of the farm always in close proximity to trees

Photo 2 Mulberry (*Morus alba)* is the major protein source for goats, cattle and rabbits

aquatica] (Photo 5) and trees for timber and fuel, including a grove of 'Guadua" (*Guadua angustifolia*) (Photos 6 and 7), and Guamo *(Inga hayesii* Benth) for shading the coffee (Photo 8).

The livestock and fuel components are chosen for their capacity to utilize the crops and by-products produced on the farm. Sugar cane stalk is fractionated into juice and residual bagasse. The tops including the growing point and some whole stalk

Photo 3 "Boton de oro" (*Tithonia diversifolia)* has excellent agronomic properties and is fed to the goats along with the mulberry foliage

Photo 4 New Cocoyam (*Xanthosoma saggitifolium*) is the preferred protein source for the pigs

are the basal diet for dual purpose cattle and goats. The juice is the energy feed for pigs (Photo 9) and the source of "sweetener" for cooking for the farm family.

The bagasse (Photo 10) is the fuel source for a gasifier (Photo 11) that provides combustible gas for an internal combustion engine linked to an electric generator.

Photo 5 Water spinach (*Ipomoea aquatica)* a high protein vegetable for people and animals. Needs neutral soils but is now grown in the farm after soil amendment with Biochar

Photo 6 "Guadua" *(Guadua angustifolia)* finds major uses on the farm for construction (Photo 7)

The goats are the means of fractionating the forage trees (Photo 12), consuming the leaves, fine stems and bark as sources of protein, with the residual stems being another source of fuel in the gasifier.

The pig unit has capacity for 40 growing-fattening pigs and 5 sows (Photo 13a, b).

Photo 7 "Guadua" provides the support structure of the plastic canopy for drying the coffee beans, the bagasse and the stems of mulberry and Tithonia

Photo 8 Guamo *(Inga hayesii* Benth) is the traditional shade tree for coffee

The goat unit (Photo 14) has ten breeding does and two bucks. There are three pens for two crossbred cows and progeny (Photo 15), kept for triple purpose production of milk, meat and manure.

Hens and ducks are raised in semi-scavenging systems (Photos 16 and 17) for eggs and meat.

Photo 9 Sugar cane juice is the basal diet for the pigs

Photo 10 The bagasse is sun-dried and separated into fine (on the *left*) and coarse particles (on the *right*); the former for the gasifier and the latter as litter for the cattle and goats

Rabbit production is a new venture on the farm, applying the principles of 100 % forage diets developed in Cambodia, Laos and Vietnam (http://www.mekarn.org/prorab/content.htm) (Photo 18).

A horse serves to transport sugar cane and forages (Photos 19 and 20).

All high moisture wastes are recycled through plug-flow, tubular plastic (Polyethylene) biodigesters. Pig and human excreta are the feedstock for four biodigesters (Photo 21). Waste water from coffee pulping, washing of dishes and clothes go to a fifth biodigester (Photo 22).

Photo 11 The down-draft gasifier for converting fibrous biomass to electricity

Photo 12 Goats are very efficient in fractionating the mulberry and the Tithonia, consuming the leaves and leaving the stems for the gasifier

Effluents from all biodigesters are combined (Photo 23) and recycled to the crops as fertilizer.

The pens for the goats and cattle have clay floors covered with a layer of bagasse to absorb the excreta (Photos 14 and 15). Periodically this manure is returned to the crops as fertilizer and as a source of organic matter (Photo 24).

The features and links of the farming system are shown in Fig. 2.

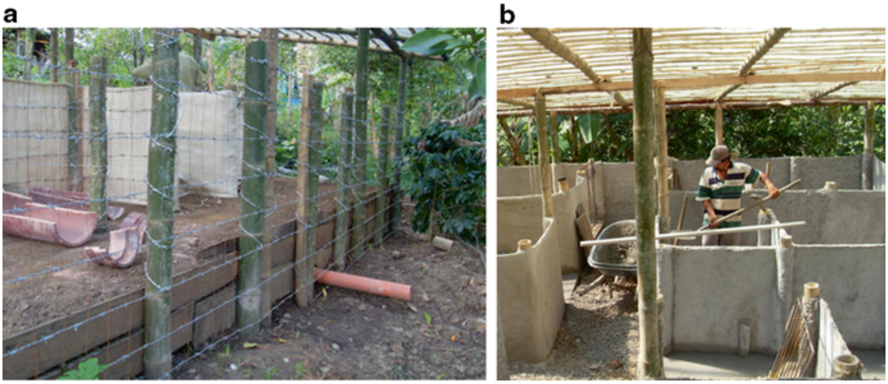


Photo 13 (**a**, **b**). New housing for pregnant and lactating sows uses local materials and a construction technique ("el muro tendenoso") that reduces cement needs by more than 50 % and eliminates need for bricks. The amount of "embedded" fossil fuel energy is much reduced by this system

Photo 14 The coarse bagasse not suitable for the gasifier is an excellent bed for the goats. Mulberry and Tithonia are suspended in racks, a technique that has been shown to stimulate feed intake (Theng Kouch et al. 2003)

Lessons Learned

The overall aim of the TOSOLY farm was to provide data that would contribute to the development of sustainable farming systems in the tropics, against a background of the triple world crises of resource depletion, especially oil, climate change and economic recession. It is argued that in order to respond to these pressures, future farming systems must produce not only food for people and feed for animals, but

Photo 15 Multi-purpose cows produce, milk, meat and manure

Photo 16 Scavenging hens help to control the weeds under the forage trees

also energy that will perform useful tasks on the farm, with surplus supplies being channelled into the electrical grid or for the use of local communities. These objectives should be met within a framework of activities that ensures an overall negative carbon footprint. Responding to the energy crisis not only requires the development of renewable sources of energy. The efficiency of using energy must

Photo 17 Duckweed (*Lemna minor*) is highly appreciated by the ducks in as semi-scavenging system

Photo 18 Rabbits are fed exclusively on forages produced on the farm

also be increased as there is no alternative form of energy that can replace fossil fuels at the present rate of usage.

For these reasons, the components that were chosen as subjects to be researched were:

- The nutritional value of the foliage of New Cocoyam (*Xanthosoma sagittarius*) as a replacement for soybean meal in diets of growing pigs

Photos 19 and 20 Horses do not need fossil fuel

Photo 21 Three biodigesters receive washings from the pig pens and from the family toilets

- The biochar produced as a byproduct of the gasification of the bagasse as a soil amendment
- Agronomic studies to measure the biomass yield of New Cocoyam
- Ensiling the combined leaves and petioles of New Cocoyam
- The gasification of sugar cane bagasse and stems of forage trees
- Measuring the EROEI for production of electricity by gasification of sugar cane bagasse

Photo 22 Waste water from the kitchen, the clothes washer and the machine for pulping fresh coffee beans is directed to this biodigester

Photo 23 Effluents from all the biodigesters are recycled to the crops and forages as fertilizer

Photo 24 Manure from the cattle and goats is a major source of fertilizer and organic matter for recycling to the crops

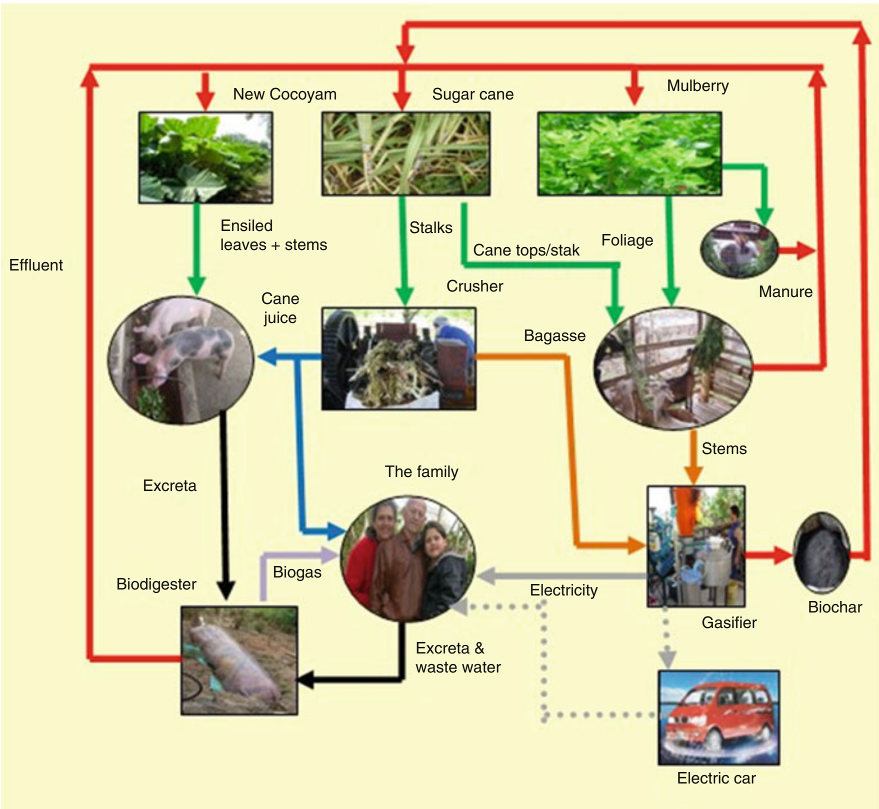


Fig. 2 The features and links of the farming system in TOSOLY

Sugar Cane and Foliage from Trees and Crop Plants as Feed Resources for Livestock and as Sources of Renewable Energy

The rationale for investigating these resources is based on several premises.

Localization of Production

The first premise is the need to develop farming systems that utilize resources that can be grown on the farm with minimal need for external sources of energy. Transport presently accounts world-wide for some 30 % of fossil fuel use and is a major component of the embodied energy in purchased feeds. This cost can be avoided to a major extent if feeds and energy are produced on the farm.

Farm Size

If the farm size is relatively small (4–7 ha), the use of animal traction instead of machines is much more feasible; and the recycling of livestock manure is facilitated. There are also social benefits when the workers are also the owners, as is possible in the "family" farm. The farm most be seen as part of a community of small scale farmers. The integrated system requires an "integrated teamwork". The system per se requires special people in terms of commitment and enthusiasm, requires capable people which does not necessarily mean people with high level of education. It is clear that, on balance, the capacity to learn by doing and learn by living counts more than the degree of education. The system needs leadership and understanding of the global issues to be able to act locally. The system must promote integration with neighbours to be able to accomplish the different tasks in the farm. The system is projected to encompass family and community development.

Efficient Capture of Solar Energy

If it is accepted that solar energy is the only sustainable source of energy, then farming systems must be designed to maximize the rate of capture of this resource. Forty years ago, Kormondy (1969) pointed out the advantages for biomass production of tropical latitudes and of perennial crops and forest compared with annual crops (Fig. 3). Similar contrasts were highlighted by Patzek (2007) (Fig. 4). In the latter case the contrast between pastures and crops and forests is especially noteworthy. The decision to base the cropping system in the TOSOLY farm on sugar cane and trees has thus a firm ecological basis.

Apart from being perhaps the most efficient known plant for capturing solar energy, sugar cane has many other advantages, linked specifically with the argument that we need to produce both food/feed and fuel energy from the farming system.

Fig. 3 Net biomass production from different ecosystems (Kormondy 1969)

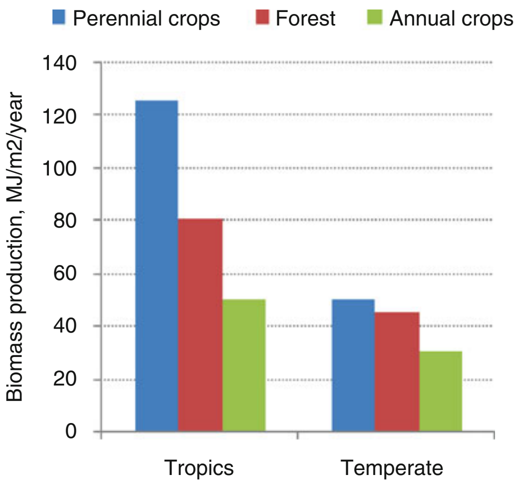
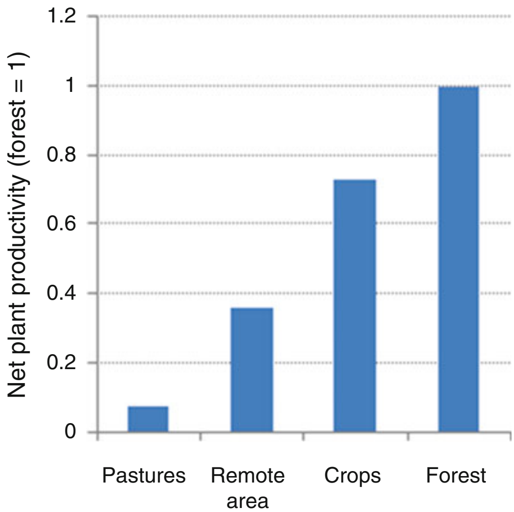


Fig. 4 Net plant productivity of different ecosystems in the USA (Adapted from Patzek 2007)



The ease of separating sugar cane stalk into juice and residual fibre (the bagasse used as fuel to evaporate the water) was exploited five centuries ago by European colonialists in the Caribbean. The fact that the juice contains no fibre and is 100 % digestible was the reason to develop it as the preferred energy source for pig feeding in the tropics (Mena et al. 1981), as it was hypothesized that the absence of fibre would facilitate incorporation in the pig diet of high yielding protein-rich foliages, the fibre content of which would have been a limiting factor if combined with conventional energy sources from cereal grains. The use of the bagasse as a source of "biofuel" was shown at that time to be technically feasible but economically unattractive in a world driven by cheap petroleum and natural gas.

New Cocoyam (Xanthosoma sagittifolium)

Using the Fresh Leaves as a Protein Source for Growing Pigs

The appreciation of the potential role of New Cocoyam (known locally as "Bore" or "Malanga") in the TOSOLY integrated farming system was accidental. Initial attempts to grow and use cassava foliage as the protein-rich forage to accompany the sugar cane juice proved to be a failure in that at 1,500 msl the plant would not survive the repeated harvesting that had proved successful at <20 msl in Vietnam and Cambodia (Preston 2001; Preston and Rodríguez 2004, 2010). Bore was found growing wild in the humid natural forest area of the farm. Observations on the pigs offered the leaves of New Cocoyam showed it to be highly palatable and led to the experiment described by Rodríguez et al. (2006) in which 50 % of the protein normally supplied by soybean meal was replaced by fresh leaves of New Cocoyam with no reduction in pig performance rates compared with the control diet of 100 % of the protein from soybean meal.

The experiment described by Rodríguez et al. (2009a) aimed to explore the effects on parameters of apparent digestibility and N retention in young growing pigs of 100 % replacement of the soybean protein by New Cocoyam leaves. In this trial the leaves were homogenized in a blender along with sugar cane juice to facilitate feeding and to avoid wastage in the metabolism cage. DM intakes were high (5 % of live weight) and similar with substitution rates of soybean protein up to 53 % and even with 100 % substitution intakes were only reduced by some 7 %. The major effect was a substantial linear decline in the digestibility of the protein as the substitution with New Cocoyam leaves was increased, and a resultant linear decrease in N retention of about 25 % at the 100 % substitution level. There was, however, a compensatory response in that N excreted in the urine decreased linearly with level of New Cocoyam leaves with the overall result that the N retention as a percentage of N digested favoured the diets with increasing proportions of New Cocoyam leaves.

Using the Ensiled Leaves as a Protein Source for Growing Pigs

The third experiment in this series (Rodríguez and Preston 2009b) aimed to determine the feasibility of using ensiled New Cocoyam leaves (ENCL), instead of the fresh leaves, as the only protein source to balance the sugar cane juice in the diet of young growing pigs (mean initial LW of 19 kg). The experimental design was a production function with the independent variable being the level of crude protein in the range of 80–160 g crude protein per kg of diet DM. The levels recorded in the experiment varied slightly (87–149 g crude protein/kg DM) equivalent to a range in proportions of diet DM as ENCL of 46–67 %.

The relationship between proportion of ENCL in the diet DM (X) and N retention (Y = g N/kg LW) was curvilinear with the maximum value of N retention being reached when the ENCL provided 66 % of the diet DM, equivalent to a crude protein concentration of 13 % in the diet DM. Intakes of DM were high on all diets with the maximum of 4.5 % of LW with 55 % of ENCL in the diet corresponding to a crude fibre content of 9 % in the diet DM.

The experimental deign can be criticized in that the eight different levels of ENCL were achieved by using the same four pigs in two consecutive periods such that there was no replication of any one chosen level. Nevertheless the results were broadly in line with theoretical expectations. The pigs easily consumed the ensiled leaves at levels (66 %) which were double those (35 %) reported by Leterme et al. (2005) who dried and ground the leaves of New Cocoyam prior to incorporating them in a diet based on maize. The maximum pig response, as measured by N retention, was achieved with 66 % of the diet in the form of ENCL. At this point the crude fiber content had reached 9 % which is within the range (7–10 % according to Kass et al. 1980) when pig growth rates begin to be depressed, as was observed in our experiment. In the experiment of Leterme et al. (2005), the basal diet contained maize, soybean meal and rice hulls, thus with only 35 % of New Cocoyam leaf meal in the diet, the overall fiber level was already 8 % in DM, relatively close to the level of 9 % fibre with 66 % ENCL in a basal diet of sugar cane juice.

In the pig feeding system described in our research, in which the basal diet of sugar cane juice contains neither fibre nor protein, these two components have opposing influences on performance when foliages are used as the protein supplement. To achieve the level of protein necessary to optimize growth rates (about 13–15 % in DM) results in reaching levels of crude fibre which act so as to reduce performance (eg: "the shielding effect on the plant cell contents by the indigestible cell walls, increased rates of passage of digesta as a result of its increased bulk and water-holding capacity, irritation of the gut wall mucosa by VFA produced in the hind-gut, possible presence of anti-nutritional factors, bulkiness, energy dilution and possibly heat stress" [Ogle 2006]). To increase the protein level in these diets without increasing the crude fiber content would require using protein sources such as fish meal or soybean meal, which have very little or no fibre. The final decision will depend on the relative economics of using locally-grown protein supplements as opposed to purchased supplements. Such economic considerations will depend on monetary costs and also increasingly on "embedded" (fossil) energy costs of the alternative feed resources. This aspect will be discussed in a later section of this Chapter.

Ensiling Leaves and Petioles of New Cocoyam

Practical experiences on the farm led to the conclusion that daily harvesting and feeding of fresh New Cocoyam leaves was not convenient from the standpoint of: (i) appropriate management of the New Cocoyam plant as leaf growth was dependent on climatic factors, which meant that daily harvesting did not always yield the required amounts of leaves, and often the leaves were harvested when they were still immature; and (ii) daily harvesting was time consuming and inefficient in the use of the horse used to transport the leaves. This led to the decision to study the ensiling of the leaves which would permit harvesting of the leaves at the most appropriate stage of growth, from the physiological viewpoint (the leaves of New Cocoyam have similar growth cycles as leaves from banana plants, in that every 2–3 weeks new leaves emerge from the stem and grow until the point of senescence is reached usually some 3–4 weeks later). The work of harvesting and ensiling was then organized on a cycle of 20–25 days in accordance with the growth stage of the plants.

The studies described by Rodríguez and Preston (2009a) were initiated in order to define the most appropriate method for ensiling the New Cocoyam foliage, as there were no references to be found in the literature on ways to process and store this foliage by ensiling. The first attempt followed conventional procedures using sugar cane juice as a substitute for molasses. The ensiled leaves produced by this process had all the required qualities of low pH, attractive colour and smell and absence of mould. The problem was the considerable effort needed to mix the cane juice with the macerated leaves and then to consolidate them in the plastic container. The other problem that arose was the disposal of the petioles. It was not convenient to leave them in the field as mulch, as this would have required transporting only the leaves – a difficult operation in sloping terrain which necessitated stacking the load in the structure mounted on the horse which is the traditional way of transporting sugar cane (Photo 8.1). Attempting to accommodate only the leaves in this structure proved to be highly inconvenient and inefficient. The other option of feeding the petioles to the pigs proved to be feasible in that they were well accepted. It was also observed that ensiling the petioles, despite the high moisture content (>90 %) was an effective way of conserving them; furthermore, it was found there was no need to add additional fermentable sugars as the pH dropped to less than 4 within 48 h. But again, the work load of separating the leaves from the petioles and macerating each of these components separately was time-consuming. Moreover, forcing the leaves into the ensiling machine was difficult. By contrast, passing the intact foliage – leaf and petiole – into the ensiling machine was easy and rapid. The logical next step was to ensile the combined leaf and petiole. This also produced excellent silage and has become the standard management system on the farm for processing New Cocoyam foliage. This procedure thus fulfilled all the requirements for producing a uniform and nutritious product, without the need for any additive.

The observation that the juice in the petiole was high in soluble sugars (4–5 % in the juice = about 25 % in the DM) explained the good results obtained by incorporating the petiole with the leaf in the silage. The negative consequence – a decrease in the protein content of the mixture (the petiole contains only 7–8 % crude protein in DM) – was compensated by the more efficient use of the plant biomass (the petioles make up some 50 % of the foliage DM. The other feature of the petiole in New Cocoyam is that, in contrast with many other forages, it is not heavily lignified as it is the water in the petiole which provides the main structural support for the leaves, in the same way that the pseudo-stem supports the leaves in the banana plant. Analysis of the leaves and petioles showed that the content of NDF was lower in the petioles (22.7 % in DM) than in the leaves (37.8 %). ADF values showed similar trends. The low content of structural carbohydrates in the petiole, together with the high content of soluble sugars, leads to the conclusion that the petiole can be

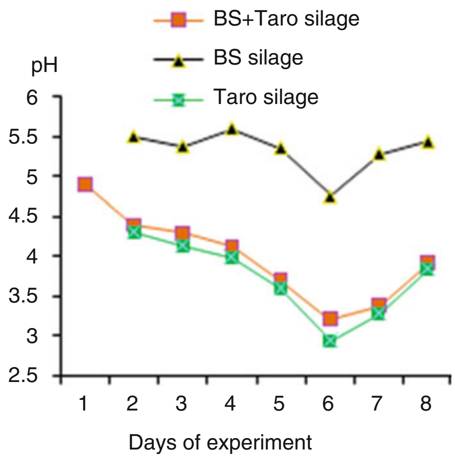


Fig. 5 Pattern of pH change in ensiled banana pseudo-stem (BS) with and without incorporation (50:50 fresh basis) of taro foliage (changes in the pH of Taro silage are also shown) (Dao Thi My Tien et al. 2010)

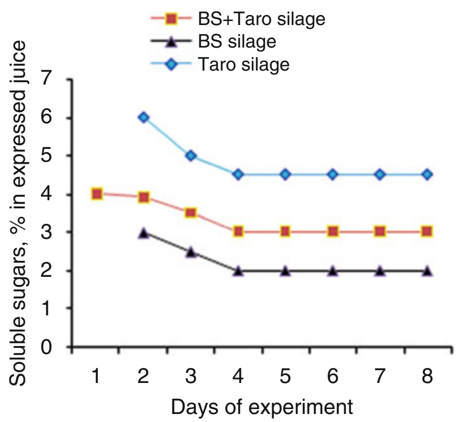


Fig. 6 Change of soluble sugars in ensiled banana pseudo-stem (BS) with and without incorporation (50:50 fresh basis) of taro foliage (changes in Taro silage are also shown) (Dao Thi My Tien et al. 2010)

considered as a potential energy source, as well as a convenient medium for facilitating the ensiling process. Some recent results from Vietnam (Figs. 5 and 6) demonstrate the beneficial effects of mixing the leaf and petiole of Taro (*Colocacia esculenta*) with the pseudo-stem of banana, which can be linked to the relatively high content of soluble sugars in the Taro.

Biomass Productivity of New Cocoyam

The research described by Rodríguez and Preston (2009b) was a first attempt to generate information on the agronomic features of the New Cocoyam plant. The results showed clearly the advantages of establishing the plant from suckers (emerging new shoots) than from sections (disks) taken from the stem. The predicted annual per ha yields, in acid soils of low fertility, of 14.5 and 1.90 tonnes of DM and crude protein, respectively, show that the plant is efficient in capturing solar energy. With

Box 1

Beginning March 1 2009, those in Gainesville, Florida USA, with new solar photovoltaic systems will be eligible to receive 32 cents per kilowatt hour of electricity produced by the system over the next 20 years. http://www.gainesville.com/article/20090206/ARTICLES/902061014?Title=Commission-gives-its-approval-to-feed-in-tariff-for-solar-power

higher and more evenly spaced fertilization (eg: from biodigester effluent) it can be expected that the yield potential will be much greater.

On the basis of the above yields and assuming that 10 % of the crude protein needs are supplied by a high protein supplement such as fish meal, soybean meal or locally produced yeast, then the area planted to New Cocoyam should be 1.5 ha, the same as sugar cane to provide feed for an average population of 50 pigs.

Gasification of Sugar Cane Bagasse and Stems of Forage Trees

It is apparent from the research described by Preston and Rodríguez (2009) and Rodríguez and Preston (2010) that supplying the electricity needs of the farm could be met from gasification of less than 20 % of the available fibrous biomass residues from 1.5 ha of sugar cane and 1 ha of forage trees. This raises the question of how to use the surplus electricity (about 35 KWh daily). Schemes for feeding the energy into the local electricity grid are on-going in cities in Europe, USA and Japan (see Box 1).

At USD 0.30/KWh, the daily surplus of electricity (about 35 KWh) from 2.5 ha of cropland would be worth USD10.5, about USD 3,650 per year. Another alternative (in the future!) is to support directly the local community by developing a facility for charging the batteries of electric vehicles.

The important feature of the system is that food/feed production is not compromised as both feedstocks represent components of the respective crops which have no value as feed or food.

Energy Returned Over Energy Invested (EROEI)

The analysis of energy gained as a combustible gas as a function of the equivalent fossil fuel energy embedded in the various farm activities indicated an EROEI of about 8 which according to Hall et al. (2009) more than provides for the needs of society (estimated by these authors as an EROEI of the order of 5). There is an urgent need to develop this information which would facilitate the calculation of more precise estimates of the EROEI of integrated food-feed-energy production in a small scale farming system.

Biochar for the Mitigation of Greenhouse Gas Emissions and as a Soil Conditioner

The biochar produced by gasification promises to have multiple uses, most of which are still relatively unexplored. The degree to which it is a sink for sequestering carbon in the soil is the subject of numerous claims (see Lehmann 2007), based almost entirely on the observations made in the Amazon of carbon-rich "terra preta" soils formed by indigenous tribes thousands of years ago (Glaser 2007). Assuming that 2 tonnes of carbon dioxide are sequestered per ha of land cropped for integrated food-feed-energy production, and that there is a potential 3 billion ha of arable land available world-wide (OECD/FAO 2009), the biochar produced on this land area would permit the sequestration of 6 billion tonnes of carbon dioxide. Present world annual emissions of carbon dioxide http://en.wikipedia.org/wiki/List_of_countries_by_carbon_dioxide_emissions) are estimated to be 24 billion tonnes.

Thus if every hectare of crop land in the world was managed for integrated food-feed-energy the potential to sequester carbon dioxide is about 25 % of present world emissions.

According to the US Energy Administration Agency (http://www.eia.doe.gov/iea/elec.html), world electricity generation in 2006 was 18 trillion KWh. Taking the figure of 20 KWh/ha/day, then on a world basis this represents a potential annual production of about 21 trillion KWh, quite close to the recorded output in 2006.

Obviously not all the world arable land would be suitable for the integrated farming system of the type described in this Chapter. Nevertheless, there is obviously considerable potential for sequestering carbon and producing electricity from biomass without compromising food production and almost certainly with attendant gains in soil fertility and with positive effects on the environment.

Conclusion

The likely impacts from the experience on the TOSOLY farm are:

- Integrated, small scale, farming systems based around multi-purpose crops and livestock, can provide food, feed and energy with no conflict among these end uses.
- Gasification of fibrous crop residues produces electricity and a soil conditioner (biochar) that is also a sink for sequestration of atmospheric carbon. Biodigestion of all liquid wastes produces a gaseous fuel for cooking with alternative use as a complement to the gaseous fuel from the gasifier.
- The ensiled foliage (combined leaves and petioles) of Taro (*Colocacia esculenta)* and New Cocoyam (*Xanthosoma sagittifolia*) offers a high degree of promise as a protein-rich forage for replacing conventional protein sources in diets for pigs
- The system delivers real benefits for the environment (a negative carbon footprint) through carbon sequestration and improvements in soil fertility.

References

Brown LR (2007) Biofuels blunder: massive diversion of U.S grain to fuel cars is raising world food prices, risking political instability. http://www.earth-policy.org/Transcripts/SenateEPW07.htm. Retrieved Mar 2009

D'Souza G, Ikerd J (1996) Small farms and sustainable development: is small more sustainable? J Agr Appl Econ 28(1996):73–83

Dao Thi My Tien, Nguyen Tuyet Giang, Preston TR (2010) A note on ensiling banana pseudo-stem with taro leaves and petioles. In: MEKARN conference 2010, Champasack University, Pakse, Lao PDR. Livestock production, climate change and resource depletion. http://mekarn.org/workshops/pakse/abstracts/tien_agu2.htm

Falvey L (2008) Equity and morality in food and technology – biofuels or food? Science Alert. http://www.sciencealert.com.au/opinions/20082808-17872.html

Glaser B (2007) Prehistorically modified soils of central Amazonia: a model for sustainable agriculture in the twenty-first century. Philos Trans R Soc 362:187–196. http://rstb.royalsocietypublishing.org/content/362/1478/187.full

Hall CAS, the "EROI study team" (2008) Provisional results from EROI assessments. The Oil Drum. http://www.theoildrum.com/node/3810

Hall CAS, Balogh S, Murphy DJR (2009) What is the minimum EROI that a sustainable society must have? Energies 2:25–47. http://www.mdpi.com/1996-1073/2/1/25/pdf

Heinberg R, Bomford M (2009) The food and farming transition: toward a post carbon food system. Post Carbon Institute. http://pc-ds.webvanta.com/files/PCI-food-and-farming-transition.pdf

Hole D, Perkins S, Wilson J, Alexander I, Grice P, Evans A (2005) Does organic farming benefit biodiversity? Biol Conserv 122:113–130

Kahn BM, Zaks D (2009) Investing in agriculture: far-reaching challenge, significant opportunity (An asset management perspective). http://www.db.com/usa/download/Ag_whitepaper_062409.pdf

Kass ML, Van Soest PJ, Pond WG, Lewis B, McDowell RE (1980) Utilization of dietary fiber from alfalfa by growing swine. I. Apparent digestibility of diet components in specific segments of the gastrointestinal tract. J Anim Sci 50:175–181. http://jas.fass.org/cgi/reprint/*50*/1/175.pdf

Kormondy EJ (1969) Concepts of ecology. Prentice-Hall, Englewood Cliffs

Lehmann J (2007) A handful of carbon. Nature 447:143–144

Lehmann J, Joseph S (eds) (2009) Biochar for environmental management; science and technology. Earthscan, London/Sterling

Leterme P, London Angela M, Fernando E, Souffrant Wolfgang B, Andr B (2005) Chemical composition, nutritive value and voluntary intake of tropical tree foliage and cocoyam in pigs. J Sci Food Agric 85:1725–1732

Mena A, Elliott R, Preston TR (1981) Sugar cane juice as an energy source for fattening pigs. Trop Anim Prod 6(4):338. http://www.utafoundation.org/UTAINFO1/TAP/TAP64/64_338.pdf

Ngo Huu Toan, Preston TR (2007) Evaluation of uncultivated vegetables for pigs kept in upland households. Livest Res Rural Dev 19, Article #150. http://www.lrrd.org/lrrd19/10/toan19150.htm

Nguyen Xuan Ba, Vu Duy Giang, Le Duc Ngoan (2005) Ensiling of mulberry foliage (Morusalba) and the nutritive value of mulberry foliage silage for goats in central Vietnam. Livest Res Rural Dev 17, Art. No. 15. http://www.lrrd.org/lrrd17/2/ba17015.htm

OECD-FAO (2009) Agricultural outlook 2009–2018. http://www.agri-outlook.org/dataoecd/2/31/43040036.pdf

Ogle RB (2006) Forages for pigs: nutritional, physiological and practical implications. In: Workshop-seminar "Forages for pigs and rabbits" MEKARN-CelAgrid, Phnom Penh, Cambodia, 22–24 Aug 2006. Article #1. http://www.mekarn.org/proprf/ogle.htm

Pathoummalangsy Khamparn, Preston TR (2008) Effects of supplementation with rumen fermentable carbohydrate and sources of 'bypass' protein on feed intake, digestibility and N retention in growing goats fed a basal diet of foliage of Tithonia diversifolia. Livest Res Rural Dev 20(supplement). http://www.lrrd.org/lrrd20/supplement/kham20076.htm

Patzek TW (2007) How can we outlive our way of life; paper prepared for the 20th round table on sustainable development of biofuels: is the cure worse than the disease? OECD Headquarters, Chateau de la Muette, Paris, 11–12 Sept 2007. http://petroleum.berkeley.edu/papers/Biofuels/OECDSept102007TWPatzek.pdf

Peng Buntha, Khieu Borin, Preston TR, Ogle B (2008) Survey of taro varieties and their use in selected areas of Cambodia. Livest Res Rural Dev 20(supplement). http://www.lrrd.org/lrrd20/supplement/bunt1.htm

Preston TR (2001) Potential of cassava in integrated farming systems. Cassava as livestock feed (23–25 July 2001) in Khon Kaen University. http://www.mekarn.org/procKK/pres.htm

Preston TR (2006) Forages as protein sources for pigs in the tropics. In: Workshop-seminar "Forages for Pigs and Rabbits" MEKARN-CelAgrid, Phnom Penh, Cambodia, 22–24 Aug 2006. Article #2. http://www.mekarn.org/proprf/preston.htm

Preston TR (2014) The role of biochar in farming systems producing food and energy from biomass. In: Goreau T, Larson R, Campe J (eds) Geotherapy: innovative methods of soil fertility restoration, carbon sequestration, and reversing CO_2 increase. Earthscan, Oxford

Preston TR, Rodríguez L (2004) Production and utilization of cassava foliage for livestock in integrated farming systems. Livest Res Rural Dev 16, Article No. 28. http://www.lrrd.org/lrrd16/5/pres16028.htm

Preston TR, Rodríguez L (2009) Energy returned on energy invested (EROEI); the case for gasification as a component of an integrated live stock based farming system. Livest Res Rural Dev 21, Article #195. http://www.lrrd.org/lrrd21/11/pres21195.htm

Rapier R (2009) Renewable fuel pretenders. The Oil Drum. Posted 3 Sept 2009. http://www.theoildrum.com/node/5733

Rodríguez L, Preston TR (2009a) A note on ensiling the foliage of New Cocoyam (Xanthosoma sagittifolium). Livest Res Rural Dev 21, Article #183. http://www.lrrd.org/lrrd21/11/rodr21183.htm

Rodríguez L, Preston TR (2009b) Effect of planting method on biomass yield of New Cocoyam (Xanthosoma sagittifolium). Livest Res Rural Dev 21, Article #137. http://www.lrrd.org/lrrd21/8/rodr21137.htm

Rodríguez L, Preston TR (2010) Gasification of fibrous crop residues and live stock production; essential elements in establishing carbon-negative farming systems. Livest Res Rural Dev 22, Article #10. http://www.lrrd.org/lrrd22/1/rodr22010.htm

Rodríguez L, Lopez DJ, Preston TR, Peters K (2006) New Cocoyam (Xanthosoma sagittifolium) leaves as partial replacement for soybean meal in sugar cane juice diets for growing pigs. Livest Res Rural Dev 18, Article #91. http://www.lrrd.org/lrrd18/7/rodr18091.htm

Rodríguez L, Irina P, Preston TR, Peters K (2009a) Nutritive value for pigs of New Cocoyam (Xanthosoma sagittifolium); digestibility and nitrogen balance with different proportions of fresh leaves and soybean meal in a basal diet of sugar cane juice. Livest Res Rural Dev 21, Article #16. http://www.lrrd.org/lrrd21/1/rodr21016.htm

Rodríguez L, Preston TR, Peters K (2009b) Studies on the nutritive value for pigs of New Cocoyam (Xanthosoma sagittifolium); digestibility and nitrogen balance with different levels of ensiled leaves in a basal diet of sugar cane juice. Livest Res Rural Dev 21, Article #27. http://www.lrrd.org/lrrd21/2/rodr21027.htm

Rodríguez L, Salazar P, Preston TR (2009c) Effect of biochar and biodigester effluent on growth of maize in acid soils. Livest Res Rural Dev 21, Article #110. http://www.lrrd.org/lrrd21/7/rodr21110.htm

Rosset P (1999) Small is bountiful. The Ecologist, vol 29, December. http://www.mindfully.org/Farm/Small-Farm-Benefits-Rosset.htm

Theng Kouch, Preston TR, Ly J (2003) Studies on utilization of trees and shrubs as the sole feedstuff by growing goats; foliage preferences and nutrient utilization. Livest Res Rural Dev 15(7). http://www.lrrd.org/lrrd15/7/kouc157.htm

Yao J, Yan B, Wang XQ, Liu JX (2000) Nutritional evaluation of mulberry leaves as feeds for ruminants. Livest Res Rural Dev 12 (2) Art. #12. http://www.lrrd.org/lrrd12/1/yao122.htm

Ecological Intensification for Crop Protection

Alain Ratnadass and Marco Barzman

Abstract We need to break away from intensive agriculture based on non-renewable and toxic inputs. Safer practices are indeed emerging. Sustainable agriculture started about 50 years ago with the design of integrated pest management (IPM) to counteract pesticide misuse and abuse. Ecological intensification emerged only a few years ago. Here we review the literature to compare ecological intensification and IPM, from the point of view of crop protection. We present also agroecology and organic farming. Neither ecological intensification nor IPM have philosophical bases such as agroecology, or to an even larger extent, biodynamic agriculture. Ecological intensification, IPM and agroecology are polysemous, flexible and pragmatic approaches, whereas organic farming is well-defined by its scope and standards. Ecological intensification, in explicitly pursuing the goal of increasing food production to feed the planet, differs from agroecology, whose proponents think that the view that world hunger will be solved by merely increasing yield is an oversimplification. In terms of cropping system design, in its actual practice, IPM often remains based on methods that increase the efficiency of chemical pesticide use. Or, along with organic agriculture, it may remain based on substitution of pesticides by less harmful alternatives. In contrast, ecologically intensive crop protection usually requires cropping system redesign.

In terms of ecosystem service provision, IPM tends to focus on the pest-pathogen regulation service. In contrast, both ecological intensification and agroecology pay attention to both practices which were designed for crop protection and biomass provision purposes, as well as practices with broader scope, primarily designed to offer other ecosystem services which are found to have indirect effects on crop

A. Ratnadass (✉)
UR HortSys, CIRAD, Boulevard de la Lironde, F-34398 Montpellier, France
e-mail: alain.ratnadass@cirad.fr

M. Barzman
Eco-Innov, INRA, F-78850 Thiverval-Grignon, France
e-mail: Marco.Barzman@grignon.inra.fr

H. Ozier-Lafontaine and M. Lesueur-Jannoyer (eds.), *Sustainable Agriculture Reviews 14: Agroecology and Global Change*, Sustainable Agriculture Reviews 14,
DOI 10.1007/978-3-319-06016-3_3,

protection. This chapter also describes selected tropical case studies of crop protection, such as upland rice seed-dressing and fruit fly control in orchards, to compare and contrast crop protection in these contexts. Finally, we propose to consider IPM and ecologically intensive crop protection as complementary rather than conflicting approaches. The concept of "ultimate IPM" brings IPM closer to ecologically intensive crop protection. This new approach involves starting from a nearly natural ecosystem to which inputs are gradually added when absolutely necessary, rather than starting from a conventional agroecosystem and gradually remove inputs from it.

Keywords Agroecology • Ecologically intensive agriculture • Integrated Pest Management • Ecological engineering • Organic farming • Conservation agriculture • Push Pull • Crop protection • Sustainable agriculture • E-S-R framework • Ecosystem services

Abbreviations

DDT	dichlorodiphenyltrichloroethane
DMC	Direct-seeding, mulch-based cropping (systems)
E-S-R	Efficiency-Substitution-Redesign
GM	Genetically modified (crop/plant)
IPM	Integrated pest management
US	United States (of America)

Introduction

A number of concepts have emerged during the last century as pathways toward sustainable agriculture. They are based on the perceived need to break away from the dominant paradigm that gave rise to an intensive type of agriculture associated with artificial conditions, biodiversity reduction and reliance on non-renewable and toxic inputs. Integrated Pest Management (IPM) emerged more than half-a-century ago from early reactions to widespread misuse and abuse of toxic inputs in agriculture (Carson 1962; Stern et al. 1959). The scope of IPM is crop protection and its driver is pesticide use reduction. More recent approaches that are broader in scope have emerged. Ecological intensification emerged a few years ago (Bonny 2011; Doré et al. 2011; Griffon 2013). It is closely related to the concept of agroecology (Altieri 1995) particularly with ecological engineering for pest management as its application to crop protection (Nicholls and Altieri 2004).

This paper describes how ecological intensification, agroecology and IPM emerged. It compares the three approaches to each other and to other possible pathways to sustainable agriculture (Pretty 2008) such as organic farming and eco-agriculture relative to their crop protection dimension. It then discusses how they differ and how they may be synergistic rather than conflicting according to:

(i) the way they fit within the Efficiency-Substitution-Redesign (E-S-R) framework (Hill and MacRae 1995), particularly with regards to their acceptance or exclusion of chemical pesticides and genetically modified (GM) crops;
(ii) the way they contribute to ecosystem services beyond crop protection, particularly in the context of global environmental changes.

The Emergence of Alternatives to Agrochemistry-Based Crop Protection

Biodynamic Agriculture

Historically, the anthroposophic movement of the Austrian thinker Rudolf Steiner in the 1920s in central Europe, and its associated biodynamic agriculture movement was the first self-claimed alternative to the industrialization of agriculture (Steiner 1924). In its rejection of science in agriculture, it excluded even "natural" (biological or mineral) crop protection substances such as copper, sulphur, or arsenic at a time when there were no synthetic pesticides per se. Nevertheless, some specific "preparations" or recipes were proposed to combat crop diseases such as boiled horsetail plant (*Equisetum arvense*) to prevent fungal diseases. Certain principles which may appear esoteric to some were also proposed to combat insect and rodent pests. These include incineration of insect pests or rodent skins, with ashes diluted at homeopathic doses and applied according to cosmic factors such as the movements of the moon and planets.

Organic Farming

Organic farming was independently developed in the 1940s in England through the work of sir Albert Howard (1943) who was inspired by his experience with traditional farming methods in India, which notably served as the basis to "*the principles which appeared to underlie the diseases of plants:*

1. *Insects and fungi are not the real cause of plant diseases but only attack unsuitable varieties or crops imperfectly grown. Their true role is that of censors for pointing out the crops that are improperly nourished and so keeping our agriculture up to the mark. In other words, the pests must be looked upon as Nature's professors of agriculture: as an integral portion of any rational system of farming.*
2. *The policy of protecting crops from pests by means of sprays, powders, and so forth is unscientific and unsound as, even when successful, such procedure merely preserves the unfit and obscures the real problem – how to grow healthy crops.*

3. *The burning of diseased plants seems to be the unnecessary destruction of organic matter as no such provision as this exists in Nature, in which insects and fungi after all live and work*".

Organic farming practices have been standardized and codified by the International Federation of Organic Agriculture Movements (IFOAM). Regarding the use of plant protection products, biological and mineral crop protection substances are allowed in organic farming, although – ideally – priority is given to preventive methods (Letourneau and van Bruggen 2006; Zehnder et al. 2007).

Integrated Pest Management

IPM as a concept appeared as a reaction to the widespread and systematic use of synthetic pesticides, particularly DDT, after World War II, and was elaborated as early as 1959 (Stern et al. 1959), prior to the publication of the renowned book "Silent Spring" by Rachel Carson (1962). The emergence of pesticide resistance further boosted its development. IPM gained worldwide recognition following the quick resolution of a food security crisis in Indonesia in the mid-1970s created by the insecticide-resistant rice brown plant-hopper and the suppression of its natural enemies. The IPM programme in question, which included from the late 1970s to the mid-1980s the phase-out of many broad spectrum insecticides and a rapid 65 % reduction in overall pesticide use was associated with an immediate 12 % increase in rice yields (Röling and van de Fliert 1994). Historically, IPM emerged in the area of insect management with the idea that an integration of practices could reduce the likelihood of requiring insecticides that may be used "only as a last resort". The use of the concept of treatment threshold was a major tool by which the frequency of pesticide treatments against arthropod pests could be reduced. It was assumed that the approach could be generalised to pathogen and weed management.

The passing in 2009 of two important pieces of European legislation (Regulation 1107/2009[1] and Directive 2009/128/EC[2]) marks a turning point and places IPM again in the limelight. The decrease in the availability and portfolio composition of plant protection products in the European Union already during the last decade and the new legislative landscape mean that in future farmers will no longer have access to the entire range of pesticides they use today and that they will have to adopt IPM, incorporating alternative approaches or techniques to reduce their dependency on pesticide use. By December 2012, most EU Member States completed and initiated the implementation of the National Action Plans which will pave the way to reach the new objectives and by January 2014, Member States are expected to show how the principles of IPM are implemented.

[1] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:309:0001:0050:EN:PDF

[2] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:309:0071:0086:en:PDF

The concept of "integrated production" (IP) was also proposed by the International Organization for Biological and Integrated Control of Noxious Animals and Plants (IOBC) as a desirable approach to the development of more sustainable crop protection. This approach takes into account not only crop protection measures, but all farming practices at the entire agroecosystem level which affect pest management (Boller et al. 2004). The approach is embodied in a series of IP guidelines that have been used in association with subsidies in Switzerland and in Emilia-Romagna Region (Italy) (BLW 2013; Stäubli 1983). In some other European countries, it was applied to vegetable and fruit production, e.g., in France where, although promising, integrated fruit production remained limited due to lack of public support (Bellon et al. 2006). Recently, with the implementation of the European Framework Directive 2009/128/EC on the Sustainable Use of Pesticides, several governments have placed emphasis on the IP guidelines in their pesticide National Action Plans.[3]

Agroecology

German zoologists in the 1930s–1960s, were among the early promoters of the term and concept of agroecology, along with European and American agronomists and crop physiologists, and emphasised the application of agroecology to pest management (Friedrichs 1930 in Wezel et al. 2009, Tischler 1950 in Wezel et al. 2009). In the 1970s–2000s, agroecology further developed as a science, a movement and a set of practices primarily as a reaction of American ecologists (e.g., Miguel Altieri, John Vandermeer) to the excesses of the Green Revolution and its negative impact on small-holders in developing countries (Altieri 1995; Vandermeer 1995; Wezel et al. 2009). Proponents of agroecology historically maintain a suspicion regarding the common wisdom goal of "feeding the planet" in the face of a "population explosion". They claim that the view that world hunger will be solved by merely increasing yields – rather than by increasing total productivity with respect to land and inputs and by addressing social inequality – is an oversimplification serving the needs of developed countries (Moore Lappé et al. 1998; Altieri and Nicholls 2012).

In his definition of agroecology, Miguel Altieri particularly stressed the "pest & disease regulation" pillar (Altieri 1995). Deguine et al. (2008) further developed the application to crop protection within the concept of agroecology, which can be referred to as agroecological crop protection. For instance, Shennan et al. (2005, in

[3] SCAR Collaborative Working Group on integrated pest management for the reduction of pesticide risks and use ANALYSIS OF RESEARCH AND EXTENSION NEEDS FOR THE DEVELOPMENT OF IPM Final report of a survey conducted among European countries. Last revision April 17, 2013 http://www.endure-network.eu/content/download/6765/48872/file/Final%20report%20SCAR%20IPM%20CWG.pdf

Deguine et al. 2008), wrote: *"An agroecological approach to agriculture involves the application of ecological knowledge to the design and management of production systems so that ecological processes are optimized to reduce or eliminate the need for external inputs. Nowhere is this more apparent than in the management of agricultural pests."* Within the agroecology mindset, it is the use of cultural techniques to effect habitat manipulation and enhance biological control that is more specifically referred to as ecological engineering for pest management (Gurr et al. 2004). Among the "affiliated" sets of practices, conservation agriculture and agroforestry place less emphasis on pest regulation – except for weed suppression in the former.

Ecological Intensification

To some extent, crop protection issues are also central in the "ecological intensification" approach, where natural ecosystems serve as a source of inspiration (Doré et al. 2011; Malézieux 2012). That is why ecologically intensive crop protection emphasises the use of biological processes to regulate pest populations as an alternative to direct control via synthetic pesticides.

In any case, the ecologically intensive approach to crop protection differs from organic farming in its flexibility regarding the use of chemicals, and from agroecology in its explicit goal of increasing the quantity of food produced to "feed the planet" via a certain form of intensification (Griffon 2006). Its explicit and primary goal of increasing agricultural production is a notable difference with agroecology which puts forward a range of environmental, economic, social and cultural goals. Proponents of ecological intensification, referring to lower yields attained in organic cereal production, do not perceive organic farming as pursuing this goal.

Thus, among the major claimed pathways to sustainable agriculture, organic farming, agroecology and ecological intensification have well-developed crop protection dimensions. Biodynamic agriculture poorly covers this aspect of crop production while IPM is obviously exclusively dedicated to pest management.

Relationship Between IPM and Ecological Intensification for Crop Protection

Definitions and Principles of IPM

IPM has a number of definitions. One, adopted by the European Network ENDURE, which has taken upon itself to provide research and development support to the implementation of IPM (ENDURE 2011) as well as by a number of national and international organisations and agencies, is the following:

> *IPM is a sustainable approach to managing pests by combining biological, cultural and chemical tools in a way that minimises economic, environmental and health risks.*

With the mandatory implementation of IPM to be achieved by 2014 in all European Union Member States as called for by Directive 2009/128/EC,[4] which regulates the use phase of pesticides and establishes a new framework to *"achieve a sustainable use of pesticides by promoting the use of integrated pest management and of alternative approaches or techniques such as non-chemical alternatives"*, much attention is paid to how this legislation defines IPM. It states that: "*IPM means careful consideration of all available plant protection methods and subsequent integration of appropriate measures that discourage the development of populations of harmful organisms and keep the use of plant protection products and other forms of intervention to levels that are economically and ecologically justified and reduce or minimize risks to human health and the environment. 'Integrated pest management' emphasizes the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms*".

According to the above-mentioned EU directive, IPM practitioners must satisfy eight principles:

- Principle 1 – Achieving prevention and/or suppression of harmful organisms
- Principle 2 – Monitoring
- Principle 3 – Decision based on monitoring and thresholds
- Principle 4 – Non-chemical methods
- Principle 5 – Pesticide selection
- Principle 6 – Reduced use
- Principle 7 – Anti-resistance strategies
- Principle 8 – Evaluation

The first principle emphasises preventive/prophylactic indirect measures, followed by pest monitoring and decision-making on curative measures based on thresholds, first with non-chemical methods, then with the least harmful pesticides if deemed necessary. ENDURE promotes the view that IPM is a continuously improving process in which innovative solutions are integrated and locally adapted as they emerge and contribute to reducing reliance on pesticides in agricultural systems. One could thus define an IPM continuum (Ohmart 2008, 2009) as follows:

- An early-stage IPM based for instance on selecting IPM-adapted pesticides or more generally on optimising pesticide use to reduce use and risks.
- More advanced stages ranging from the use of threshold-based pesticide application to combination of tactics and prevention strategies, or more generally aiming to reduce reliance on pesticides.
- "Ultimate IPM" where no direct control methods are needed once cropping systems with in-built robustness vis-à-vis pests, weeds and diseases is established.

For the purposes of our comparison, the main message regarding IPM from the point of view of what it has achieved in the field, is that it is helpful in reducing pesticide use and impact but that at least in its de-facto implementation, it has tended to remain within the realm of chemically-dependent crop protection.

[4] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:309:0071:0086:en:PDF

Definition and Principles of Ecological Intensification for Crop Protection

While the goal of IPM centers on crop protection, ecological intensification covers all aspects of production. It can nevertheless be compared to IPM with regards to its application to crop protection. Michel Griffon, one of the founders of ecological intensification, defined it as *"an approach based on the enhancement of agroecosystem functionalities, of agroecosystem component complexity and diversity to improve agroecosystem resilience, and on the harnessing of 'biologically-inspired' innovations"*. The latter concept refers to techniques that mimic natural functions (Griffon 2013). He also characterised ecological intensification as a genuine ecological engineering approach: "*a management and design of sustainable, adaptive, multifunctional environments, inspired by or based on mechanisms that govern ecological systems*". "Ecological engineering" was first proposed as an approach in its own right, defined as "*the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both*" (Mitsch and Jorgensen 2003), not necessarily encompassing agroecosystems per se. In its application to agroecosystems, it is, however, the use of cultural techniques to effect habitat manipulation and enhance biological control that most readily fits the philosophy of ecological engineering, as a part of the agroecology mindset (Gurr et al. 2004). It could therefore more appropriately be termed "agroecological engineering".

In its crop protection dimension, ecological intensification proposes to develop pest management strategies based on cultural practices informed by ecological knowledge and believe this can result in significantly increased crop production due to decreased crop loss, added to other beneficial effects on crop physiology, rather than on high-technology approaches that include synthetic pesticides and genetically engineered crops. Some nevertheless believe the latter to be compatible with ecological engineering, and in any case necessary if the objective of food security is to be met (Birch et al. 2011).

Positioning organic farming and IPM relative to ecological intensification, i.e., in reference to their reliance on ecological processes, is not easy. While the definition of organic farming is very clear, IFOAM standards have allowed the emergence of two distinctive approaches. One, which we term "low-input organic farming", is based on prevention and indirect methods of controls and is close to agroecology. The other, which we term "large-scale organic farming", is based on substitution of synthetic inputs with external organic inputs and does not in the end differ much from industrial conventional farming (Darnhofer et al. 2010; Guthman 2000; Rosset and Altieri 1997).

IPM – within a continuum ranging from early-stage to ultimate IPM – , agroecology and ecological intensification take on a number of meanings as well. For instance, Griffon (2013) considers ecological intensification to encompass the entire range from low to high "environmental value" practices, with conventional agriculture considered as having low, conservation agriculture as having low to medium, and organic farming as having high environmental value.

For our comparison of approaches, it is the "intensification" aspect of ecological intensification that is most pertinent as it conveys active and interventionist research and extension attitudes regarding the manipulation of ecological processes. This contrasts with the more descriptive attitudes historically prevalent in the science of ecology (Jackson and Piper 1989) and possibly with agroecology which, at least in its earlier phases, devoted much effort in documenting and understanding the ecological rationale underlying traditional tropical agriculture.

However, the "engineering" aspect of ecological engineering applied to agroecosystems, as a part of agroecology (see above) also conveys such active attitude, but with a view of sustaining rather than increasing agricultural production. In addition, the idea of sort of "controlling" the nature, via the engineering of ecological processes, which is part of the ecological intensification mindset, is much less so in the agroecological mindset, even if it comes to ecological engineering. Also, the idea of a compulsory need for changing human nature, calling rather for sufficiency in a world of scarcity (Rahbi 2008; Mathijs 2012), is part of the agroecological movement (although more in its philosophical than scientific mindset), whereas it is not in essence part of the ecological intensification thinking. Actually, neither ecological intensification nor IPM have philosophical bases such as agroecology, or to an even larger extent, biodynamic agriculture.

The "ecological" dimension of ecological intensification, agroecology and low-input organic farming is in any case more developed than in IPM, which, although scientifically based, mainly mobilizes knowledge on the phenology of the crop and the bio-ecology of pests in view of combining control tactics and establishing economic injury levels and treatment thresholds. So, at least in its practice, IPM implementation remains dependent on pesticides, and the ecological concepts and processes are less essential than in the ecological intensification approach. One can note in this regard that in the practice of IPM, the notion on "ecology" mainly refers to reducing adverse ecological impacts rather than making full use of ecological processes, which are central in ecologically intensive crop protection.

Conflicts, Synergies or Necessary Trade-Offs Between IPM & Ecologically Intensive Crop Protection

IPM Versus *Ecological Intensification in the E-S-R Framework*

In the E-S-R (Efficiency-Substitution-Redesign) framework provided by Hill and MacRae (1995), IPM may in its early-stage remain based on methods aiming at increasing the efficiency of pesticides (E), or on the substitution of these pesticides by less harmful alternatives (S). Complete redesign of agroecosystems (R), in view of achieving "deep sustainability" or attaining "ultimate IPM", is not mandatory. In contrast, ecological intensification and ecological engineering applied to crop protection make use of biotic and abiotic processes rather than substituting one sort of input by another.

Reliance on ecological processes usually requires redesign of cropping systems achieved via plant spatial and temporal diversification, and the creation of an environment that is favourable to natural enemies. Although one could think that redesign is necessarily based on the integration of multiple management tactics with partial effects, this is not mandatory, since a single agroecosystem redesign measure via plant species diversification may result in pest/pathogen regulation via several parallel pathways (Ratnadass et al. 2012a). The regulation pathways may be "bottom-up", from lower to higher trophic levels, i.e., from autotrophic plants to herbivore pests or plant pathogens (e.g. allelopathic effects, or stimulo-diversionary effects). Or they may be "top-down", i.e., from higher to lower trophic levels, i.e., from predators to pests (namely the various forms of biological control). In contrast, with the present understanding of the rapid capacity of pests to evolve and adapt to single tactical control measures, the IPM approach is necessarily based on the combination of several management methods with partial effects, with a view to preventing or delaying their being circumvented by the target pests.

So one major difference between the actual practice of IPM and ecologically intensive crop protection is that the former may remain based on methods aiming at increasing the efficiency of chemical pesticides, or on their substitution by less harmful alternatives, while the latter usually requires complete cropping system redesign. A second major difference is that while IPM necessarily involves the integration of several management methods with partial effects, to simultaneously address multiple pests or delay overcoming by pests, pathogens and weeds, while ecologically intensive crop protection may rest on a single redesign measure, resulting in their regulation via a number of pathways.

Regarding Chemical Pesticides

So unlike organic farming, both IPM and ecologically intensive crop protection allow pesticides, even though they admit that those should be "ideally" avoided. The IPM approach summarized by Vandermeer (1995) emphasises IPM principle 1 (prevention): *"don't spray poisons unless it is necessary and manage the ecosystem in such a way that it doesn't become necessary"*. Thus, agroecological or ecologically intensive crop protection can be seen as key to the first principle of IPM and to the ultimate stage of IPM, when redesign has been so successful that no other measure is necessary.

The perspective of IPM is reduction of pesticide use, but not that of other agrochemicals. It is also based on the integration of several techniques and externally produced inputs, such as semio-chemicals, precision agriculture, biological control agents for inundative release. These are not generally part of the toolbox of agroecology or ecological intensification, or that of low-input organic agriculture, particularly regarding synthetic pesticides and chemical fertilizers.

The emphasis of "agroecology-based approaches" such as ecological engineering applied to agroecosystems and ecologically intensive agriculture, is on the enhancement of biological processes as replacement of chemical inputs. Such inputs are excluded from organic farming, while they are allowed, at minimal doses, in agroecology-based approaches, possibly as "starters" to mobilize biological processes for farmers' benefit with a view to their eventual suppression ultimately. In contrast, non-use of chemical inputs is a key pre-requisite in organic farming.

In the actual practice of IPM – as opposed to IPM theory which purports that pesticide use is only as a last resort – some observers think that relying on thresholds could even unintentionally encourage the use of pesticides. Indeed, the use of thresholds requires intensive monitoring of pests which in some cases may give pests excessive attention which, coupled with risk aversion, would frequently translate to a decision to spray. Other proponents of IPM emphasise the importance of ensuring the availability of a wide range of pesticides. Such availability is seen to help reduce the emergence of pesticide resistance and to function as a "safety net" making it possible to experiment with innovative approaches with the guarantee that pesticides could be used as a last resort if something goes wrong. "Minor use" proponents, recognising the diversification of arable cropping systems as a major strategy to generate more robust cropping systems, also emphasise the need for pesticides registered for use on new crops to be inserted in a crop sequence. Otherwise, in the absence of operational control methods, they argue, farmers will not experiment with the new crops.

Ecological intensification and IPM – unlike organic farming – are polysemous or encompass a broad continuum. They are therefore not easily defined by their scope or precise codification in view of certification. Standards of organic farming are relatively well harmonized worldwide at all levels, and farmers identify themselves with organic farming, which has gained high credibility. The flexibility of both IPM and ecological intensification as compared to organic farming explains why they are difficult to label.

Although organic farming and both agroecology and ecological intensification have many crop protection aspects in common (Letourneau and van Bruggen 2006; Zehnder et al. 2007), there are differences. The exclusion of chemical pesticide treatments in organic farming is a consequence of its market orientation and dependence on certification. That is why in cases of a massive pest attack, an organic farmer would rather lose the crop than the certification, something which agroecological subsistence farmers cannot afford.

Organic agriculture may be environmentally and economically sustainable at more local scales, but ecological intensification proponents question its social sustainability at the global scale, in terms of its ability to feed the planet. The debate over the capacity of organic agriculture in terms of production is still open. In any case social sustainability via the "food production" service is considered primordial in ecological intensification.

The attitude of IPM and ecologically intensive agriculture toward the use of agrochemicals is therefore more pragmatic than that of organic farming. However, within an ideal classical IPM framework, synthetic pesticides cannot be applied as a systematic preventive measure, but only as a last resort curative option decided via the use of thresholds. Conversely, the preventive use of pesticides, even synthetic, is not excluded from the ecologically intensive approach, if it can boost some ecological processes. It should however be kept to a minimum, avoiding adverse impacts on other ecological processes pertinent to agricultural production, on human health or on other environmental dimensions.

For instance, ecological intensification might favour the application of herbicide on a natural cover, as in conservation agriculture systems, to allow direct seeding into the mulch thus avoiding ploughing to reap the full benefit of undisturbed soil biological activity (Séguy et al. 2012). Similarly, seed-dressing with a targeted systemic insecticide could be included in an ecological intensification programme if it is deemed mandatory to avoid total crop failure in some specific environments: see § "Relevance of seed-dressing with targeted systemic insecticides under the "ecological intensification for crop protection" approach" in this chapter.

The targeted use of insecticide may also help extend the range of application of another typically agroecological or "ecologically intensive" technique such as push-pull technology (Cook et al. 2007; Khan et al. 2010). When "dead-end" trap plants are not available, using chemical pesticides in alternation with biological insecticides may be desirable. Chemical pesticides in alternation with Bt toxins from the soil bacterium *Bacillus thuringiensis* or with Spinosad from the soil bacterium *Saccharopolyspora spinosa* -both allowed in organic agriculture- in an "assisted push-pull" or "attract & kill" approach may delay the build-up of resistance to the latter. In this case also, the adverse impact of pesticides is kept at a minimum, since those mainly biological products are not sprayed on the crop but on the trap plants, either directly or in mixture with liquid baits, at very low rates, namely 0.02 % in the case of Spinosad in GF-120.

So for this chapter, one may actually consider that in both ecological intensification and IPM, priority is given to the absence of synthetic pesticide residues in the crop, food, and environment, rather than totally excluding use of pesticides or other chemical substances in the production process – a characteristic of organic farming. There may however be some differences in the way IPM and ecological intensification relate to pesticide use. IPM principles 1 (on prevention) and 3 (on basing decisions on observation) do not warrant the systematic preventive use of synthetic pesticides. In ecological intensification, such pesticide use is not excluded as long as its potential negative impacts are compensated by the boosting of positive ecological feedback loops.

Regarding Botanical Pesticides and Biological Control

Under IPM principle 4 (preference given to non-chemical methods), and principle 5 (selection of the least disruptive chemical), the use of botanical pesticides is encouraged. However, although more renewable than synthetic chemical pesticides, plant-derived pesticides are not necessarily in line with the agroecological and ecological intensification approaches, since they rely on "substitution" rather than cropping system redesign (Ratnadass 2013). In addition, some plant-derived pesticides are not necessarily benign for the environment, e.g., rotenone, a broad-spectrum insecticide harmful to natural enemies and pollinators. This reservation however also applies to toxins of bacteria, e.g. Bt-toxins and Spinosad, if they are used in substitution to chemical insecticide sprays.

Nevertheless, the use of plant-derived pesticides may be a component of ecological engineering if sources of natural pesticides are part of the agricultural system. This is the case with Jatropha live-hedges planted around market-gardens to keep domestic animals away, or neem wind-breaks planted around orchards, with both also contributing to conservation biological control (Ratnadass and Wink 2012).

Regarding natural enemies, most IPM (ultimate IPM aside), relies more on augmentative biological control than on conservation biological control. Augmentation, which is the repeated release of purchased arthropod natural enemies or entomopathogenic fungi or nematodes may be considered as a mere substitute to chemical treatments, and would therefore not fit very well within the ecological intensification mindset. On the other hand, conservation biological control via natural enemy habitat management is very much in line with ecological intensification for crop protection and usually requires agroecosystem redesign.

So substitution of chemical pesticides by plant-derived pesticides, while it is welcome under IPM Principles 4 and 5, does not fit in the mindset of ecological intensification, unless plants producing pesticidal extracts are included in the redesign of the cropping system. Similarly, while augmentative biological control satisfies IPM Principles 1, 3 and 4, it is less in line with ecological intensification which gives preference to conservation biological control achieved via natural enemy habitat management, and usually requires redesign of the agroecosystem.

Regarding Genetically Modified (GM) Crops

While there is no question regarding the important role host plant genetic resistance plays as a preventive measure in IPM programs, the acceptance of GM crops is less clear-cut. The use of GM crops is considered by some as a tool for IPM just like that of any other pest-resistant cultivar (Birch et al. 2011; IPM CRSP 2011; Kennedy 2008). However, the use of Bt-transgenic crops, particularly cotton and maize, within the IPM framework, has been surrounded by unprecedented ethical debate and concerns about its safety for human health and the environment, including non-target effects, gene flow, resistance build-up, emergence of secondary pests, as well as regulatory issues about the corporate control of agriculture, particularly in developing countries (Kennedy 2008).

As Bt-transgenic crops are "insecticidal plants", unlike conventionally bred insect resistant cultivars, their use is conflicting with IPM principle 3 (on pesticide application based on threshold), since, like for seed-dressing, "treatment" (=pesticide application) is systematic. In this respect, it is also conflicting with IPM principle 7 (on anti-resistance strategies), although resistance management refugia may delay Bt resistance buildup (Meissle et al. 2011). Furthermore, gene flow can contaminate non-GM crops, especially in neighbouring organic farms. They can also induce resistance, e.g., stem borers resistant to Bt, which, as sprays, is one of the only biopesticide options for organic farmers. Also, gene flow from herbicide-tolerant oilseed rape can make some weeds herbicide tolerant, which may pose a problem both in GM and conventional non-GM, and ecologically intensively managed fields.

On the other hand, while the use of “Round-UP® ready” herbicide-tolerant crops is considered by some a major tool of some forms of conservation agriculture, which is itself part of the agroecology and ecological intensification sets of practices, one can also stress that it is not part of IPM since it is predicated on the use of glyphosate, a synthetic herbicide.

Many proponents of IPM who emphasise the “I” of IPM, for example researchers from the ENDURE network who devote their efforts to combining multiple tactics to obtain a robust strategy, warn GM developers against the “silver bullet” attitude that a GM solution alone would sustainably solve a pest problem.

At present, regarding agroecological or ecological engineering approaches as well, even though it may mimic naturally occurring ecological processes, the use of genetically engineered plants is also still under debate. These plants may have negative effects on plant biodiversity in ecosystems via pathways such as gene flow (Altieri et al. 2004). Conversely, the use of herbicide-tolerant GM crops benefits soil biota biodiversity via enhanced no-till cultivation, and the use of Bt-transgenic crops benefits arthropod biodiversity via reduced insecticide use (Ammann 2005). On the other hand, GM crop proponents argue that within the ecological intensification framework, genetic engineering would be helpful in making GM “dead-end” trap plants available, such as Bt-collard or Bt-Indian mustard to protect cabbage from diamond-back moth damage (Shelton et al. 2008). Also, the use of a GM herbicide-tolerant crop would make easier combination with flower-strips as beetle banks and the management of the latter as potential weeds.

So while some consider GM crops as preventive tools for IPM just like any other pest-resistant cultivars, others stress that the prophylactic/systematic use of “insecticidal plants” is conflicting with IPM principles. The use of GM crops is also under debate within the ecological intensification approach, depending on whether one stresses its negative effects on plant biodiversity in ecosystems via other pathways, or the benefits for microbial and non-target arthropod biodiversity of the use of respectively herbicide-tolerant GM crops, via enhanced no-till cultivation, and insect resistant GM crops, via reduced insecticide use.

Provision of Ecosystem Services in IPM and Ecological Intensification

Crop pests and pathogens induce “negative” ecosystem services (or “disservices”) to agricultural production, while beneficial biodiversity namely natural enemies of the former, provide “positive” ecosystem services (Zhang et al. 2007). Natural pest control is a major ecosystem regulating service contributing to the major provisioning service of biomass (food, forage, fibre or fuel) production to humans by agriculture (Millennium Ecosystem Assessment 2005; Power 2010). In this regards, farmers are the direct recipients of this service of reduction of crop loss (Avelino et al. 2011).

The question raised now is to what extent IPM on the one hand, and ecological intensification on the other, may contribute to ecosystem services beyond this pest and pathogen regulation service – the reduction of biomass loss. Biodiversity conservation per se is for instance considered a major supporting service, and a source of controversy between different approaches. The first controversy pertains to the rationale of biodiversity conservation, namely for its mere intrinsic value or for its anthropocentric value (Maguire and Justus 2008; Nash 1967; Reyers et al. 2012). With such a mindset, having field borders or corridors "used" for ecological services such as crop protection is not "true" biodiversity conservation. Other controversies are embodied in the debates on land-sparing versus land-sharing (Ben Phalan et al. 2011), and eco-agriculture versus agroecology (Altieri 2004; McNeely and Scherr 2003), and their respective contribution to the biodiversity conservation.

Those latter controversies stem from conflicting results on the relationship between management intensity and species richness, and thus opportunity for biodiversity conservation in agroecosystems (Perfecto et al. 2005; Perfecto and Vandermeer 2008). Actually, this also refers to the increasing consideration of landscape ecology for crop protection goals within the ecological intensification framework. In this respect, this trend is shared with the IPM approach, and the increased consideration of area-wide IPM, which is somehow a way of re-designing cropping systems at the landscape scale (Chandler and Faust 1998).

Ecological intensification for crop protection pays attention to agroecological practices such as "push-pull" (Cook et al. 2007; Khan et al. 2010) or rice-duck farming (Ahmed et al. 2004; Furuno 2001; Su et al. 2012), which were primarily designed for crop protection and food and feed provision purposes. On the other hand, agroecology and ecological intensification also encompass sets of practices with broader scope, which were found to have indirect effects on crop protection, e.g. conservation agriculture (Ratnadass et al. 2006) (Fig. 1) and agroforestry (Avelino et al. 2011) (Fig. 2). The latter two practices were actually designed to offer other ecosystem services such as soil conservation/erosion prevention and hydrologic services, or greenhouse gas emission mitigation via carbon sequestration, which is particularly important in the context of climate change. While they obviously also make both producers and consumers benefit from indirect services such as improved health associated with reduced reliance on agrochemicals (Avelino et al. 2011), they are less attractive to consumers for their image of impact on human health, than organic farming is to its "customers". Without a market, payments for environmental services are thus needed to promote the development of such systems less dependent on pesticides, while maintaining or even improving yield and quality (Avelino et al. 2011). Provision of such other ecosystem services is also gaining importance in the context of global environmental changes and their impact on societal demands.

So regarding ecosystem services, ecological intensification addresses both practices which were designed for crop protection and food and feed provision purposes as well as practices with broader scope, which are found to generate indirect effects on crop protection. IPM is more seen as focussed on the mere pest/pathogen

Fig. 1 Conservation agriculture: upland rice on a perennial groundnut live cover (Madagascar)

Fig. 2 Agroforestry: coffee under *Erythrina* shade trees (Costa Rica)

regulation ecosystem service. However, both approaches contribute to the major supporting ecosystem service of biodiversity conservation, and make producers and consumers benefit from indirect ecosystem services like increased human health due to reduced reliance on agrochemicals.

Lessons from Some Tropical Case Studies

Seed-Dressing with Targeted Systemic Insecticides

The question of relevance of seed-dressing in ecological intensification is illustrated by the use of insecticides against black beetles in rainfed cereals, notably upland rice in Madagascar. Unless seeds are treated with a systemic insecticide, these pests (*Heteronychus* spp.) completely prevent the development of upland rice production and the adoption of Direct-seeding, Mulch-based Cropping (DMC) systems (Fig. 3), conservation agriculture systems that otherwise provide a number of significant ecosystem services such as soil conservation and carbon sequestration (Ratnadass et al. 2006).

Results suggest that in some DMC systems, seed dressing, which is mandatory to control damage but only during the initial years following a break with conventional management, namely foregoing ploughing, becomes no longer necessary after a few years of such DMC management (Ratnadass et al. 2008). Beyond inducing changes in the below-ground fauna composition (e.g. replacement of herbivore taxa, particularly rhizophagous white grubs, by detritivorous species, including white grubs like *Hexodon unicolor* (Fig. 4), and facilitating activity of predators like tiger beetles, e.g. *Hipparidium equestre* (Fig. 5)), some DMC systems induce changes of the status of other white grub according to the organic status of the soil (e.g. having grubs of some black beetle species turn from rhizophagous to detritivorous) (Ratnadass et al. 2013).

Seed-dressing has a starter effect on biomass production, triggering biological processes particularly below ground, that more than compensate the minor adverse impact of the small amount of pesticide used (Ratnadass et al. 2012b). However, ways

Fig. 3 Damage caused by black beetles (*Heteronychus* spp) to ploughed (*left*) and mulched (*right*) upland rice, with (*background*) and without (*foreground*) seed-dressing (Madagascar)

Fig. 4 Adults of a detritivorous white grub species, *Hexodon unicolor*, on a mulch

Fig. 5 Adults of a predatory tiger beetle (*Hipparidium equestre*), on a mulch (Madagascar)

of minimizing some non-negligible side-effects of neonicotinoid insecticides used in seed-dressing should be sought in the initial years when treatment is mandatory. Since rice, as a self-pollinated plant, does not require entomophilous pollination on the one hand, and that beekeeping may be of a particular importance in some regions like the south-eastern part of the island, a "push-pull" combination of bee-repelling (push) cover plants inside seed-dressed upland rice fields, with bee-attractive (pull)

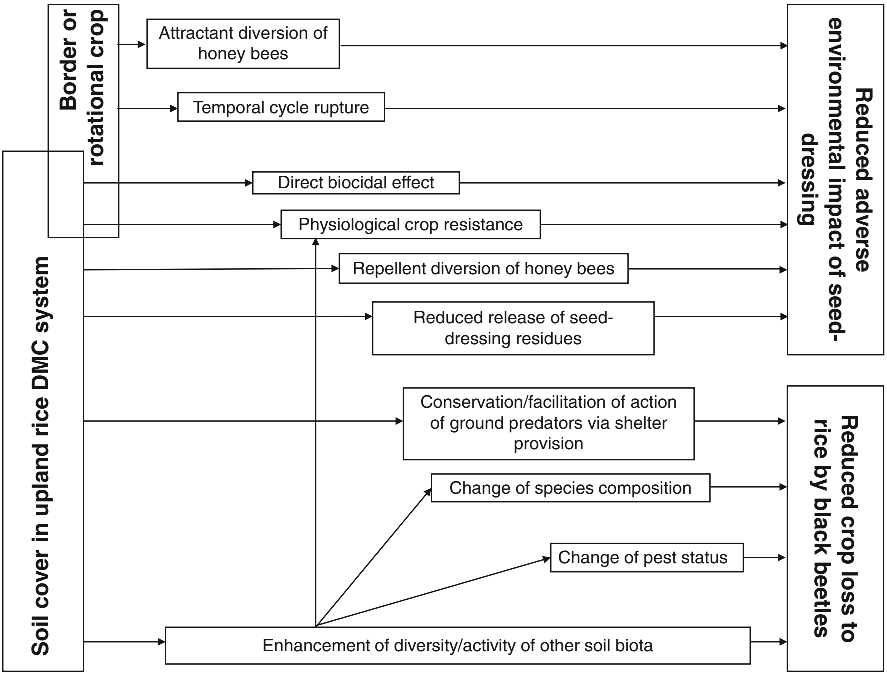


Fig. 6 Crop protection-related effects of an upland rice-based conservation agriculture system (After Ratnadass et al. 2008, 2012a, b, c, 2013). *Ecosystem services beyond pest regulation, provided by this conservation agriculture system, are not shown*

melliferous plants either as rice field borders, or as plots in rotation, would guarantee a harmonious rice cropping-beekeeping integration in these regions.

The way various ecological processes are harnessed to meet the objectives of reduced pest impact and minimal adverse environmental impact in an ecologically intensive crop protection system is presented in Fig. 6. It does not fit very well within the IPM framework since it involves systematic preventive chemical seed-dressing. Nevertheless, studies are underway to replace synthetic seed-dressing insecticides by biological ones, either plant-derived or entomopathogenic (Ratnadass et al. 2012b, c; Razafindrakoto Raliearisoa et al. 2010).

So this case-study provides an example of a technique which is not IPM *stricto* sensu, but can still be part of the ecological intensification approach, as long as it boosts some ecological pest regulation processes, provides other ecological services, and is associated with measures that reduce other potential negative impacts.

Use of GF-120 for Fruit Fly Control in Orchards

GF-120, a mixture of food attractant and Spinosad, a biological insecticide at the rate of 0.02 %, was successfully used in an “attract & kill” approach to control mango fruit flies in Benin (Vayssières et al. 2009). Since the mixture is “spot-sprayed” on

Fig. 7 Maggot and damage of the jujube fruit fly *Carpomya incompleta* on a Sahel apple (Niger)

part of the canopy of the crop, it could be so only when the economic injury level is reached, and thus follow IPM principles. Furthermore, as part of IPM Principle 7, namely that of anti-resistance strategy, chemical insecticides other than Spinosad could be recommended in alternation.

There is actually a second case when GF-120 could be used both as a repellent to protect "Sahel apples" (fruits from grafted jujube trees) from the specialist fruit fly *Carpomya incompleta* (Fig. 7), and as an "attractant & killer" to protect watermelon, which is part of the Dryland Eco-Farm system (Fatondji et al. 2011), along with jujube tree, from oliphagous Dacus fruit flies, thus "killing two flies with one spray", and even a third one, namely *Bactrocera invadens*, which is gaining importance as a highly polyphagous fruit pest in Niger (Zakari-Moussa et al. 2012). In this latter case (shown in Fig. 8), since the repellent effect may be considered a preventive measure, it fits well within ecological engineering in agroecology, or ecological intensification for crop protection approaches.

This example illustrates how a single treatment method can be either "curative" and therefore comply with IPM principles, or be systematic and therefore not theoretically compatible with IPM, while still complying with ecological intensification, although only "mimicking" natural processes.

Increased Positive Effect of Weaver Ants on Fruit Trees

The tree-inhabiting weaver ant Oecophylla (*Oecophylla smaragdina* in Asia and Oceania, and *O. longinoda* in Africa (Fig. 9)) effectively protects tropical tree crops as it actively patrols canopies and preys upon or deters a wide range of potential pests. Weaver ant husbandry in citrus orchards dates back to the fourth century AD in southern China and is recognized as the oldest known instance of man-mediated biological control (Huang and Pei 1987). In Vietnam, it is effective at reducing

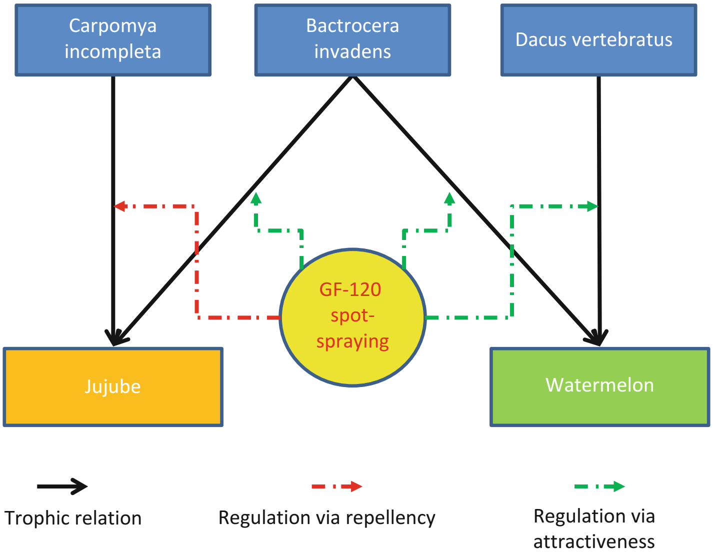


Fig. 8 Representation of a "win-win" strategy to "kill three fly species with one spray" in a Dryland Eco-Farm system (Excerpted from Zakari-Moussa et al. 2012)

Fig. 9 *Oecophylla longinoda* ants weaving a nest on a citrus tree (Benin)

populations of a range of citrus pests (stinkbugs, swallowtail, aphids, leafminer, rindborer: Barzman 2000). Weaver ants are also used against coconut-sucking bugs in Africa and Oceania (Barzman 2000; Seguni et al. 2011), and mango fruit flies in Africa (Van Mele et al. 2007).

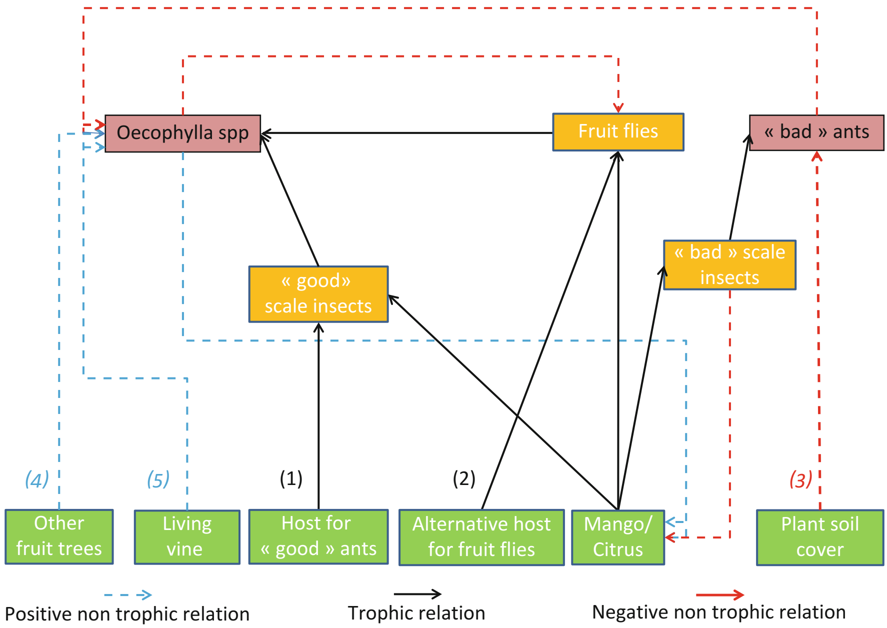


Fig. 10 Representation of an ecologically-engineered orchard/grove optimized vis-à-vis positive effect of weaver ants via food webs (After Barzman et al. 1996; Barzman 2000; Van Mele et al. 2007, 2009; Seguni et al. 2011). *Provision of plants suitable for weaver ant nests* via *host suitability for ant-tended little-damaging, non viral disease-transmitting scale insects (1), or intercropping with fruit trees with leaves suitable for ant nests in the case of coconut groves (4); Suppression of alternate fruit fly hosts in orchards or in their vicinity (2); Maintenance of plant cover in orchards to prevent antagonistic ants to displace weaver ants from the fruit tree canopy and to bring with them damaging and viral disease-transmitting scale insects (3); Provision of living vines to facilitate patrolling of weaver ants on fruit trees and their positive effect either directly on citrus, or indirectly* via *pest predation and/or repellency on citrus and mango fruit flies and on other citrus and coconut pests (5)*

Figure 10 shows how ecological processes in orchards and groves may be harnessed, particularly playing on plant diversity, so as to improve positive action of weaver ants on fruits, via various pathways.

The active human-mediated establishment of ants creates "ecologically-engineered" orchards that fit very well within ecologically intensive crop protection. Since no chemical pesticides are involved, this approach also provides an image of what an "ultimate IPM" agroecosystem could be.

Conclusion

With the new European legislative and R&D efforts, IPM is receiving renewed attention and the concept of prevention – IPM principle 1 – via the design of cropping systems inherently less vulnerable to pests is given centre stage. The term “ultimate IPM” was introduced by Cliff Ohmart (personal communication, 2008) as an ideal and unattainable situation where the cropping system design has been so well crafted that no crop protection intervention is needed to manage pests once the system is in place. Originally thought of as an artefact useful to create the IPM continuum, which is itself a useful tool to include nearly all farmers onboard, the authors believe it is also a useful yardstick on the horizon to compare the goals of the various approaches. This might imply a change of perspective. In current IPM development, researchers and advisors start from a conventional agroecosystem and gradually remove inputs from it. The new approach would be to start from a nearly natural ecosystem to which inputs are gradually added when absolutely necessary (Brown 1999).

This new perspective would bring IPM closer to ecological intensification for crop protection (even closer then under the “integrated production” concept) and to low-input organic farming giving priority to agroecological practices such as polyculture, use of on-farm produced inputs and preventive strategies. It would also help to distinguish it from a low-level of IPM embodied by the pun “Intelligent Pesticide Management” (Nicholls and Altieri 2004), or from large-scale organic farming. The same criticism is actually applicable to large-scale organic farming regarding the practice of substitution – rather than redesign – translating to reliance on broad-spectrum “natural” pesticides, either mineral, e.g. copper and sulphur in organic viticulture, or broad spectrum plant-derived insecticides e.g., until recently rotenone, and the repeated release of massive numbers of short-lived natural enemies in augmentative biological control as a substitute to chemical treatments. It also applies to industrial no-till systems that claim to be agroecological even though many are reliant on GM crops and herbicide applications.

Given scientific evidence and increasing societal pressure due to the perception that the main risks now come from humans rather than from “Nature” (Beck 1986), it is likely that the current trend in pesticide use reduction will speed up. In this context, one should be ready to face situations such as the ban of DDT in US agriculture in 1972, the phase-out of a set of “dirty dozen” pesticides on rice in Indonesia in the late 1970s, or the “special period” in Cuba following the dissolution of the Soviet Union in the early 1990s (Altieri et al. 2012; Funes-Monzote et al. 2009). Although those were drastic measures, they largely contributed to the rise of IPM in the USA and Indonesia, and of agroecology – especially in its crop protection dimension – in Cuba.

We depict in Figs. 11 and 12 the current and future positioning of the major pathways to sustainable agriculture discussed in this paper, as compared to conventional intensive agriculture.

“Ultimate IPM”, as depicted in Fig. 12, will thus no longer rely on increased efficiency of synthetic pesticides, and much less on some substitution of inputs than organic farming, with an increased share of re-design of the cropping system (more than organic farming, although less than agroecology and ecological intensification). As compared to the other approaches, IPM will continue to be more “pest regulation service-oriented”, while ecological intensification will be more “food provision service-oriented”.

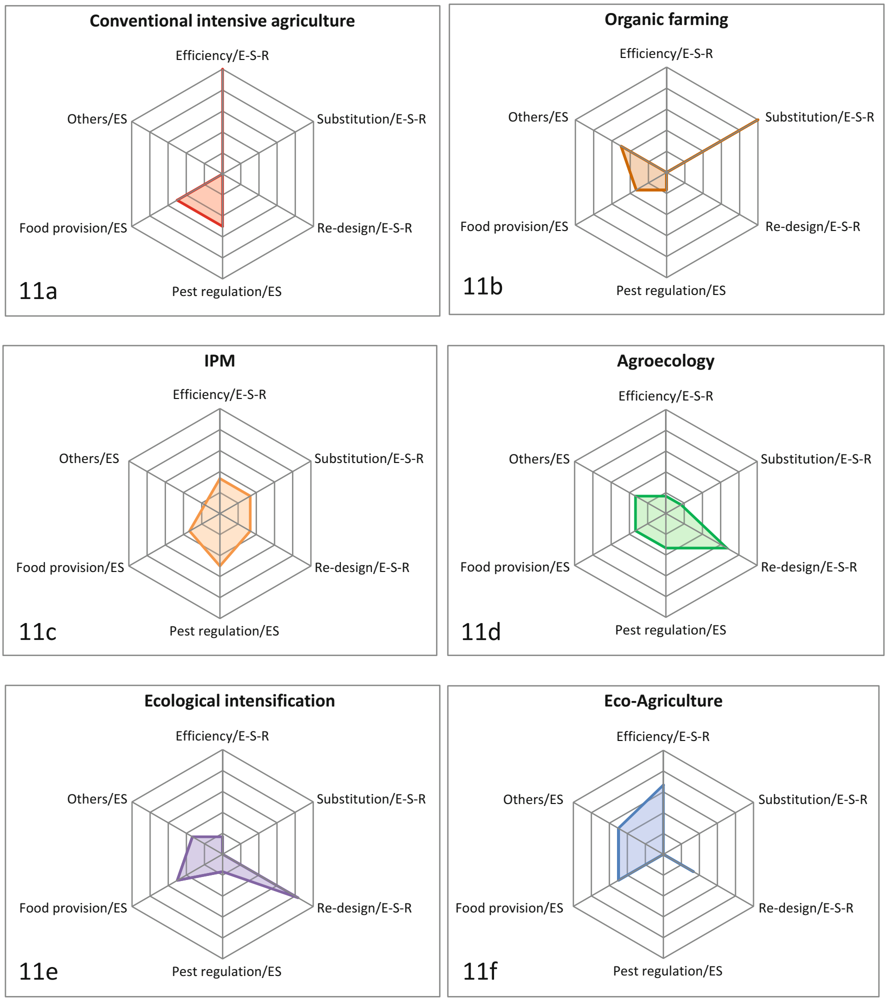


Fig. 11 Radar graphs showing the current positioning (on 0–100 % scales) of five pathways to sustainable agriculture (11b thru 11f), as compared with conventional intensive agriculture (11a), according to their respective share between the three components of the Efficiency – Substitution – Re-design (E-S-R) framework (*top-right* part of the graphs) and their respective contributions to three types of ecosystems services (ES): Pest regulation, Food provision, and other ES, including Human & Environmental health and Biodiversity conservation (*bottom-left* part of the graphs)

We thus propose to consider IPM and crop protection in ecological intensification as complementary rather than conflicting approaches. Both approaches aim at managing rather than eradicating pests. Both allow pesticide use in certain circumstances. Future avenues to develop more sustainable crop protection could focus on

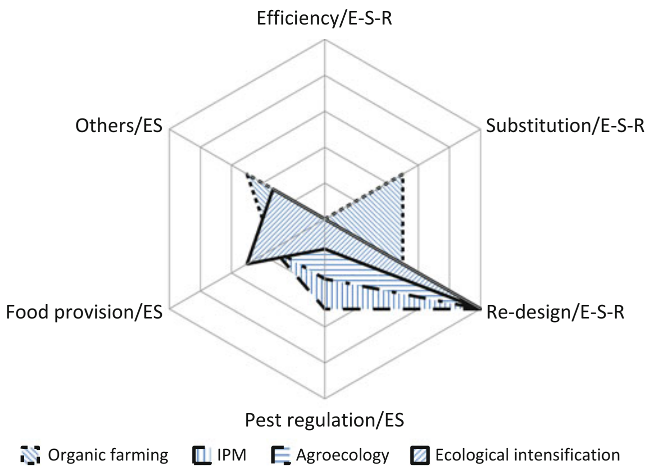


Fig. 12 Radar graph showing the positioning according to the same lines as in Fig. 11, of ecological intensification as compared to the evolution of three of the above pathways, namely IPM in its "ultimate" form, Organic farming restricted to its "low-input" form, and Agroecology excluding the industrial no-till systems

the management of biodiversity within a two-pronged approach, as suggested by Avelino et al. (2011):

- reduction of pesticide use in intensified systems, while retaining as high a yield as possible
- yield increase in rustic or low-technology systems, while maintaining ecological functions of pest and disease control at high levels.

The engineering stance of ecological intensification makes it suited to reconciling traditionally descriptive disciplines around ecology and anthropology of indigenous knowledge systems with more action-oriented fields such as agricultural sciences, entomology, plant pathology, or weed sciences. It can also enrich fields such as the French school of agronomy – a field that historically only considered physico-chemical processes, their interactions with crop physiology and agronomic practices – with aspects on biological interactions and regulation processes in agro-ecosystems (Hénin 1967; Wezel et al. 2009).

Finally, considering the current climate change and globalization contexts, one must admit that agriculture in the northern hemisphere may benefit from the experience of research in the tropics to anticipate increased pest and disease risks. On the one hand, in the tropics, biodiversity levels, including those of destructive organisms, are higher, and life cycles of pests and pathogens shorter than in temperate areas. On the other hand, high "resource" biodiversity levels in most tropical agro-ecosystems make it possible to design cropping systems that are more sustainably resilient to crop pests and diseases by relying on increased biodiversity/ecological regulation processes instead of non-renewable and toxic inputs. In this respect, we hope that the case studies provided here are food for thought for future development, particularly in the context of global climate change, globalization of exchanges, and increased societal pressure against pesticide use, in view of designing agroecosystems resilient vis-à-vis invasive and emerging pests.

Acknowledgments The authors wish to thank the Endure network since the idea of this chapter emerged from discussions held at Volterra, Italy, during the 2012 Endure Summer School.

References

Ahmed GJU, Hossain ST, Islam MR, Rabbi MF (2004) Rice-duck farming reduces weeding and insecticide requirement and increases grain yield and income of farmers. Int Rice Res Notes 29:73–76

Altieri MA (1995) Agroecology: the science of sustainable agriculture, 2nd edn. Westview Press, Boulder

Altieri MA (2004) Agroecology versus ecoagriculture: balancing food production and biodiversity conservation in the midst of social inequity. CEESP Occas Pap 3:8–28

Altieri MA, Nicholls CI (2012) Agroecology scaling up for food sovereignty and resiliency. In: Lichtfouse E (ed) Sustainable agriculture reviews 11. pp 1–29. Springer, Dordrecht

Altieri MA, Gurr GM, Wratten SD (2004) Genetic engineering and ecological engineering: a clash of paradigms or scope for synergy? In: Gurr GM, Wratten SD, Altieri MA et al (eds) Ecological engineering for pest management: advances in habitat manipulation for arthropods. CSIRO Publishing, Collingwood, pp 13–31

Altieri MA, Funes-Monzote FR, Petersen P (2012) Agroecologically efficient agricultural systems for smallholder farmers: contributions to food sovereignty. Agron Sustain Dev 32:1–13

Ammann K (2005) Effects of biotechnology on biodiversity: herbicide-tolerant and insect-resistant GM crops. Trends Biotechnol 23:388–394

Avelino J, Ten Hoopen GM, DeClerck F (2011) Ecological mechanisms for pest and disease control in coffee and cacao agroecosystems of the neotropics. In: Rapidel B, Le Coq JF, Beer J (eds) Ecosystem services from agriculture and agroforestry: measurement and payment. Earthscan Publications, London, pp 91–117

Barzman MS (2000) Weaver ants in orchards and groves. In: Stoll G (ed) Natural crop protection in the tropics. Margraf Verlag, Weikersheim, pp 99–100

Barzman MS, Mills NJ, Nguyen TTC (1996) Traditional knowledge and rationale for weaver ant husbandry in the Mekong delta of Vietnam. Agr Hum Val 13:2–9

Beck U (1986) Risikogesellschaft. Suhrkamp Verlag, Francfort

Bellon S, de Sainte Marie C, Lauri PE, Navarrete M, Nesme T, Plénet D, Pluvinage J, Habib R (2006) La production fruitière en France: le vert est-il dans le fruit? Le Courrier de l'environnement de l'INRA 53:5–18

Birch ANE, Begg GS, Squire GR (2011) How agro-ecological research helps to address food security issues under new IPM and pesticide reduction policies for global crop production systems. J Exp Bot 62:3251–3261

BLW (Bundesamt für Landwirtschaft) (2013) Agrarbericht 2012. Download BLW – Agrarbericht 2012. http://www.blw.admin.ch/dokumentation/00018/00498/01688/ind ex.html?lang=de

Boller EF, Avilla J, Joerg E, Malavolta C, Wijnands FG, Esbjerg P (2004) Integrated production, principles and technical guidelines. IOBC WPRS Bull 27:1–49

Bonny S (2011) L'agriculture écologiquement intensive: nature et défis. Cah Agric 20:451–462

Brown MW (1999) Applying principles of community ecology to pest management in orchards. Agric Ecosyst Environ 73:103–106

Carson R (1962) Silent spring. The Riverside Press, Cambridge, MA
Chandler LD, Faust RM (1998) Overview of areawide management. J Agric Entomol 15:319–325
Cook SM, Khan ZR, Pickett JA (2007) The use of push–pull strategies in integrated pest management. Annu Rev Entomol 52:375–400
Darnhofer I, Lindenthal T, Bartel-Kratochvil R, Zollitsch W (2010) Conventionalisation of organic farming practices: from structural criteria towards an assessment based on organic principles. A review. Agron Sustain Dev 30:67–81
Deguine JP, Ferron P, Russell D (2008) Protection des cultures: de l'agrochimie à l'agroécologie. Quae, Versailles
Doré T, Makowski D, Malézieux E, Munier-Jolain N, Tchamitchian M, Tittonell P (2011) Facing up to the paradigm of ecological intensification in agronomy: revisiting methods, concepts and knowledge. Eur J Agron 34:197–210
ENDURE (2011) On the implementation of the eight principles of IPM. 15 pp. http://www.endure-network.eu/about_ipm/endure_position_papers
Fatondji D, Pasternak D, Nikiema A, Senbeto D, Woltering L, Ndjeunga J, Abdoussalam S (2011) The dryland eco-farm: a potential solution to the main constraints of rain-fed agriculture in the semi-arid tropics of Africa: exploring the scientific facts. In: Bationo A, Waswa B, Okeyo JM, Maina F, Kihara J (eds) Innovations as key to the green revolution in Africa. Springer, Dordrecht, pp 1115–1123
Funes-Monzote FR, Monzote M, Lantinga EA, Ter Braak CJF, Sánchez JE, Van Keulen H (2009) Agro-ecological indicators (AEIs) for dairy and mixed farming systems classification: identifying alternatives for the Cuban livestock sector. J Sustain Agric 33:435–460
Furuno T (2001) The power of duck: integrated rice and duck farming. Tagari Publications, Tasmania
Griffon M (2006) Nourrir la planète. Odile Jacob, Paris
Griffon M (2013) Qu'est-ce que l'agriculture ecologiquement intensive? Quae, Versailles
Gurr GM, Scarratt SL, Wratten SD, Berndt L, Irvin N (2004) Ecological engineering, habitat manipulation and pest management. In: Gurr GM, Wratten SD, Altieri MA (eds) Ecological engineering for pest management: advances in habitat manipulation for arthropods. CSIRO Publishing, Collingwood, pp 1–12
Guthman J (2000) Raising organic: an agro-ecological assessment of grower practices in California. Agric Hum Val 17:257–266
Hénin S (1967) Les acquisitions techniques en production végétale et leurs applications. Économie Rurale 74:31–44
Hill SB, MacRae RJ (1995) Conceptual frameworks for the transition from conventional to sustainable agriculture. J Sust Agric 7:81–87
Howard A (1943) An agricultural testament. Oxford University Press, London
Huang HT, Pei Y (1987) The ancient cultured citrus ant, a tropical ant is used to control insect pests in southern china. Bioscience 37:665–671
IPM CRSP/Virginia Tech (2011) http://www.oired.vt.edu/ipmcrsp/AboutUs/FAQs.html
Jackson W, Piper J (1989) The necessary marriage between ecology and agriculture. Ecology 70:1591–1593
Kennedy G (2008) Integration of insect-resistant genetically modified crops within IPM programs. In: Romeis J, Shelton AM, Kennedy G (eds) Integration of insect-resistant genetically modified crops within IPM programs (progress in biological control). Springer, New York, pp 1–26
Khan ZR, Midega CAO, Bruce TJA, Hooper AM, Pickett JA (2010) Exploiting phytochemicals for developing a 'push–pull' crop protection strategy for cereal farmers in Africa. J Exp Bot 61:4185–4196
Letourneau DK, van Bruggen AHG (2006) Crop protection in organic agriculture. In: Kristiansen P, Taji A, Reganold J (eds) Organic agriculture – a global perspective. CSIRO Publishing, Collingwood, pp 93–121
Maguire LA, Justus J (2008) Why intrinsic value is a poor basis for conservation decisions. Bioscience 58:910–911
Malézieux E (2012) Designing cropping systems from nature. Agron Sustain Dev 32:15–29

Mathijs E (2012) Sustainable food consumption and production in a resource-constrained world. The futures of agriculture. Brief No. 01 – English. Global Forum on Agricultural Research (GFAR), Rome

McNeely J, Scherr S (2003) Ecoagriculture: strategies to feed the world and save wild biodiversity. Island Press, Washington, DC

Meissle M, Romeis J, Bigler F (2011) Bt maize and integrated pest management – a European perspective. Pest Manag Sci 67:1049–1058

Millennium Ecosystem Assessment (2005) Ecosystems and human well-being: synthesis. Island Press, Washington, DC

Mitsch WJ, Jorgensen SE (2003) Ecological engineering: a field whose time has come. Ecol Eng 20:363–377

Moore Lappé F, Collins J, Rosset P, Esparza L (1998) World hunger: twelve myths. Grove Press, New York

Nash R (1967) Wilderness and the American mind. Yale University Press, New Haven/London

Nicholls CI, Altieri MA (2004) Agroecological bases of ecological engineering for pest management. In: Gurr GM, Wratten SD, Altieri MA (eds) Ecological engineering for pest management: advances in habitat manipulation for arthropods. CSIRO Publishing, Collingwood, pp 33–54

Ohmart C (2008) IPM implementation at field level: "What are the impediments to grower adoption of IPM? Why do they exist and what can be done to get around them?". ENDURE International Conference 2008 Diversifying crop protection, 12–15 October 2008, La Grande-Motte, France, pp 1–10. http://www.endure-network.eu/international_conference_2008/proceedings/monday_october_13

Ohmart C (2009) IPM implementation – overcoming barriers to grower adoption. Pestic News 85:22–25

Perfecto I, Vandermeer J (2008) Biodiversity conservation in tropical agroecosystems: a new conservation paradigm. Ann NY Acad Sci 1134:173–200

Perfecto I, Vandermeer J, Masa A, Soto Pinto L (2005) Biodiversity, yield, and shade coffee certification. Ecol Econ 54:435–446

Phalan B, Onial M, Balmford A, Green RE (2011) Reconciling food production and biodiversity conservation: land sharing and land sparing compared. Science 333:1289–1291

Power AG (2010) Ecosystem services and agriculture: tradeoffs and synergies. Philos Trans R Soc Lond B 365:2959–2971

Pretty J (2008) Agricultural sustainability: concepts, principles and evidence. Philos Trans R Soc Lond B 363:447–465

Rahbi P (2008) Manifeste pour la terre et l'humanisme: pour une insurrection des consciences. Actes Sud, Paris

Ratnadass A (2013) Room for plant derived pesticides in agroecological management of crop pests? Experience from some African cropping systems. In: Ogendo JO, Lukhoba CW, Bett PK, Machocho AK (eds) Proceedings of the first international conference on pesticidal plants, ADAPPT-Network. Egerton University, Nakuru, pp 179–183. Nakuru, Kenya

Ratnadass A, Wink M (2012) The phorbol ester fraction from *Jatropha curcas* seed oil: potential and limits for crop protection against insect pests. Int J Mol Sci 13:16157–16171

Ratnadass A, Michellon R, Randriamanantsoa R, Séguy L (2006) Effects of soil and plant management on crop pests and diseases. In: Uphoff NT, Ball AS, Fernandes ECM, Herren HR, Husson O, Laing MV, Palm C, Pretty J, Sanchez P, Sanginga N, Thies J (eds) Biological approaches to sustainable soil systems. CRC Press, Boca Raton, pp 589–602

Ratnadass A, Rafamatanantsoa E, Rajaonera TE, Ramahandry F, Ramarofidy M, Randriamanantsoa R, Séguy L (2008) Dispositifs pour l'évaluation des impacts des systèmes de culture sur les dégâts des insectes terricoles sur le riz pluvial à Madagascar. Terre malgache 26:153–155

Ratnadass A, Fernandes P, Avelino J, Habib R (2012a) Plant species diversity for sustainable management of crop pests and diseases in agroecosystems: a review. Agron Sustain Dev 32:273–303

Ratnadass A, Razafindrakoto Raeliarisoa C, Andriamizehy H, Ravaomanarivo LH, Rakotoarisoa HL, Ramahandry F, Ramarofidy M, Randriamanantsoa R, Dzido JL, Rafarasoa LS (2012b) Protection of upland rice at Lake Alaotra (Madagascar) from black beetle damage (*Heteronychus plebejus*) (Coleoptera: Dynastidae) by seed dressing. Afr Entomol 20:177–181

Ratnadass A, Randriamanantsoa R, Douzet JM, Rakotoalibera H, Andriamasinoro V, Rafamatanantsoa E, Michellon R (2012c) Evaluation des risques liés au traitement de semences contre les attaques d'insectes terricoles sur riz pluvial à Madagascar et d'alternatives biologiques aux molécules de synthèse. 1st Conference on Organic Rice Farming and Production Systems, Montpellier, France, 27–30 Aug 2012

Ratnadass A, Randriamanantsoa R, Rajaonera TE, Rabearisoa M, Rafamatanantsoa E, Moussa N, Michellon R (2013) Interaction between cropping systems and white grub (Coleoptera: Scarabeoidea) status (pest or beneficial) on upland rice. Cah Agric 22:432–441. doi: 10.1684/agr.2013.064

Razafindrakoto Raeliarisoa C, Rakotoarisoa HL, Razafindrakotomamonjy A, Ratnadass A, Vercambre B (2010) Lutte biologique intégrée contre des insectes terricoles, *Heteronychus* spp à Madagascar, par un champignon entomopathogène sur riz pluvial en semis direct sous couverture végétale. Etude et Gestion des Sols 17:159–168

Reyers B, Polasky S, Tallis H, Mooney HA, Larigauderie A (2012) Finding common ground for biodiversity and ecosystem services. Bioscience 62:503–507

Röling N, van de Fliert E (1994) Transforming extension for sustainable agriculture: the case of integrated pest management in rice in Indonesia. Agric Hum Value 3:96–108

Rosset PM, Altieri MA (1997) Agroecology versus input substitution: a fundamental contradiction in sustainable agriculture. Soc Nat Resour 10:283–295

Seguni ZSK, Way MJ, Van Mele P (2011) The effect of ground vegetation management on competition between the ants *Oecophylla longinoda* and *Pheidole megacephala* and implications for conservation biological control. Crop Prot 30:713–717

Séguy L, Husson O, Charpentier H, Bouzinac S, Michellon R, Chabanne A, Boulakia S, Tivet F, Naudin K, Enjalric F, Chabierski S, Rakotodralambo P, Ramaroson I, Rakotondramana (2012) Principles and functioning of ecosystems cultivated under Direct seeding Mulch-based Cropping systems (DMC). CIRAD-GSDM-TAFA, Antananarivo

Shelton AM, Hatch SL, Zhao JZ, Chena M, Earle ED, Cao J (2008) Suppression of diamondback moth using Bt-transgenic plants as a trap crop. Crop Prot 27:403–409

Stäubli A (1983) Le fruit d'une harmonie entre l'homme et la nature. Revue suisse de viticulture arboriculture horticulture 15:317–318

Steiner R (1924) Agriculture course, the birth of the biodynamic method, eight lectures and discussions. Skylark Books, Hastings

Stern VM, van den Bosch R, Hagen KS (1959) The integrated control concept. Hilgardia 29:81–101

Su P, Liao XI, Zhang Y, Huang H (2012) Influencing factors on rice sheath blight epidemics in integrated rice-duck system. J Integr Agric 11:1462–1473

Van Mele P, Vayssières JF, van Tellingen E, Vrolijks J (2007) Effects of an African weaver ant, *Oecophylla longinoda*, in controlling mango fruit flies (Diptera: Tephritidae) in Benin. J Econ Entomol 100:695–701

Van Mele P, Vayssières JF, Adandonon A, Sinzogan A (2009) Ant cues affect the oviposition behaviour of fruit flies (Diptera: Tephritidae) in Africa. Physiol Entomol 34:256–261

Vandermeer J (1995) The ecological basis of alternative agriculture. Annu Rev Ecol Syst 26:201–224

Vayssières JF, Sinzogan A, Ouagoussounon I, Korie S, Thomas-Odjo A (2009) Effectiveness of spinosad bait sprays (GF-120) in controlling mango-infesting fruit flies (Diptera Tephritidae) in Benin. J Econ Entomol 102:515–521

Wezel A, Bellon S, Doré T, Francis C, Vallod D, David C (2009) Agroecology as a science, a movement and a practice. A review. Agron Sustain Dev 29:503–515

Zakari-Moussa O, Ratnadass A, Vayssières JF, Nikiema A, Fatondji D, Salha H, Aboubacar K, Ryckewaert P, Pasternak D (2012) GF120 Effects on fruit fly species (Diptera: Tephritidae) in Sahelian agroforestry-based horticultural cropping systems. Fruits 67:333–339

Zehnder G, Gurr GM, Kuhne S, Wade MR, Wratten SD, Wyss E (2007) Arthropod pest management in organic crops. Annu Rev Entomol 52:57–80

Zhang W, Ricketts TH, Kremen C, Carney K, Swinton SM (2007) Ecosystem services and disservices to agriculture. Ecol Econ 64:253–26

Livestock Farming Systems and Agroecology in the Tropics

Gisèle Alexandre, Audrey Fanchone, Harry Ozier-Lafontaine, and Jean-Louis Diman

Abstract The climate change crisis is inducing severe energy and food shortages in tropical regions. A potential solution is to build agroecological systems as an alternative to intensive and industrial agriculture. For that research should focus on the functions of animal and livestock farming systems. Positive and negative function effects should be assessed. This is particularly important in developing countries where most of tomorrow's food and feed will have to be produced. What are the main issues for animal production in the tropics? The major challenges are how to redesign productivity and food security, economic efficiency and environmental preservation, and how to integrate economy and environment. A multidisciplinary approach is necessary to address such complex problems, where interactions among interdependent components of the system result in multicausality.

The concept of livestock farming system, with its double consistency of social and biophysical dimensions, can help address complex problems. The concepts of livestock farming system and of agroecology can be easily combined to design sustainable animal production systems. Enhancing agroecological approaches that lead to both food security and biodiversity conservation must involve spreading concepts through practices, particularly to solve the problems of small farmers. As so, the purpose of the paper is to highlight many case studies. The animal and farming system ecoservices are described at the animal level with the case of the multifunctional tropical goat and also at the territory level with the case of agrosylvopastoral-

G. Alexandre (✉) • A. Fanchone
INRA, UR143, Unité de Recherches Zootechniques, 97170 Petit-Bourg, Guadeloupe
e-mail: Gisele.Alexandre@antilles.inra.fr; Audrey.Fanchone@antilles.inra.fr

H. Ozier-Lafontaine
INRA, UR1321, ASTRO Agrosystèmes Tropicaux, F-97170 Petit-Bourg, France
e-mail: Harry.ozier-lafontaine@antilles.inra.fr

J.-L. Diman
UR1321, Unité de Recherches sur les Agrosystèmes Tropicaux,
97170 Petit-Bourg, Guadeloupe
e-mail: Jean-Louis.Diman@antilles.inra.fr

H. Ozier-Lafontaine and M. Lesueur-Jannoyer (eds.), *Sustainable Agriculture Reviews 14: Agroecology and Global Change*, Sustainable Agriculture Reviews 14,
DOI 10.1007/978-3-319-06016-3_4,

ism focusing the role played by the animal. Finally, the socio-cultural functions of animals or systems in this region are described. The double dimension of livestock system concept allows the integration of the livestock keepers in the human and societal context to attain agroecological objectives which is recognised as a core objective to attain according through the agroecological perspective. Topical livestock farming systems can show their potential to reach sustainability and help family economy.

Keywords Agroecology • Livestock farming system • Ecoservices • Goat • Mixed farming system • Tropics

Introduction

Our societies and territories are facing major food, climate and energy crises. In this context of uncertainty, agroecological systems (Tomich et al. 2011), as a support for food security and territorial sustainability, are regaining recognition by farmers, scientists, consumers and governments (this book). This recognition is particularly important in developing countries where most of tomorrow's food and feed will have to be produced (Godfray et al. 2010). Agroecology, as a concept or a set of practices (Wezel et al. 2009), can be used in different agricultural systems, such as food-crop, or agroforestry. Not enough is known about its development through animal farming systems. Recently, Dumont et al. (2013) have explored potential routes for developing ecology-based alternatives for animal production through different examples, showing a gradient of intensification and/or biogeographical conditions. Classically, in the natural ecosystem, animals are ranked as primary (or secondary) consumers in the food chain. However, in an agroecosystem, the farmers choose their different agricultural activities and manage their own farming units according to their main objectives, means of production, and constraints.

Traditionally, animals were an asset to society by converting biomass and particularly marginal resources into products useful for humans. By contrast, in some intensive modern systems, animal production can be disconnected from the natural food chain and may or may not come after crop production (Naylor et al. 2005). Livestock activities and the sciences related to them are now locked in paradoxical situations, particularly in developing countries, since (i) it is fully recognized that demand for animal products will increase significantly (Wirsenius et al. 2010), (ii) animal husbandry plays an important role for sustainability in mixed farming systems by recycling waste and sub-products (Devendra 2007; Herrero et al. 2010), (iii) livestock gives livelihood support to numerous poor people in rural areas (Gerber and Steinfeld 2008; Dedieu et al. 2011), but (iv) much criticism is meanwhile directed at the negative environmental impacts ascribed to animal production (Steinfeld et al. 2006), and suspicion has fallen on some animal products (e.g. meat) as safe components of a healthy diet (Webb and O'Neill 2008).

Faced with the crisis of global change, it is clear that animal production and livestock production systems have never before been given so much importance by policy makers and environmentalist. For all these related reasons and taking the animal scientist pathways, there is a pressing need to focus on animal production and functions. We must qualify and quantify their potential contributions, whether positive i.e. ecosystem services or negative i.e. impediments, to the sustainability of the system. The questions of how to deal with productivity and food security, economic efficiency and environmental preservation objectives, and how to integrate economy and environment are challenges for scientific agendas. Our purpose here is to show how livestock farming system and agroecology concepts can be combined. Our main methodology has a multidisciplinary basis. Following the main conclusions of Malézieux et al. (2009) and Dedieu et al. (2011) on multi-species cropping systems and livestock systems, we emphasize the need to enhance agricultural research through a multidisciplinary approach. This latter must combine agronomic and ecological concepts and tools. Mixing scientific approaches also means sharing many concepts involved in the development of this domain. Our aim is thus to enrich the livestock system concept and broaden thinking.

Core Concepts

An Overview of Different Concepts

Farming System and Participatory Research

Two major review papers (Keating and McCown 2001; Lynam 2002) set out the main definitions and issues related to the system approach. Historically, **farming system research** was a response to the failure of agricultural research to generate a green revolution in the rain-fed areas of the tropics. The farming system, rather than the commodity, and the farmer's objectives rather the sector's economic interest were the organizational framework for research (Fig. 1). Over time, farming system research moved the research off-station and on-farm and became a diagnostic process, providing methods for understanding farm households. Having achieved a better understanding of systems, farming system research thus became a more effective bridge between research and extension, a perpetually weak link, and another item in the growing system research agenda. Farming system research created the whole concept of adaptive research and the notion of an interlocking continuum stretching from strategic, applied, and adaptive research to extension.

The adaptive research area, or what might be the researcher-farmer interface, has over the last 30 years been the focal point for a radical redefinition of research issues with the development of participatory research. The important basic difference is that **participatory research** focuses on farmers' learning, while farming system research has traditionally focused on the improved understanding of farmers' conditions by researchers. The core of the farming system research methodology has provided the framework for the development of participatory methods. The participatory approach started out with participatory rural appraisal.

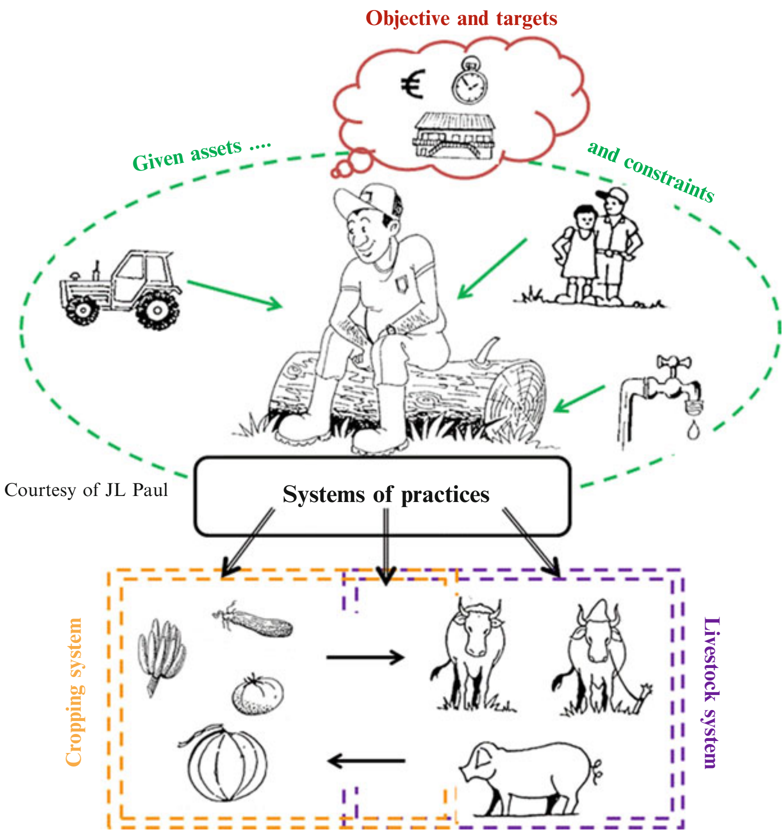


Fig. 1 The production unit: the farmer tries to reach his objectives and targets as a human being, for his family, belonging to his social group, according to assets and constraints (environmental factors, availability and conditions of land, working force, money, equipment, level of training…). Then he implements a combination of crops, animal husbandry (that are diverse in space and time) plus non rural activities

Research has moved on from the farming system research approach, consisting of diagnosis, causal analysis, experimentation, and solutions mainly in the biotechnical dimension, to the farmer participatory approach, consisting of diagnosis, problem ranking, and solutions mainly in the decisional dimension (this will be especially emphasized through the livestock system concept). Today the synergies between FSR and participatory research have been positive, to the extent that it is not useful to demarcate the two.

> The farming system research concept is an essentially operational process with a focus on the farming system and community levels in a systems hierarchy. Participatory research has incorporated the process components together with the farming system and community levels in its approach to adaptive research. Adaptive research is to be devolved to farmers, who are to disseminate innovations to other farmers. These benchmark sites then form the linkage point between researchers and farmers.

As we have stated, the concept of farming system was a response to the failure of agricultural research to generate a green revolution in the rain-fed areas of the tropics (Lynam 2002). One question that arises is whether it is actually relevant and productive to foster the double green revolution, and to promote adapted development plans through more participatory research. But nowadays, participatory methods are prevalent and farmers' learning has become the center of the adaptive research enterprise. Consequently, farmers' learning and experimentations are key to the adoption of many of the complex management-intensive techniques being developed in agroecological practices. These practices concern as well soils, pest, and crop management. This approach is surely the right direction in which to move. With time, and owing to many ecological and food shortage crises, ecology, rather than farming systems, have set a new trend. Integrated pest management, integrated nutrient management, agroforestry systems, crop-livestock systems, and natural resource management have all been developed within the framework of agroecosystems, firmly underpinned by biological and social science.

Different Visions to Achieve Sustainability

There are many visions of how to achieve a sustainable agriculture (Rigby and Caceres 2001; Doré et al. 2011) that provides enough food (Godfray et al. 2010) and ecosystem services (MEA 2005) for present and future generations in an era of climate change, increasing energy costs, social unrest, financial instability and increasing environmental degradation. Our purpose here is not to present an exhaustive study (see for instance Buttel 2003; Gliessman 2006; Wezel et al. 2009; Stassart et al. 2012), but instead to highlight some of the main conclusions shared by many of the contributors to this book.

Although the term **sustainable agriculture** is singular in form, it comprises a multidimensional concept, covering such diverse motivations as saving rare breeds, preserving land from deforestation, preventing soil degradation and reducing effluent production. Originally emphasizing the importance of ecological constraints, it now includes economic, social and cultural dimensions. Sustainable development in agriculture (*sensus lato*) conserves land, water, and plant and animal genetic resources. It is environmentally non-degrading, technically appropriate, economically viable and socially acceptable. However, such complex definitions, combining non-comparable objectives, tools and current problems with no clear hierarchy, are problematic for practical application. In addition, the great heterogeneity of agroecosystems and the non-linear relationship between agricultural production and agroecological criteria add to the difficulty.

Sustainability of livestock production systems has received increasing attention in the last 10 years (see reviews of McDermott et al. 2010; Udo et al. 2011). Increasing livestock productivity can, in some situations, be a tool to promote sustainability, whereas in others it may aggravate sustainability problems, depending on system-specific characteristics (Udo et al. 2011). A system-specific analysis is therefore needed to assess the overall effect of livestock inclusion in an agricultural system on each of the proposed general criteria for sustainability (de Wit et al. 1995). Such a system-specific analysis raises a new challenge in the formulation of multi-criteria performances – by the way of modeling for instance (Tichit et al. 2011) – or an assessment of trade-offs between the criteria (Stoorvogel et al. 2004). Many intricately related problems have simultaneously arisen, which Hellstrand et al. (2009) tried to conceptualize in their review paper. The concept of sustainability is a dynamic one: what was once considered sustainable may no longer be deemed so today or in the future because conditions or attitudes change. In addition, sustainability varies with the frame of reference in which it is viewed, particularly with respect to socio-cultural, economic and political factors.

To implement eco-friendly agroecosystems we must mimic nature: **nature becomes a model and a target** (Preston and Leng 1987; Rodríguez 2010; Malézieux 2012). Another complementary point of view presented by Via Campesina (2010) is that to feed future populations, we must nurture the land. In most tropical countries, sustainable peasant agriculture stems from a combination of recovery and revalorization of traditional peasant farming methods, and the innovation of new ecological practices. Also, it is argued (Chappell and LaValle 2011; SOCLA 2011) that agroecology can feed the world, meaning preferentially the poor, in diverse biophysical conditions (De Schutter 2011). Nelson et al. (2009) advocated institutionalizing agroecology on the basis of the Cuban model, described as being successful at the levels of both territory and society.

Agrobiodiversity includes biota on and around farms, and is natural capital that provides options for food security and other ecosystem services. At the field scale, agrobiodiversity sustains crop and livestock productivity, nutrient cycling, pathogen suppression, pest control and human nutrition (Malézieux et al. 2009; Jackson et al. 2012). At the landscape scale, agrobiodiversity supports water quality and mitigation of greenhouse gas emissions (e.g. through nutrient and carbon storage by plants and soil biota), pollination and pest control (e.g. through ecological connectivity for flora and fauna), and protection of nearby wildland ecosystems (e.g. when biodiversity is used for ecological functions that reduce inputs and impacts of agricultural chemicals). Conversely, agrobiodiversity is frequently lost when high agrochemical inputs (e.g. synthetic fertilizers, pesticides, and fossil fuels) are used to intensify agriculture and increase land and labor productivity. **Ecological intensification** (Stassart et al. 2012) promotes high, reliable agricultural production, but with a strong role for agrobiodiversity and biological processes (Doré et al. 2011). Ecological intensification typically invokes a land-sharing or wildlife-friendly farming approach, rather than segregation of land for nature and production (land-sparing). The challenge of ecological intensification is to encourage innovations for biodiversity-rich farming systems that are resilient and sustainable, and thus improve the livelihood of farmers, while supporting the conservation of wild species by limiting the adverse effects of agriculture on wild-land habitats.

Following the critical review of Altieri (2002) "**greening**" **the green revolution** will not be enough, because "*unless the root causes of poverty and inequity are confronted head-on, tensions between socially equitable development and ecologically sound conservation are bound to worsen*". Organic farming systems do not challenge the monocultural systems, and rely on foreign and expensive certification seals. This is one of the arguments studied by Janzen (2011) who states that reintroducing livestock into the ecosystem can play a core role in re-greening the earth (instead of spoiling it). Integrated pest management systems that only reduce insecticide use while leaving the rest of the agrochemical package untouched, or fair-trade systems destined only for agroexport (a niche market for the rich), may in some cases benefit biodiversity, but in general offer very little to small farmers. Profound differences mark the division between agroecology "*a truly pro-poor farmers' science*" and ecoagriculture. For agroecologists, environmentalists should no longer ignore issues related to land distribution, indigenous peoples' and farmers' rights, or the impacts of globalization on food security, and of biotechnology on traditional agriculture.

A comprehensive holistic analysis of how the agroecosystems could bring safe products to the consumer requires broadening the concept of a "food system" beyond those agricultural activities: current organization of food production, processing, distribution and consumption contribute to food security. In the review of Ericksen (2008), **food security** is defined as "*when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life.*" Food systems have usually been conceived as a set of activities ranging from production through to consumption. However, food security is a complex issue with multiple environmental, social, political and economic determinants. It encompasses components of availability, access and utilization. Both food systems and food security in the twenty-first century are fundamentally characterized by social and economic change. Global environmental change includes changes in the biogeophysical environment, which may be due to natural processes and/or human activities. Food systems also contribute to global environmental change, and future trends (Godfray et al. 2010), such as increased demand for food, with increases in incomes and populations, will affect global environmental change processes. Although food insecurity persists in critical areas (hunger crises in developing countries), overall dietary concerns are focusing less on under-nutrition and more on obesity and food safety.

According to the Millennium Ecosystem Assessment (MEA 2005), the most important direct driver of terrestrial ecosystem change during the past 50 years has been land cover change, in particular the conversion of ecosystems to agricultural land. Together with the adoption of new technologies and increased agricultural inputs, the expansion of agricultural land has enabled extraordinary progress in nutrition levels and food security. At the same time, undernourishment still affects about 920 million people in low and medium-income regions (Godfray et al. 2010).

Enhancing agroecological approaches that lead to both food security and biodiversity conservation must rely upon **spreading concepts through practices** (Wezel et al. 2009). Given the present and predicted near-future climate, energy and economic scenarios, agroecology has emerged as one of the most robust pathways towards sustainable development through the three dimensions of sustainability. Many recent papers (Wezel et al. 2009; Altieri et al. 2012) reviewing agroecological trends and issues, indicate that the food challenge will be met using environmentally friendly and socially equitable technologies and methods, in a world with a shrinking arable land base -due to changing demography-, with fewer and costlier energy sources, increasingly limited supplies of water, against a background of a rapidly changing climate, social unrest, and economic uncertainty. This picture is developed below for animal production or animal ecoservices. The concept of livestock farming system is first described.

The Livestock Farming System Concept

In the scientific domain of animal systems and animal production, the question arises of whether the livestock farming system concept is a useful approach for implementing agroecological practices and/or guiding agroecological studies. Our purpose is to show how livestock system and agroecology concepts can be combined. Our main methodology stands on a multidisciplinary basis.

Livestock system research is currently based on a conceptual model of the whole livestock farm (or livestock sub-part of a farm), which represents two dimensions that are totally interrelated between the view of a farm as a human activity system and the view of a farm as a production process (Fig. 2). According to Gibon et al. (1999), the view of a farm as a production process implicitly underlies classical animal science, and focuses on the transformation of physical inputs to physical outputs (here the term "physical" is taken *sensu lato*, meaning for example, vegetal biomass, water, labor force, or other farm equipment). By contrast, in viewing the livestock farm as a human activity system, the farmer (farm family) is seen as a person (a small social group) pursuing specific objectives through farming activities. Information from the farm environment is used to make decisions, which themselves adapt farming activities to achieve further objectives in response to environmental and other pressures.

> Livestock system research aims to gain a better understanding of the whole livestock system at the farm scale by linking technical and biological information with knowledge of farmers' decisions and practices. The decisional sub-system relies on farmers' decision-making with respect to the planning and operation of the production process.

This double integrated approach is a core area of livestock studies, with a specific area devoted to modeling methods (Dedieu et al. 2008). This approach generally requires animal production scientists to work with experts from other disciplines, especially ecology, sociology, economics and the more recently developed operational management. The theoretical advances in decision and regulation processes in complex systems are of paramount importance (Le Moigne 1990 cited by Gibon et al. 1999) to study the decisional sub-system. They allow assessment of the operation and dynamics of a system according to a general strategy of control that in turn defines a set of objectives and correlated actions (practices of the farmer).

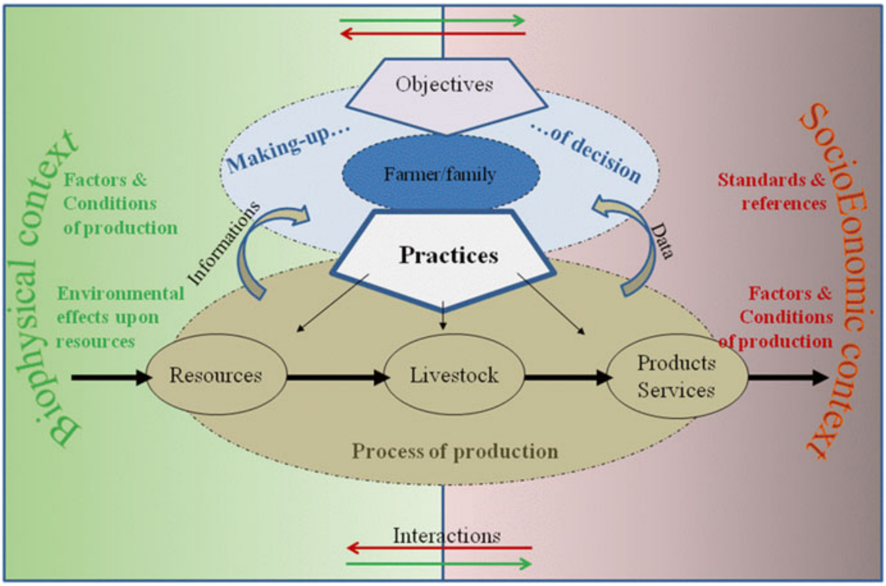


Fig. 2 Conceptual representation of the animal production unit (see Fig. 1). The livestock farming system (LFS) concept with the two sub-model: decisional and bio-technical (Dedieu et al. 2008). Between the two sub-models are the practices and data feed-back that induces the choice of the farmers and explains the farming type implemented. The decision making process depends also of the standards and references of the man within its family and society. The system is complex between biotechnical processes and psychological and sociological dimensions. The system is open and is submitted to the direct and indirect effects of the environment (*s.l.* biophysical and socioeconomic) and generates also flux of materials, products or provides ecoservices to the environment

There is a tradition in both the social and biophysical sciences of using the concept of a system to help to address complex problems with multi-causality resulting from interactions among interdependent components. Systems approaches help in understanding the critical factors that lead to particular outcomes or the interactions that govern a specific behavior of interest.

Agroecosystems, and even in a broader perspective whole food systems, are complex, heterogeneous in space and time and replete with non-linear feedbacks. The objectives of sustainable development are multiple, ranging from enhancing soil fertility (territory) to providing the markets (society) with safe products. There is a need to be fully inter-disciplinary, aiming for a marriage of natural and social science akin to that suggested by Holling (2001) describing coupled social-ecological systems. This conceptualization of human-environment interactions is useful for LFS, agroecological activities and food systems, although the links between the social and environmental components may in many cases be indirect.

As a partial conclusion, we recognize, with Keating and McCown (2001), two key components of farming systems, namely the biophysical "production system" of crops, pastures, animals, soil and climate, together with certain physical inputs and outputs, and the "management system", made up of people, values, goals, knowledge, resources, monitoring opportunities, and decision making. AE*,* defined as the ecology of agro-food systems (Francis et al. 2003), offers a response to this need for a systemic approach. In their review, Dumont et al. (2013) demonstrate that "*agroecology implies considering agro-ecosystems as a whole, in their biological, technical and social dimensions*" (as does the livestock system concept). "*It goes further than adjusting practices in current agroecosystems; it integrates interactions among all agroecosystem components and recognizes the complex dynamics of ecological processes*". Hence it appears that the concepts AE and LFS can be easily combined.

What are the main trends and issues for animal production in the tropics? Dumont et al. (2013), prospecting for the challenges of the twenty-first century, state in their review that "*surprisingly, animal farming systems have so far been ignored in most agroecological thinking*." Even so, for many years, studies have addressed these objectives more specifically in the tropical regions such as in Brazil (Figueiredo 2002) or Cuba (Funes-Monzote and Monzote 2001). Ahrens et al. (2009) have reviewed research carried out from 2004 to 2009 under the auspices of the Agroecology Programme of Paraná (Brazil), counting at least nine animal production programs. Altieri and Toledo (2011) provide an overview of what they call the "agroecological revolution" in Latin America, and indicate among the numerous case studies, those dealing with livestock, integrated within agroecosystems or not. Hence AE is also of major concern for animal production or animal raising.

Livestock farming system was presented *as a concept promoting a new paradigm (in the 1980s). Combined with agroecology objectives, the livestock concept could be used:*

- *As a grid to study the different elements of the agroecosystem (and food system) and their interactions with the global environment (natural and socio-economic);*
- *As a framework for the design and evaluation of models adapted to human and technical conditions;*
- *As a subject of research and development and "teaching" for sustainable territory development;*
- *As a tool to share experience and empower case-to-case lessons for the future, with prospects for building enhanced linkages between projects targeting different problems.*

The following sections will focus on some of these points through diverse case studies in the tropical regions. Our purpose is to highlight some positive examples (praxis) relevant to some of the above-mentioned dimensions of the concepts (theory).

The Environmental Dimension of Livestock Production

Agronomic and ecological conceptual frameworks are examined in a combined way for a clearer understanding of animal systems, including at least two major dimensions, biotechnical and human, that will help design and assess farming systems involving animals. However, in a first step it is important to show how the livestock enterprise and the environment interact, in the light of recent criticisms that have caused tremendous shifts in thinking throughout the animal science community.

A Rapid Overview of the Agroecological Conditions

In their review of the world livestock production systems, Seré and Steifeld (1996) gave an agro-ecological classification of the world regions (see Photo 1 describing ecological conditions in insular regions of the Caribbean) based on length of available growing period, and describe the systems that reflect the conditions prevailing in these regions. Arid zones are areas where the growing period is less than 75 days, too short for reliable rain-fed agriculture. The main systems found in these zones are the mobile systems on communal lands. Some cases of ranching occur. Progressively, biotic factors, human pressure and the resulting land use define the state of the natural resources. Agricultural areas compete with pastoral lands. The livestock systems are diverse: transhumant and semi-transhumant pastoralism, agro-pastoralism, along with ranching. Non-equilibrium systems are found in these areas where rainfall is persistently erratic, both in timing and spatial distribution. In these environments, it is no longer appropriate to conceive management as the manipulation of the biological system to achieve maximum output or revenue. In sub-humid areas, where the growing season lasts between 75 and 270 days, the limitation of stock farming is more dependent on the quality than on the quantity of pasture available. The systems are also transhumant and semi-transhumant pastoralism, sedentary grassland farming and ranching. With the growing season exceeding 270 days in humid zones, the natural vegetation is mostly the rainforest. Livestock and grasslands can compete with forest. Part of agriculture is based on tree crop plantations. Agro-pastoralism, ranching and grassland farming are practised. Tropical highlands are areas with daily mean temperature during the growing period in the range 5–20 °C. Temperature is a seasonal limitation to plant growth, more than rainfall. All systems can be found in these zones. Other situations are characterized by having Mediterranean and continental climates with marked seasonality, cold and wet in winter and with prolonged periods of drought and hot weather, particularly in the summer and fall. Dry environments have extended periods of annual drought, and are also subject to periodic successions of years of drought that compound feed scarcity. In addition, a limited availability of water results in limited grazing opportunities.

Arid and semi-arid lands cover about one third of the earth's land surface, but nearly two thirds of the African continent. Most African livestock and possibly 30 million livestock-dependent people reside in these dry zones, along with the greatest and most diverse concentrations of large wild mammals in existence. Many of the world's 20 poorest countries are situated in this zone.

Animals are raised under wide-ranging natural conditions, generating very diverse types of livestock farming systems (Lhoste et al. 1993; Dedieu et al. 2011).

Photo 1 Different agroecological conditions in insular Caribbean of Haiti or Guadeloupe, respectively

It is critical to recognize animal output as a complex trait dependent upon numerous abiotic, biotic and socio-economic factors. In addition, these factors of variation are interrelated. Increasing reproductive performances, reducing mortality rate, accelerating growth rate and improving carcass merit are multiple interdependent objectives. Thus animals and systems, together with their different combined factors of variation, must be characterized for the different interrelated animal traits contributing to production. Only a multidisciplinary analysis that includes multiple aspects: environmental (availability of herbaceous sources), economic (stability, alternative sources of income) and socio-political (land-tenure, control over resources), enables us to define and distinguish between the various production units in the region studied.

Taking into consideration the place of the animals in the natural food chain, and given that the livestock farming system is defined as an open system) we must recognize that it is linked to a specific environment sharing different physical materials (inputs), subjected to both direct and indirect effects of the environment upon the system, and impacting in different ways upon the materials, the soil and the atmosphere, and of course the biomass.

Theoretical Approach of Animal Performances

Animal performance is determined by two major components: genetic effects and environmental effects, and the concomitant interactions between genotype and environment (see Photo 2). Among the factors inimical to livestock production in the tropics, the most important are high ambient temperatures, high relative humidity, and erratic and/or low rainfall regimes. These have concomitant effects on the quality and quantity of available feeds, a wide variety of diseases and low levels of animal productivity. Ways to mitigate these environmental effects are known: (i) limiting or avoiding stress by appropriate flock management, and/or (ii) increasing animal resistance to harsh environments through genetic adaptation. Before describing how these actions will be involved, we may recall the main factors of variation and the parameters of animal production in a global approach.

Climatic conditions have direct and indirect effects via biotic parameters (feed resources level and quality, pathogen occurrence and pathogenicity). Growth, milk production and reproduction are impaired under heat stress conditions as a result of the drastic changes in biological functions caused by the physiological modifications made to cope with heat stress. This means that from an agroecological perspective it makes sense to **raise well-adapted species and genotypes** (Wilson 2009; Hoffmann 2010), such as the indigenous ones living in the region (Naves et al. 2000). Exotic species will need higher external inputs or very costly artificialized husbandry techniques. Secondly, feeding animals well is obviously of fundamental importance to the success of the whole enterprise. Feeding conditions both in quantity and quality (Archimede et al. 2011) determine the overall nutritional status of the flock, and are deciding factors for animal survival and for meeting nutrient needs for maintenance, reproduction, lactation and growth potential. Feeding and nutrition-related factors also interfere in and often determine individual vulnerability to potential diseases or climatic constraints. Feeding practices should ideally match the available local resources, as mentioned earlier by Preston and Leng (1987), giving in their time a very agroecological recommendation. The occurrence of diseases and the prevalence of parasites markedly affect both animal survival and levels of performance. Maintaining animals in a good healthy state is obviously of great importance for economic results and flock maintenance. Pathogens and

Photo 2 Different grazing conditions and genotypes of goat in Guatemala (dry zone and indigenous goat) and Jamaica (humid pasture grazing and exotic goat), respectively

parasites must be studied with their proper agroecological conditions. Here again the recommended agroecological practice is an integrated management of parasites instead of the application of the zero risk strategy (Mahieu et al. 2009). In addition to feeding level and prophylaxis measures, animal husbandry *per se* is directly responsible for success or failure in the animal production process. Frequently, farmers do not interact with the life cycles of their animals, i.e. they do not manage them. Animal husbandry techniques, including stocking rate and housing conditions, are often not really controlled. In many tropical countries, it is evident that there is a lack of essential technical support and infrastructure for an efficient collective organization and for appropriate extension services in the sector.

The question of the genotype is very sensitive and complex. To simplify the issue, we can consider the multiple physiological functions that an animal must exert in such an adverse context (immunity, reproduction, nutrition, lactation, growth, Gunia et al. 2013). Overall animal productivity finally depends on numerous components: genotype, environment and husbandry factors. The low level of present productivity in arid and tropical environments may be attributed to poor genetic potential along with harsh and erratic climatic conditions. But what is the most important factor? Is it poor genetic potential for production when adaptation is much more prevalent? The potential for production is a result of the effect of the environment on an animal that has adapted along the centuries to high pathological constraints and nutritional deficiencies. The scarce nutrient resources are used for the different physiological functions: immunity, metabolism to cope with heat stress and/or water scarcity, reproduction/lactation and growth. We must consider that higher potential means higher nutritional requirements for productive performances, and lower nutrient availability for the immune function. Higher potential means, among other things, artificialization, and costly technical inputs. The challenge for agroecological purposes is to reach an equilibrium between adaptation to the environment, implementing soft innovations and lowering negative environmental impacts, while ensuring benefit to society.

Livestock Farming System as a Framework for Practical Case Studies

Graphical Approaches

The livestock system concept is defined as being an open system monitored by humans for their multiple benefits. It can be studied more deeply at the biotechnical level (Fig. 3). The tropical livestock farming system is multipurpose as regards both the animals themselves and the animals' activities. Animal husbandry is a reductionist term not used in this case. The following graphs (Fig. 3a, b, c) are the extension of the first conceptual graph (Fig. 2) with a focus on the sub-part that is studied. For better comprehension, the interrelations between the livestock system and the environment with double consistency, biophysical and also socio-economic, are given (Fig. 3a).

Keeping in mind the natural environment and the socioeconomic context, the focus of the animal scientist can settle on different sub-parts. The pastoralist will look at the interrelationships between pastures, composed of a stand of diverse resources, herds constituted of different animals and/or physiological status and management (Fig. 3b). The study will deal with the agroecological modes of management (see Boval et al., this special issue). The technologist will look at the products (Fig. 3c) as a resultant of the animals transforming the resources. Thus he will study the quality standards in response to the consumers' demands such as healthy foods, no toxic residues, fatty acid profiles, and animal welfare (Faye et al. 2011). In both cases, the animal plays a leading role by definition.

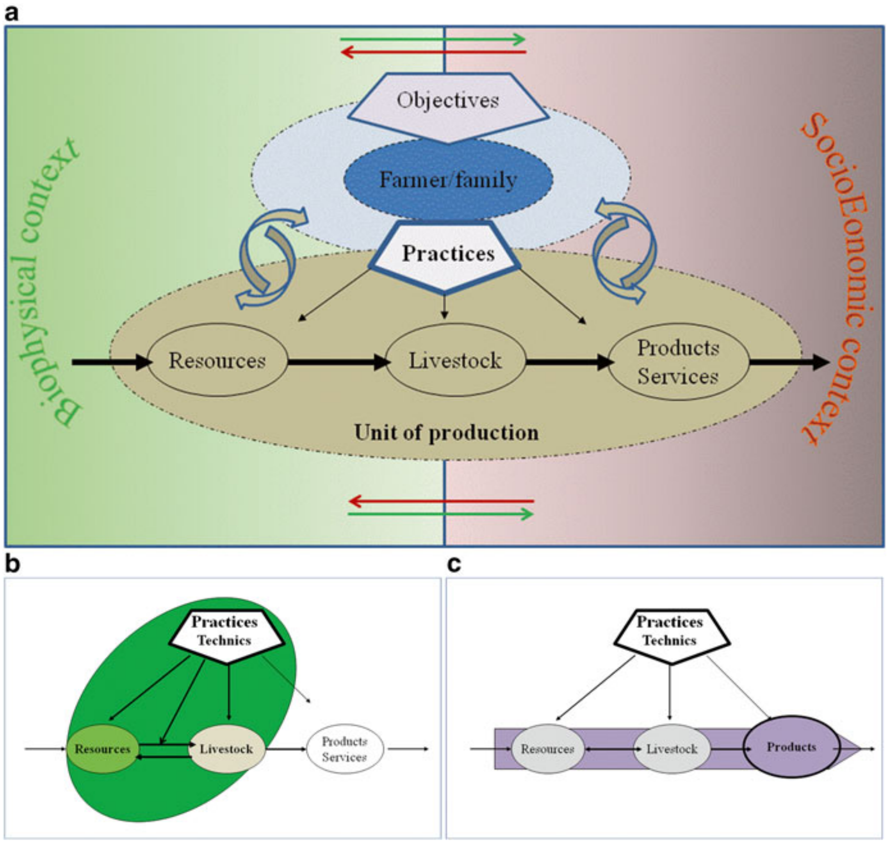


Fig. 3 (**a**) The LFS concept approach allows to describe the biotechnical sub-part: i.e. the animal husbandry practices (termed techniques when provided by researchers or extension agents) that are implemented through the resources, the herds and the products and their relationships and interactions between elements. (**b**) Focuses on the grazing system which is based upon intricate links between grasslands and livestock under the management of the farmer (or not). (**c**) Focuses on the product which results from the transformation of the resources by the animals under the control of the farmer (or not)

The same conceptual model can be used in the case of an integrated crop-livestock system with a focus upon the intertwining of crop and livestock components (Fig. 4). The specific features of agroecology come from the simultaneous integration of multiple objectives where many species, activities and functions are interrelated within the same system. The importance of mixing many crop productions has already been assessed (Valet and Ozier-Lafontaine, this special issue), and it has been proved that multispecies systems provide valuable food crops and ecosystemic services. The major livestock production systems in Africa or Latin America (Dedieu et al. 2011) include grazing, e.g. pastoral and agro-pastoral, mixed crop/livestock and industrial animal-based production systems. Generally, the crop-livestock systems are the most densely populated and hold the largest number of

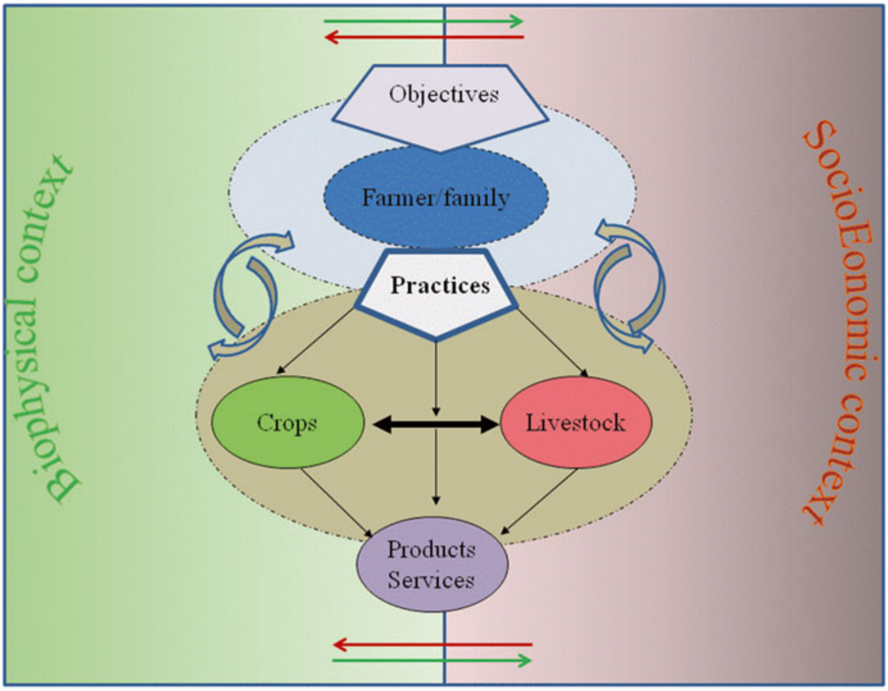


Fig. 4 The conceptual approach to describe the integrated crop-livestock system; the links and interactions are simplified, the diverse flux of materials, the different integrated relationships between sub-activities (crop or livestock production), or the multi-species existing are not notified in this scheme

ruminant livestock. Integrated crop-livestock systems have been diagnosed as the key to future food security: two-thirds of the global population already lives in these systems (Herrero et al. 2010). Currently, they produce 41 % of the maize, 86 % of the rice and 74 % of the millet production. They also generate 75 % of the milk and 60 % of the meat, and employ many millions of people in farms, formal and informal markets, processing plants and other parts of long value chains.

These systems are very well established in the Caribbean (Buchmann 2009; González-García et al. 2012). Studies are ongoing in Guadeloupe (Stark et al. 2012; Fanchone et al. 2013) on the major assertion that integrated crop-livestock system are a prerequisite to comply with the main agroecological principles – *inter alia*: improve energy and nutrient turnover, ensure soil quality, increase genetic diversification, and promote biological interactions-.

For instance, the case of Cuban crop-livestock system (Funes-Monzote and Monzote 2001; Buchmann 2009) indicates that these systems are a way to reduce vulnerability. Diversification not only serves as insurance against unexpected or disruptive events, it also provides many components that facilitate adaptive renewal following a disturbance, and of course promotes agrobiodiversity (both planned and associated biodiversity as defined by Perfecto and Vandermeer 2008). In addition, as a result of high agrobiodiversity, essential nutrients and micronutrients are provided for the farming family, thereby enhancing the dietary diversity of the household.

Agroecological Techniques for Animal Husbandry

Combining concepts of livestock system and agroecology and taking the animal scientist or livestock farmer pathway, we can indicate a set of rules based on the above description of animal production. Some of the animal husbandry techniques implemented through agroecological principles have been reviewed by Alexandre et al. (2013c) for the Latin and Central American regions. Reducing the use of external inputs, and increasing the biological efficiency of the animals are among their main objectives. Some case studies are developed for different species and at different scales: (i) the animal/physiology scale, (ii) the plot/field scale, (iii) the agroecosystem/farm scale, and (iv) on the food system approach. The bio-technical sub-part under study is described in Fig. 2 (see practices, resources and animals):

- Steering the whole LFS through reproduction management without any hormonal treatment, while facilitating system reproducibility is implemented through the use of male effect in small ruminant production, which allows induction of oestrus and increases reproductive performances, as developed over at least 30 years in Guadeloupe and also in Mexico. Today research is being conducted by work on natural soft techniques through light programs for males (Mexico);
- Matching the farm system to the available feed and by-products instead of building a feeding system according to production requirements (multiple use of resources – ligneous, glucidic, amylolityc, tanniferous, protein – for mono- and polygastrics) (in Guadeloupe, Trinidad and Colombia);
- Managing pastoral resources through environment-friendly practices based on the use of local grasses through management that is better adapted to their morphogenesis, and on organic fertilization and the best fit of the land surfaces proposed by taking into account the real availability of grass and integrating traditional strategies of management (see also Boval et al., this book) (in Guadeloupe, Cuba and Jamaica);
- Choosing the best adapted genotypes, while enhancing the population biodiversity (pigs and ruminants, Guadeloupe, Colombia and Cuba);
- Controlling health constraints by reducing chemical treatments (targeted drenching) or use of nutriceuticals for small ruminants instead of zero risks strategy (Guadeloupe, Cuba, Mexico);
- Mitigating the climate constraints by using soft techniques (less energy-rich feeds or natural cooling for pigs and chickens, Guadeloupe);
- Producing healthy foods (goat and cattle meat) with low inputs (forage), while restoring local self-reliance, conserving and regenerating natural agrobiodiversity resources (Guadeloupe).

This overview outlines the utility of the livestock farming system approach, and offers a general framework for the numerous factors of variation involved in animal performances so as to propose guidelines. The whole approach, from gametes to the animal product, is built on case studies gathered from different experiences in many countries of the Caribbean basin (*sensu lato*). This overview hopes to convince scientists and stakeholders in the animal sector of the viability of agroecology as a way to help achieve food security and sustainability. We advocate agroecology as a new approach to orientate the transition from unsustainable models of livestock farming systems and development to sustainable styles of animal production: a nature-like approach to "renovate" agriculture that can be defined as smart investments (vs. industrial business).

Socio-ecological Services of Livestock Systems

From the outset, and particularly under tropical conditions, a major challenge was the capacity of livestock farming system to recognise the importance and benefits of the non-productive functions of animals and husbandry activities for the farmer/household and society (Lhoste et al. 1993). Livestock farming system, is concerned not only with the production of commodities (and their related qualities) to meet the objective of food security, but also with providing the multiple ecoservices (see Photo 3) as prescribed by the Millennium Assessment Report (2005). Animals and LFS are considered as highly multifunctional in tropical agroecosystems (Dedieu et al. 2011). Two case studies are examined at the animal and territory levels.

Services at the Animal Level

The case study concerns goat species. Many papers reviewed by Alexandre et al. (2012) show that goat is the best suited animal to harsh environments, being mainly prevalent in arid (38 %) and semi-arid (26 %) agroecological zones. Goats are the principal ruminants in many scrublands, and form a part of traditional extensive grazing systems in many countries. It is frequently reported that wherever near-uncultivable land is the main feed source, the goat is the most beneficial animal to rear. However, the goat is found under a wide range of agroecological conditions (Alexandre and Mandonnet 2005). Besides thriving in arid desert areas it is known to fare well in tropical rain forests, being the domesticated animal with the broadest ecological distribution. For example, 88 % of the world's goat population is located in Asia and Africa, mostly (80 %) in the tropics and sub-tropics. The goat's physiological capacities, and her very high flexibility make this animal a marvel of multifunctionality and perhaps also of resilience (Alexandre and Mandonnet 2012).

In the harshest conditions, goats generally exceed cattle in numbers, and often sheep. The Morand-Fehr prospective expertise (2012) indicates that goat will be the

Photo 3 Tropical genotypes are valorizing marginal zones of the Caribbean regions

specie with the best prospects (increasing numbers, worldwide spread) in the decades to come, specifically through this agroecological perspective of designing systems best adapted to climate change. Many breeds are represented, and flocks are distributed over a wide range of systems of production and husbandry conditions. According to many reports, goats, found in all developing countries, are chiefly reared by subsistence farmers alongside their primary occupation. They are described as an important component of a considerable number of vulnerable and resource-poor production systems (Peacock 2005).

The reputation of the goat as a prime cause of overgrazing and landscape degradation has contributed to its disappearance from the rangelands, although environmentally it often has very positive effects in sustaining open mountain meadows, valorising many types of feedstuffs. However, there is a growing interest in livestock (e.g. goats) grazing on woody rangelands as a mean of controlling shrub encroachment and reducing fire hazard. This concern justifies and encourages the re-introduction of goats into their native rangeland. Knowledge of species selection, diet quality, and voluntary intake may allow the control of feeding behaviour and maintenance of a certain equilibrium. Numerous studies reviewed by Alexandre et al. (2012) report that this species thrives well under more intensive conditions, and provides very high quality commodities, such as milk, meat and fibre, and skins, (Silanikove et al. 2010; Mahgoub et al. 2012). Goats are generally defined as multifunctional animals (Table 1): Peacock (1996, cited by Alexandre et al. 2012) has listed at least 19 useful products and services. They play a crucial role in providing protein and non-food commodities, and also serve as a cash reserve and a form of savings for the rural population, and as a protection against agricultural crop failure: goats are chiefly reared by subsistence farmers in addition to their primary occupation. Moreover, they contribute by facilitating the management of flocks, guiding sheep in some regions, and by supplying manure that is highly valued for cropping (as indicated for all ICLS). The situation can also be one where the animals are primarily consumed by the household, and occasionally sold in rural areas at low prices. Hence goats provide not only sustenance and cash income, but also socio-cultural links and act as insurance against risks in fragile and harsh environments. In addition to all these items, some studies signal the use of goats as draft animals in Central America (for ploughing in Honduras or recreational outings in the Caribbean). In the field of economic performances, very few situations have been assessed, possibly due to the lack of adapted methods for broad multifunctionality, and/or the importance of the informal sector (Alexandre et al. 2008). However, some specific niche markets can be highlighted (Alexandre and Mandonnet 2005).

Services at the Territory Level

The case study concerns the use of animals to enhance the whole sustainable development of a small region of the Guadeloupe Island (Alexandre et al. 2002). The leeward side of Guadeloupe is characterized by very diverse altitude, climatic and biophysical constraints. Inadequate land management policies and natural disasters have been responsible for its low level of development. The National Park of Guadeloupe has promoted a sustainable development program for this area through work done by a multidisciplinary team composed of environmentalists, forest rangers, land managers and agronomists. Valuable human and natural

Table 1 Some examples (number of studies) of economic roles, functions and meat niche markets of goat in different regions

According to FAO pictograms	Items	Regions	Number of occurrence of papers
	<u>Economic contributions</u>		
	Whole rural economy	Harsh environments	6
	Most marginalized sector of the poor population	Central America	3
		South-East Asia	4
		Africa	7
		India	5
		Latin America	4
	Small-holder farmers	Worldwide	4
		Africa	3
		Asia	3
		Latin America	2
	Household consumption and income	South-East Asia	3
	Cash reserve	Africa	4
		Asia	3
		Latin America	3
		Worldwide	5
	<u>Multifunctions</u>		
	At least 19 useful products and services	Africa	1
	Non food commodities (medicines)	Africa	2
		Asia	1
	Supplying manure	Asia	3
		Latin America	3
	Draft animals	Central America	3
	Positive effects upon environment	Worldwide	6
	Insurance against ecological risks (protection against crop failure)	Latin America	4
		Middle-East	3
		Worldwide	4
		Middle-Esat	3
		Central America	1
	Landscapes, aesthetic functions	Central America	2
	Socio-cultural linkages	Africa	4
		Central America	2
		Latin America	3
	<u>Special niche meat market</u>		

(continued)

Table 1 (continued)

According to FAO pictograms	Items	Regions	Number of occurrence of papers
	All products are sold	Central America	3
	Suckling kids (cabritos)	Latin Amercia	3
	Sale of meat kids	Middle-East	3
	Goats target religious festivities	Asia	6
		Asia	8
		Central America	3
		Africa	4

Sources: Alexandre and Mandonnet (2005) and Alexandre et al. (2012)

characteristics, very attractive landscapes and a wide biodiversity of natural and agricultural areas support this programme. Focused group discussions were held with knowledgeable persons (soil and forest specialists, historians, economists and tourism managers) to diagnose the strengths and weaknesses of the area and to build the final version of the development program. Additionally, these specialists were questioned about the contributions of livestock production to the sustainable plan (see Photo 4). Surveys were executed to determine the typology of the farming systems, their interactions with the environment and the characteristics of their retail markets. Consumers (restaurants and tourists) were questioned about their eating habits and their willingness to pay more for local animal products. Agro-sylvo-pastoral systems in the region are generated by the traditional knowledge of the populations. Animal production is one of the numerous activities undertaken by the farmers. Forestland and rangeland, managed as natural ecosystems, are used as grazed land. Products are used for family consumption and sometimes for sale at the local market. Agroforestry systems offer many advantage: the productivity of crops, animals and trees is increased through sustainable use of positive relationships among these groups. The animals use crop residues, fallow, foliage or forage grown on marginal land, and help to recycle waste products. As a result, manure is produced as a source of plant nutrients and soil organic matter. Herbivores are efficient in controlling weeds in fruit plantations or forest undergrowth. Owing to the different focused group discussions, the main interactions occurring among the different components of the sustainable development program (production systems, environment, society, economy and tourism) have been described (Fig. 5, Alexandre et al. 2002). In our conditions, as in many other regions, when correctly managed, livestock has very positive effects on the environment: reduced chemical pollution, preservation of soil fertility, maintenance of open spaces; these are the goals of the development plan. Also, livestock makes an important contribution to total food production and to the rural economy. Good qualitative local animal products are available for local consumers or tourists (such as honey, curry goat or horse riding). The agro-sylvo-pastoral systems provide picturesque scenes and landscapes that are very attractive to tourists. Horse-riding is available for eco-tourists. Hence livestock takes part in the sustainable development plan by way

Photo 4 Some examples of animal services building typical landscapes and picturesque scenes of the Leeward side of Guadeloupe

of its interactions with tourists' activities. The plan is not only environmentally sound, but is also people-centred. It does not ignore the human component in the region; it enhances the traditional know-how in agriculture, and the social and cultural significance of livestock keeping. In sum, the integration of livestock and agriculture increases both the short-term benefits and longer-term sustainability of the

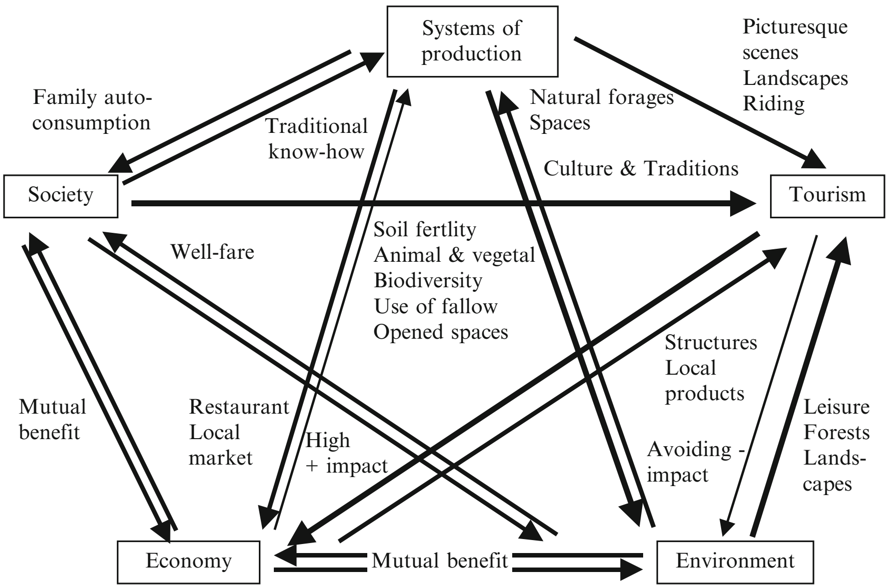


Fig. 5 Ecosystem services of the agroecosystems and interactions existing between the different components of the sustainable development plan of Guadeloupe Leeward region: systems of production, environment, society, economy and tourism (Source Alexandre et al. 2002)

region. The livestock sector is both multifaceted and flexible enough to make an important contribution to the local sustainable development of the leeward side of Guadeloupe.

The same could be said for Haiti, where agroforestry systems (see Photo 5) are of paramount importance for the family and the territory (Simon 2011). Agroforestry systems combine annual and perennial, herbaceous and woody species, in a complex system in terms of the number of plant species, biological interactions, and practices (see review of Greenberg et al. 2008; Cubbage et al. 2012). Widespread in Asia, Oceania, Africa, and Latin America, they ensure both subsistence for local populations and major environmental and socio-economic services. These agroforestry systems stand out from specialized cropping systems by three essential aspects arising from natural ecosystems (Perfecto and Vandermeer 2008; Greenberg et al. 2008): (i) their functioning is based on relations between species (competition, facilitation), (ii) they offer high constituent biodiversity, and (iii) they produce a multiplicity of products and environmental services that monocultures do not offer. Cubbage et al. (2012) have described and compared different sylvo-pastoral systems in Latin America, New Zealand and the United States. Some countries use native trees and existing forests; others use plantations, particularly of exotic species. Natural forest sylvo-pasture systems generally add livestock in extensive systems, to capture the benefits of shade, forage, and income diversification without many added inputs. These authors also note that these systems depend not only on the biophysical, but also the economic, cultural, and market factors in a region.

Photo 5 Positive effects of agrosylvopastoralism fighting against deforestation in mountainous regions of Haiti

The Decisional Sub-part of Livestock Farming System

The double dimension of livestock system concept allows the integration of the livestock keepers in the human and societal context to attain agroecological objectives as recommended by Altieri et al. (2012). Among the ecosystems services detailed above, many are linked to the socio-economic and the socio-cultural dimensions of the farmer, family or society.

The agroecological pathway induces a pressing need particularly at a time of global climate change and hunger and energy crises. Improving the current systems and practices is urgently needed, particularly in the context of small farmer natural resource management systems that predominate in tropical developing countries. Unfortunately, social-ecological systems theory, sustainability evaluation frameworks, and assessment methods are still foreign to many farmers, and sometimes to policy makers/operators, or even to researchers, students, and NGOs. At the same time, most peasant farmers manage complex and diverse agroecosystems, and constantly adapt management strategies with multiple aims. There are at least two paths that lead to increased agricultural production and provide commodities and services. They are labeled traditional and modern or preindustrial and industrial. But this dichotomy obscures significant differences and narrows our thinking.

Instead of remaining stuck in the dichotomous extensive-intensive or even North-south schemes of thinking, age-old systems can reveal potential for alternatives to address system sustainability, provided conditions and objectives of production can be changed. Dedieu et al. (2011) have reviewed the main livestock system studies ongoing in the tropical countries. These examples highlight the need for a better understanding of livestock functions, productive or not, for farmers and families. They provided also patterns of integration between livestock and other activities to design innovative sustainable livestock farming systems, with their double consistency decisional and biotechnical. Hence they suggest using the livestock system concept not only as a framework for modelling (as also suggested for crop systems, Malézieux et al. 2009), but also as a grid to understand the system functioning. This latter could promote the design of better adapted innovations. Recently Alexandre et al. (2013b) have shown how innovations can take advantage of the farmers' traditional know-how. There is a growing concern about the lack of adoption of certain technologies at the farm level, and particularly in tropical regions. It can be hypothesized that the context as a whole, known to interact with the farming system, may exert direct or indirect effects on the successful use of innovative technology. The transfer of technology has been promoted for years in the developing countries without bringing positive modifications in the long term (Alexandre et al. 2013a, b), and particularly because it was shaped by a top-down scheme of thinking. The transfer of technology policy is generally also criticized for its poor fit with the farmers' socio-cultural context. Meanwhile, livestock keepers have steadily accumulated indigenous traditional experience that has built sustainable LFS supported by their resilience. Alexandre et al. (2013a) have tried to revisit some of the traditional practices that have helped design innovative products or processes:

– Using the very traditional male effect practice for small ruminants (as mentioned earlier) as an efficient reproduction management alternative, increasing herd productivity with no hormone treatment;
– Exploiting the crop by-products at the farm level is empowered at the agro-industrial sector level by the production of pellets combining different

non-conventional feed sources (on the basis of their nutritional and agronomic characteristics);
– Determining, through an ethno-veterinary survey, the natural or agro-resources that are employed in animal healthcare, has led to specific biochemical studies to enhance the use of neutroceuticals against parasitism in small ruminants;
– Managing the pasture (and land) resources through tethering practices, while reducing cost of production (traditional LFS) has become a very relevant and efficient experimental tool to assess individual intake at pasture (through sound experimental design, see also Boval et al., this book);
– Sharing the livestock capital by dividing offspring between owners and breeders (known as *di-moitié*, meaning 'half-half') is the key principle used for creating a connective system between donors (NGOs or international foundations) and landless farmers where recipients agree to share the offspring of gift animals with others in order to implement animal activities within their farm-family units.

These examples provide a general framework for a contextualized research agenda by means of participatory action approaches:

– Allowing synergistic interactions (for mutual learning) that promote diverse flows of traditional and modern knowledge as recommended by IAASTD-UNESCO (2008);
– Strengthening individual and collective capabilities to innovate; improving organizational cultures and behaviors and fostering networks and linkages (Angeon et al. 2010);
– Aiming at introducing new products and processes that are socially or economically relevant to smallholder farmers and other actors in the LFS sector;
– With the last two aims above, analyzing and identifying the cognitive and historical sources of a general process of appropriation-rejection likely to hamper the development of relevant products in an area. For example, identifying, in terms of human values, the causes leading to the rejection or subdued use of local breeds in an official context, while in a non-official context, these breeds are useful to the local farmers (Angeon et al. 2010).
– Reorganizing the innovation process, while changing the mental map of technology transfer for a territorial development plan embedded in the natural and socio-economic context (Alexandre et al. 2013b).

Conclusion

Our intention is not to offer ready-made solutions, but rather to highlight important guidelines by factual data obtained in different countries, in order to share these experiences and allow readers to form their own opinion according to their situations.

Setting development priorities and implementing research must be accomplished through the farming system concept. The sustainability of livestock farming systems depends on the local context. Beyond the general characteristics of biotic and abiotic factors, the human and cultural values and the socio-economic constraints induce a high variability in livestock farming systems in the Tropics. Promoting integrated and sustainable tropical livestock farming systems requires a better understanding of productive and non-productive functions of livestock at the farming, sector and territory levels. Patterns of integration between livestock and other activities will be considered for the design of innovative sustainable systems, in terms of their decisional and biotechnical consistency.

It is stated that the use of combined set of practices suggested and illustrated here should favor (i) valorization of tropical resources, genotypes and people, and (ii) increased cycling and integration between biomasses, livestock and farmers. The tropical livestock systems offer a laboratory for further scientific study. This argues for taking advantage of traditional know-how to promote well-adapted modern innovations.

The livestock farming system concept was developed to assess the interactions between the human and biotechnical dimensions of livestock husbandry activities. Another viewpoint is that historically, the concept has emerged from the many failures of the transfer of technology model of development in tropical and Mediterranean regions.. The major challenge now facing systemic science and agro-environmentalists is not how to increase production overall, but how to enable resource-poor farmers to produce more, and so improve their food security and household livability.

Acknowledgements The authors would like to thank all colleagues of Animal Research Unit of INRA Guadeloupe for their discussions. They are grateful to chief editor for advices. Studies were sponsored by Region Guadeloupe and Martinique.

References

Ahrens DC, Pellini T, Santoro PH (2009) Agroecology at IAPAR: summaries of research projects and published works from 2004 to 2009. Ahrens DC, Pellini T, Santoro PH (eds). Instituto Agronomico do Parana (IAPAR), Londrina

Alexandre G, Mandonnet N (2005) Goat meat production in harsh environments. Small Rumin Res 60:53–66

Alexandre G, Mandonnet N (2012) Questioning the resilience of goat production in the Tropics at different levels from the animal to the whole farming system. In: 21st international conference on goats. 153, Gran Canaria, Spain, 23–27 September 2012

Alexandre G, Larade A, Arrigue A, Anselme M, Archimède H (2002) Contributions of livestock rearing and products to the sustainable development plan of the Leeward side of Guadeloupe. In: 19th general meeting of European Grassland Federation, La Rochelle, France, 27–30 May 2002. EGF 2002/AFPF INRA, Versailles, pp 1004–1005

Alexandre G, Asselin deBeauville S, Shitalou E, Zébus MF (2008) An overview of the goat meat sector in Guadeloupe: conditions of production, consumer preferences, cultural functions and economic implications. Livest Res Rural Dev 20. http://www.cipav.org.co/lrrd/lrrd20/1/alex20014.htm

Alexandre G, Arquet R, Fleury J, Troupe W, Boval M, Archimede H, Mahieu M, Mandonnet N (2012) Systèmes d'élevage caprins en zone tropicale: analyse des fonctions et des performances. INRA Prod Anim 25:305–316

Alexandre G, Facthum-Sainton J, Angeon V (2013a) Tradition and innovation in Caribbean LFS: old rhum in new barrels. In: 64th annual meeting of the Animal Science, Nantes, France, 26–30 August 2013, Wageningen Academic Publishers, Wageningen, p 281
Alexandre G, Garcia G, Janini-Eyma D, Rodriguez L, Stark F, Angeon V (2013b) Pour une approche globale et intégrée de recherche-formation-action dans les systèmes d'élevage tropicaux. L'exemple de quatre expériences dans le bassin Caraïbe. In: Angeon V, Lardon S, LeBlanc P (eds) Compétences, formation et apprentissage collectif territorial, (in press) L'Harmattan
Alexandre G, Rodriguez L, Garcia-Arece J, Delgadillo J, Garcia G, Habermeier K, Fanchone A, Gourdine JL, Mahieu M, Archimède H (2013c) Agroecological practices to sustain tropical livestock farming system: a Caribbean perspective. Trop Anim Health Prod (in progress)
Altieri MA (2002) Agroecology: the science of natural resource management for poor farmers in marginal environments. Agric Ecosyst Environ 9:1–24
Altieri MA, Toledo MV (2011) The agroecological revolution in Latin America: rescuing nature, ensuring food sovereignty and empowering peasants. J Peasant Stud 38:587–612
Altieri MA, Funes-Monzote FR, Petersen P (2012) Agroecologically efficient agricultural systems for smallholder farmers: contributions to food sovereignty. Agron Sustain Dev 32:1–13
Angeon V, Sainton J, Alexandre G (2010) Representations of breeders about local breeds in the livestock farming system of the French West Indies: between rejection and appropriation of Creole goat. Adv Anim Biosci 1:489–490
Archimède H, Bastianelli D, Boval M, Tran G, Sauvant D (2011) Ressources tropicales : disponibilité et valeur alimentaire. INRA Prod Anim 24:23–40
Buchmann C (2009) Cuban home gardens and their role in social–ecological resilience. Hum Ecol 37:705–721
Buttel FH (2003) Envisioning the future development of farming in the USA: agroecology between extinction and multifunctionality? New Dir Agroecol Res Educ 1–14. www.agroecology.wisc.edu/downloads/buttel.pdf. Accessed Oct 2012
Chappell MJ, LaValle LA (2011) Food security and biodiversity: can we have both? An agroecological analysis. Agric Hum Value 26:3–26
Cubbage F, Balmelli G, Bussoni A, Noellemeyer E, Pachas AN, Fassola H, Colcombet L, Rossner B, Frey G, Dube F, de Silva ML, Stevenson H, Hamilton J, Hubbard W (2012) Comparing silvopastoral systems and prospects in eight regions of the world. Agroforest Syst 86:303–314
de Figueiredo EAP (2002) Livestock and agroecology in Brazil. Cadernos de Ciencia and Technologia 19:235–265
De Schutter O (2011) Agroecology and the right to food. 16th Session of the United Nation, Human Rights Council 5A/HRC/16/49). http://www.agroecology.be/img/download/De_Schutter_2011_agroecology_and_food_right.pdf. Accessed Oct 2012
de Wit J, Oldenbroek PJK, van Keulen H, Zwart D (1995) Criteria for sustainable livestock production: a proposal for implementation. Agric Ecosyst Environ 53:219–229
Dedieu B, Faverdin P, Dourmad JY, Gibon A (2008) Système d'élevage, un concept pour raisonner les transformations de l'élevage. INRA Prod Anim 21:45–58
Dedieu B, Aubin J, Duteurtre G, Alexandre G, Vayssières J, Bommel P, Faye B (2011) Conception et évaluation de systèmes d'élevage durables en régions chaudes à l'échelle de l'exploitation. INRA Prod Anim 24:113–128
Devendra C (2007) Perspectives on animal production systems in Asia. Livest Sci 106:1–18
Doré T, Makowski D, Malézieux E, Munier-Jolain N, Tchamitchian M, Tittonel P (2011) Facing up to the paradigm of ecological intensification in agronomy: revisiting methods, concepts and knowledge. Eur J Agronomy 34:197–210
Dumont B, Fortun-Lamothe L, Jouven M, Thomas M, Tichit M (2013) Prospects from agroecology and industrial ecology for animal production in the 21st century. Animal 1028–43
Ericksen PJ (2008) Conceptualizing food systems for global environmental change research. Global Environ Change 18:234–245
Fanchone A, Stark F, Alexandre G, Diman JL, Gourdine JL, Ozier-Lafontaine H, Sierra J, Tournebize T, Archimède H (2013) The use of agroecological concepts to design integrated

crop-livestock systems: the case of the French West Indies. In: 64th annual meeting of the Animal Science, Nantes, France, 26–30 August 2013, Wageningen Academic Publishers, Wageningen, p 161

Faye B, Alexandre G, Bonnet P, Boutonnet JP, Cardinale E, Duteurtre G, Loiseau G, Montet D, Mourot J, Regina F (2011) Elevage et qualité des produits en régions chaudes. INRA Prod Anim 24:77–88

Francis C, Lieblein G, Gliessman S, Breland TA, Creamer N, Harwood R, Salomonsson L, Helenieus J, Rickerl D, Salvador R, Wiedenhoeft M, Simmons S, Allen P, Altieri M, Flora C, Poincelot R (2003) Agroecology: the ecology of food systems. J Sust Agric 22:99–118

Funes-Monzote F, Monzote M (2001) Integrated agroecological systems as a way forward for Cuban agriculture. Livest Res Rural Dev (13) 1 2001/http://www.cipav.org.co/lrrd/lrrd13/1/fune131.htm

Gerber P, Steinfeld H (2008) Global environmental consequences of the livestock sector's growth. Outlook Agric 37:7–13

Gibon A, Sibbald AR, Flamant JC, Lhoste P, Revilla R, Rubino R, Sørensen JT (1999) Livestock farming systems research in Europe and its potential contribution for managing towards sustainability in livestock farming. Lives Prod Sci 61:121–137

Gliessman SR (2006) Animals in agroecosystems. In: Agroecology: the ecology of sustainable food systems. CRC Press Taylor & Francis group, Boca Raton, pp 269–285

Godfray CHJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty J, Robinson S, Thomas SM, Toulmin C (2010) Food Security: the challenge of feeding 9 billion people. Science 327:812–818

González-García E, Gourdine JL, Alexandre G, Archimède H, Vaarst M (2012) The complex nature of mixed farming systems requires multidimensional actions supported by integrative research and development efforts. Animal 6:763–777

Greenberg R, Perfecto I, Philpott SM (2008) Agroforests as model systems for tropical ecology. Ecology 89:913–914

Gunia M, Mandonnet N, Arquet R, Alexandre G, Gourdine JL, Naves M, Angeon V, Phocas F (2013) Economic values of body weight, reproduction and parasite resistance traits for a Creole goat breeding goal. Animal 7:22–33

Hellstrand S, Skanberg K, Drake L (2009) The relevance of ecological and economic policies for sustainable development. Environ Dev Sust 11:853–870

Herrero M, Thornton PK, Notenbaert AM, Wood S, Msangi S, Freeman HA, Bossio D, Dixon J, Peters M, van de Steeg J, Lynam J, Parthasarathy Rao P, Macmillan S, Gerard B, McDermott J, Seré C, Rosegrant M (2010) Smart investments in sustainable food production: revisiting mixed crop-livestock systems. Science 327:822–825

Hoffmann I (2010) Climate change and the characterization, breeding and conservation of animal genetic resources. Anim Genet 41:32–46

Holling CS (2001) Understanding the complexity of economic, ecological, and social systems. Ecosystems 4:390–405

IAASTD-UNESCO (2008) Évaluation internationale des connaissances, des sciences et des technologies agricoles pour le développement (IAASTD). http://www.agassessment.org/French.pdf

Jackson LE, Pulleman MM, Brussaard L, Bawa KS, Brown GG, Cardoso IM, de Ruiter PC, Garcı´a-Barrios L, Hollander AD, Lavelle P, Oue´draogo E, Pascual U, Setty S, Smukler SM, Tscharntke T, Van Noordwij M (2012) Social-ecological and regional adaptation of agrobiodiversity management across a global set of research regions. Global Environ Change 22:623–639

Janzen HH (2011) What place for livestock on a re-greening earth? Anim Feed Sci Technol 166–67:783–796

Keating BA, McCown RL (2001) Advances in farming systems analysis and intervention. Agric Syst 70:555–579

Lhoste P, Dollé V, Rousseau J, Soltner D (1993) Zootechnie des régions chaudes. Les systèmes d'élevage. Ministère de la Coopération-CIRAD, Paris. Manuels et précis d'élevage

Lynam J (2002) Book review. A history of farming systems research: edited by M. Collinson, CABI Publishing, Wallingford, 2000. Agric Syst 73:227–232

Mahgoub O, Kadim IT, Webb EC (2012) Goat Meat Production and Quality. CABI, Wallingford, United Kingdom, 2012
Mahieu M, Arquet R, Fleury J, Coppry O, Marie-Magdeleine C, Boval M, Archimède H, Alexandre G, Bambou JC, Mandonnet N (2009) Contrôle intégré du parasitisme gastro-intestinal des petits ruminants en zone tropicale humide. In: 16ème Rencontres Recherches Ruminants. INRA – Institut de l'Elevage, Paris, pp 265–268
Malézieux E (2012) Designing cropping systems from nature. Agron Sustain Dev 32:15–29
Malézieux E, Crozat Y, Dupraz C, Laurans M, Makowski D, Ozier-Lafontaine H, Rapidel B, de Tourdonnet S, Valantin-Morison M (2009) Mixing plant species in cropping systems: concepts, tools and models. A review. Agron Sustain Dev 29:43–62
McDermott JJ, Staal SJ, Freeman HA, Herrero M, Van de Steeg JA (2010) Sustaining intensification of smallholder livestock systems in the tropics. Livest Sci 13:95–109
MEA (2005) Millennium ecosystem assessment. Ecosystem and human well-being: synthesis. Island Press, Washington, DC
Morand-Fehr P (2012) Prospectives sur l'élevage caprin. INRA Prod Anim 25:1–2
Naves M, Alexandre G, Leimbacher F, Mandonnet N, Menendez-Buxadera A (2000) Le point sur les programmes de gestion des ressources génétiques chez les espèces de ruminants dans la Caraïbe. INRA Prod Anim 14:182–192
Naylor RL, Steinfeld H, Falcon W, Galloway J, Smill V, Bradford E, Alder J, Mooney H (2005) Agriculture: losing the links between livestock and land. Science 310(5754):621–1622
Nelson E, Scott S, Cukier J, Galan AL (2009) Institutionalizing agroecology: successes and challenges in Cuba. Agric Hum Value 26:233–243
Peacock C (2005) Goats – a pathway out of poverty. Small Rumin Res 60:179–186
Perfecto I, Vandermeer J (2008) Biodiversity conservation in tropical agroecosystems. Ann NY Acad Sci 1134:173–200
Preston TR, Leng RA (1987) Matching ruminant production systems with available resources in the tropics and sub-tropics. CTA, Wageningen
Rigby D, Caceres D (2001) Organic farming and the sustainability of agricultural systems. Agric Syst 68:21–40
Rodríguez L (2010) Integrated farming systems for food and energy in a warming, resource-declining World. Thesis of Humboldt University, Berlin towards the Degree of Doctor of Philosophy
Seré C, Steifeld H (1996) World livestock production systems. Current status, issues and trends. FAO Prod Health Paper 127
Silanikove N, Leitner G, Merin U, Prosser CG (2010) Recent advances in exploiting goat's milk: quality, safety and production aspects. Small Rum Res 89:110–124
Simon B (2011) Le pain des Tropiques Production arc-en-ciel-prod et Ouest-France. http://www.film-documentaire.fr/Pain-tropiques.html,film,36689
SOCLA (Latin American scientific society for agroecology) (2011) Ecologically efficient agricultural systems for smallholder farmers. Farmers. http://www.srfood.org/index.php/en/component/content/article/1174-report-agroecology-and-the-right-to-food
Stark F, Diman JL, Fanchone A, Alexandre R, Alexandre G, Archimède H (2012) Characterization of mixed farming systems and crop-livestock integration in Guadeloupe (French West Indies). In: 2nd international symposium on integrated crop-livestock, 8–12 October 2012, Porto-Alegre Brazil
Stassart PM, Baret P, Grégoire JC, Hance T, Mormont M, Reheul D, Stilmant D, Vanloqueren G, Visser M (2012) L'agroécologie: trajectoire et potentiel. Pour une transition vers des systèmes alimentaires durables. In: Van Dam D, Stassart PM, Nizet J, Streith M (eds) Agroécologie entre pratiques et sciences sociales, Copyright Educagri édition, Educagri éditions, Dijon, pp 5–51
Steinfeld HP, Gerber T, Wassenaar V, Castel MR, de Haan C (2006) Livestock's long shadow. Environmental issues and options. FAO, Rome
Stoorvogel JJ, Antle JM, Crissman CC, Bowen W (2004) The tradeoff analysis model: integrated bio-physical and economic modeling of agricultural production systems. Agric Syst 80:43–66
Tichit M, Puillet L, Sabatier R, Teillard F (2011) Multicriteria performance and sustainability in livestock farming systems: functional diversity matters. Livest Sci 139:161–171

Tomich TP, Brodt S, Ferris H, Galt R, Horwath WR, Kebreab E, Leveau J, Liptzin D, Lubell M, Merel P, Michelmore R, Rosenstock T, Scow K, Six J, Williams N, Yang L (2011) Agroecology: a review from a global-change perspective. Annu Rev Environ Res 36:193–202

Udo HMJ, Aklilu HA, Phong LT, Bosma RH, Budisatria IGS, Patil BR, Samdup T, Bebe BO (2011) Impact of intensification of different types of livestock production in smallholder crop-livestock systems. Livest Sci 139:22–29

Via Campesina (2010) Sustainable peasant and family farm agriculture can feed the World. Via Campesina Views Jakarta,

Webb EC, O'Neill HA (2008) The animal fat paradox and meat quality. Meat Sci 80:28–36

Wezel A, Bellon S, Dore T, Francis C, Vallod D, David C (2009) Agroecology as a science, a movement and a practice. A review. Agron Sust Dev 29:503–515

Wilson TR (2009) Fit for purpose – the right animal in the right place. Trop Anim Health Prod 41:1081–1090

Wirsenius S, Azar C, Berndes G (2010) How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? Agric Syst 103:621–638

Cropping Systems to Improve Soil Biodiversity and Ecosystem Services: The Outlook and Lines of Research

Cathy Clermont-Dauphin, Eric Blanchart, Gladys Loranger-Merciris, and Jean-Marc Meynard

Abstract The intensive farming practices that have been developed over the past 60 years are based mainly on the use of chemical inputs such as fertilisers and pesticides, mechanical tillage and monoculture. The limitations of these methods are now clear: long-term degradation of soil fertility, impacts on the environment and human health, high consumption of fossil fuels, low efficiency of inputs and threats to food security in a context of climate change. Would farming practices that rely on the activation of ecological processes be an alternative to achieve a balance between high productivity and environmental preservation? While many studies suggest a positive relationship between soil biodiversity and ecosystem services, there is considerable debate on the form such agricultural systems should take. This study reviewed the state of current knowledge and identified aspects requiring further research to achieve the aim of sustainable intensification of agriculture. The following major points emerged:

C. Clermont-Dauphin (✉) • E. Blanchart
UMR 210 Eco&Sols, Institut de Recherche pour le Développement (IRD),
Bat 12, 2 Place Viala 34060, Montpellier Cedex 2, France
e-mail: Cathy.clermont@ird.fr; eric.blanchart@ird.fr

G. Loranger-Merciris
UFR Sciences Exactes et Naturelles, Université des Antilles et de la Guyane,
Campus de Fouillole BP. 592, Pointe-à-Pitre Cedex 97157, Guadeloupe (FWI), France

INRA, UR1321, ASTRO Agrosystèmes tropicaux,
Petit-Bourg F-97170, Guadeloupe (FWI), France
e-mail: gladys.loranger-merciris@antilles.inra.fr

J.-M. Meynard
INRA, Département Sciences pour l'Action et le Développement,
Campus de Grignon F, Thiverval-Grignon 78850, France
e-mail: meynard@grignon.inra.fr

H. Ozier-Lafontaine and M. Lesueur-Jannoyer (eds.), *Sustainable Agriculture Reviews 14: Agroecology and Global Change*, Sustainable Agriculture Reviews 14,
DOI 10.1007/978-3-319-06016-3_5,

(i) Most studies focused on the evaluation of individual practices. However, changes in farmers' cropping practices to take advantage of soil biodiversity services would need to manage not only the interactions between various practices but also the trade-off between the technical and socio economic constraints of cropping systems. Advances in agricultural system design approaches may help to ensure appropriate trade-offs.
(ii) More attention should be given to drawing on knowledge from different sources: laboratory studies focusing on the ecological functions of soil biodiversity, experimental surveys on farmers' fields to rank the farming practices and processes to be included in site-specific models, and on- station experiments to test hypotheses and acquire additional reference material.
(iii) Whereas advances in technical and scientific knowledge provide an increasing number of relevant indicators for characterizing biodiversity and ecological functions, studies are rarely targeted at the development of indicators that are accessible to farmers or their technical advisors. The lack of indicators accessible to grassroots players for evaluating the impacts of their decisions on soil biodiversity remains a serious obstacle to the development of innovative agroecological systems.

Keywords Cropping systems • Soil biodiversity • Ecosystem services • Bioindicators • Ecological intensification • Agroecology • Ecodesign

Introduction

The spectacular increase in yields over the past 60 years is due to a significant artificialisation of agriculture through varietal selection, development of chemical fertilization, irrigation, mechanized tillage and increased chemical pest control. Cereal yields at least doubled between 1960 and 1995 (Tillman 1999). In tropical countries, high-input cropping systems have enabled the development of various export crops such as bananas in the Caribbean and Central America and cotton in West Africa. However, these agricultural systems have many disadvantages: they contribute to the depletion of natural resources such as fossil fuels, phosphorus and water and affect many ecosystem services, notably by the soil biodiversity (Millennium Ecosystem Assessment 2005). They rely mainly on high cost inputs, which creates a significant financial risk for farmers in a context of climate change.

One option for achieving high yields without having to use high levels of external inputs is to develop cropping systems that improve soil ecological services. Several studies suggest that the activity of soil organisms could be managed to increase ecological services (Millennium Ecosystem Assessment 2005). Ecological services can be sorted into three main groups related to agricultural management as proposed by Le Roux et al. (2008): (1) – "Input" services, such as nutrient supply, pest control, maintenance of soil structural stability and regulation of microclimate; (2) – "Direct output" services directly contributing to agricultural income, such as plant and animal production and (3 – “Indirect output” services that do not directly contribute to agricultural income, such as, water purification, carbon sequestration and wildfire mitigation. All these services are based on processes or functions that depend on the ecosystem biodiversity. In fact, maintenance or improvement of soil nutrient availability in cultivated systems may rely on processes such as organic matter mineralisation and nutrient solubilisation and recycling by soil micro-organisms and cultivated plants. Pests and diseases can be controlled by predation and parasitism by certain soil organisms. A favourable soil structure for agriculture can be maintained by plant roots and macrofauna activity rather than by mechanical tillage (Kibblewhite et al. 2008).

Although many studies have described the relationship between ecosystem services, ecological functions and related groups of organisms or species, there is still considerable debate on the design of cropping systems to improve functional soil biodiversity and services. Unlike plant biodiversity, soil biodiversity is almost invisible to the naked eye and is hard to characterise. Soil biodiversity is, therefore, more difficult to manage for ecological intensification of agriculture.

The approach proposed for developing this ‘new’ agricultural paradigm is based on both ecological and agronomic sciences (Wezel et al. 2009; Altieri et al. 2012). Ecology focuses on the soil biological processes across various spatial and temporal scales. Agronomy is a science of action, which has developed methods bridging biological systems and socio-economic systems in order to improve the multifunctional management of soils and crops (Sebillotte 1974). This paper examines the state of current knowledge and the research required for the design of agro-ecological cropping systems. Section “The Cropping System Concept: Consequences for Ecological Intensification of Agriculture” examines the cropping system concept and shows how the technical, ecological and socio-economic constraints of farming practices must be taken into account if they are to be redesigned. Section “Relationships Between Cropping Systems, Soil Biodiversity, Functions and Services: State of the Art” reviews current knowledge of the relationships between cropping systems, soil biodiversity, ecological functions and services and section “Taking Account of Soil Biodiversity and Its Services in the Design of Agro-ecological Cropping Systems” identifies the research required to improve the integration of soil biodiversity and services into the design of innovative cropping systems.

The Cropping System Concept: Consequences for Ecological Intensification of Agriculture

The “cropping system” concept covers the set of agricultural methods that are applied to one or more fields treated in the same way for several successive years (Sebillotte 1980). Agronomists use this term to indicate that the farming practices form a system, i.e. all the practices are interlinked. It is often impossible to change one practice without having to change several others (Meynard et al. 2001; Spedding 1979).

Fig. 1 Comparison of conventional intensive (*left*) and traditional (*right*) banana cropping systems in the West Indies

For instance, if the sowing date of an annual crop is changed it will often be necessary to change the variety, the fertilizer application date and the pest control method. This "coherence" in the cropping system is established by farmers by drawing on their own production targets, available resources, knowledge and know-how, the information they collect and their interactions with many others involved in the agricultural system. If farmers are to be encouraged to change their practices with a view to preserving and building-up soil biodiversity, consideration must be given to their particular aims, material resources and labour resources, as well as to the characteristics of their fields, their social networks and the information to which they have access (Cairns 2000; Meynard et al. 2001).

The Relationship Between Cropping Systems and the Farmers' Aims and Available Resources

Farming practices depend on the farmers' aims and available resources (Sebillotte 1974). For example, in the French West Indies, bananas for export and bananas for local markets are not cultivated in the same way: varieties, replanting frequency and use of pesticides differ owing to the specific quality requirements of the export market (Fig. 1). Similarly, a cattle farmer and a cereal farmer will not cultivate their maize or wheat in the same way. Cattle farmers use livestock manure as a fertilizer for wheat, whereas chemical fertilizers are the main source of nutrients for cereal farmers. The work loads are not spread in the same way over the year. In the Paris basin, cereal farmers generally apply their spring pesticide at the optimal period,

Fig. 2 In the south of Haïti, local fruit markets offer limited opportunities for producers © Eric Auguste

whereas cattle farmers often have to postpone treatment because the fodder crops have to be harvested during the same period.

A farmers' perception of the socio-economic context is a major factor for changes in cropping systems. The choice of crops may change over time depending on market prices. If a crop becomes profitable over time, it may be planted more frequently at the expense of others, leading to shorter crop rotations. This can be seen, for example, in the Argentinian Pampa, where soybeans have become increasingly dominant (Meynard 2012) and in northeast Thailand, where hevea plantations have been gradually increasing, even though climatic conditions are not ideal (Clermont-Dauphin et al. 2013). In Haiti, farmers have considerable experience in selecting crop rotations, dates and sowing densities that limit the risks of pests and diseases for the crops. The development of practices that increased these risks, such as the elimination of fallow and the increased frequency of the bean/maize intercrop, was not due to a lack of awareness of the adverse long-term effects of these practices: this was the response to the scarcity of food resulting from a rapidly growing population (Clermont-Dauphin et al. 2005). The reduction of tree density can be interpreted in a similar way. Fruit trees are being cut down by many Haitian farmers to produce and sell charcoal, the main source of energy for many households. This seems quite logical when they consider the lack of markets for fruit production (Fig. 2). The emergence of new openings, such as access to new markets, would drive other changes.

A particular innovation will not interest all farmers to the same extent and, although it may be of potential interest to all of them, it will not be adopted universally. A good example in this regard is the "no-till systems" or "conservation agriculture" which includes permanent soil cover, using living or dead cover crops in

Fig. 3 The need for crop residues as forage for livestock is one of the major causes of sparse soil mulching in annual crop rotations in West Africa

the rotations. This system has spread widely in recent decades in mechanized farms in South America and the USA and was clearly efficient to prevent soil erosion risks in intensive cotton production systems in Brazil. However, only a few smallholdings of South America adopted no-till owing to the need for special costly tools and lack of information about managing weeds and pests (Derpsch 2008). In peasant farming in West Africa, although most of the key elements of conservation agriculture, such as minimum tillage and introduction of legumes in the rotation or in association with the cereal crops, are commonly found, a permanent soil cover is often hard to actually achieve (Serpantié 2009). There are many reasons for this: crop residues may be used as forage for livestock (Fig. 3), the crops may have low biomass production owing to climatic conditions and high soil degradation, the residues may be rapidly mineralized as a result of microbial activity and termites, or they may increase the risks of wildfire in areas with a long dry season, insecure land use rights may discourage farmers from investing in resources to improve or preserve soil fertility. In Madagascar, the studies of Villemaine (2011), Queinnec (2013) and our own observations suggest that some causes of rejection of this technology were the need for smallholders to change their allocation of ressources such as soil and labor, the lack of acces to, and use of external inputs as herbicides, and the risk of yield decrease at short term due to the competition between the main crop and the cover crop and to the incidence of weeds and pests. In fact, the no-till system has only succeeded where it was able to overcome serious production problems in the short term, as in the Mid West of Vakinankaratra, where a permanent cover of *Stylosanthes guianensis* proved to be the only effective means of controlling the parasitism of

Fig. 4 Complex cropping system of the "Creole Garden" in the Caribbean. *Left*: general view, a garden in Martinique; *Right*: inside view, a garden in Haiti. In Haiti, kitchen waste is recycled in this garden

rice crops by *Striga asiatica,* and in the south east where a cover of *Arachis pintoi* under coffee trees contributed to weed management, increased land use efficiency and production diversification. In the mountains of Haiti, intercropping of various staple food species probably contributes to the soil cover at critical periods as the different crops have complementary canopies. Trees, contribute little to soil erosion control in the fields cultivated with annual crops. The few surviving trees are around the farmers' houses, where they can benefit from organic waste and have many different functions (Bellande et al. 1994) (Fig. 4).

The Relationship Between Cropping Systems and the Functioning of the Agro-ecosystem

The relationships between practices and compartments of the ecosystem, such as soil biodiversity, are not simple. Each practice may affect several compartments. For instance, tillage affects the water use, soil aeration and the location of weed seeds and crop residues. Tillage also affects the decomposition of residues and has a significant effect on the soil biological activity. Conversely, the same agro-ecosystem compartment may be affected by several practices. For example, the population of weeds in a field depends on the type of tillage, the date of planting, use of herbicides and the competitiveness of the crop itself, which in turn depends on the variety, density, type of amendment used, etc. (Sebillotte1974). These complex relationships between farming practices and agro-ecosystem compartments lead to significant interactions between the farming practices. The efficiency of mineral fertilization depends on controlling root diseases which is more difficult for short crop rotations than for long rotations (Clermont-Dauphin et al. 2003). The interaction of crop rotation and tillage affects the localisation of the residues infected by various diseases (Colbach and Meynard 1995). Soil compaction, caused, for example, by tractor wheels during tillage, affects the water and nitrogen use efficiency. In north western

Europe, where there is pressure to reduce the use of pesticides, integrated pest management (IPM) requires knowledge about the effects of each of the techniques used on pest and weed populations. For example, crop rotations have been lengthened to reduce the use of herbicides and fungicides, and the wheat sowing date has been delayed to reduce the use of fungicides and insecticides (Mischler et al. 2009). The selection of disease-resistant varieties helps to reduce the amount of fungicide used and to increase the numbers of beneficial insects in the borders of fields. Hedges or buffer strips may also help to reduce the use of insecticides. In most cases, each of the techniques used for IPM only provides limited control of pathogens. These effects are less radical and not as spectacular as the effects of pesticides. Different techniques with limited effects that work in synergy must be combined to control pests successfully.

Peasant farmers in the southern hemisphere have considerable expertise in managing soil and plant biodiversity. In the Caribbean, the complex "Creole Garden" intercropping system, where different species are selected to play complementary roles in term of pest control, nutrient cycles, shade, etc., is an interesting approach which merits further study (Fig. 4). The practices adopted by these farmers are based on knowledge drawn from various sources: traditional knowledge, personal learning, information provided by development agencies etc. (Altieri et al. 2012).

However, a farmer who is not familiar with a particular process or is unable to assess its consequences will not consider using it. For example, in the early years of mechanization in France, no attention was paid to soil compaction by tractor tyres. Later, clear evidence of the significant impact of soil compaction led to changes in cropping systems to reduce soil compaction. More recently, Schneider et al. (2010) showed that many French farmers underestimated the beneficial effects of growing legumes. This has contributed to their gradual disappearance from crop rotations. More generally, the collective representation of the agro-ecosystem that is related to industrial agricultural practices is simplistic. For each "limiting factor" there is an input that enables to remove it: fertilisation to prevent mineral deficiencies, application of pesticides to control pests and irrigation if there is risk of water stress. The Green Revolution technology package and intensive monoculture systems for corn, bananas, cotton, soybeans, etc., were based on this simplistic view of the agrosystem. Other methods of managing water and mineral availability for crops and controlling pests and weeds have been forgotten.

The Relationship Between Cropping Systems and Information Flows

There is a relationship between the cropping systems and the considerable flow of information processed by farmers. In adapting their practices, farmers rely on observations of the soil and crop status: the soil moisture which determines whether it is practicable to work the fields, air temperature and wind speed which determine the success of pesticide treatments, the development stage of the crop and yellowing

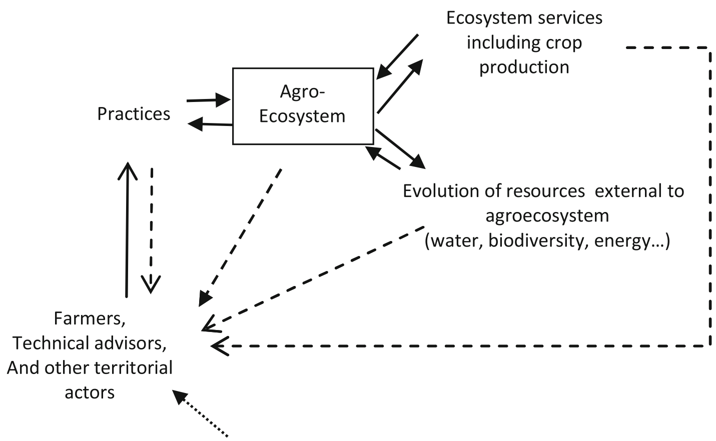


Fig. 5 Relationship between farming practices and the agro-ecosystem: direct effects and indirect effects via information flows (*dotted lines*). The practices are fundamental to a network of determinants that have to be taken into account with a view to evaluating or improving agro-ecosystem management

which could trigger nitrogen application, clod size which determines the type of tillage before sowing, etc. Farmers also collect information to assess, *a posteriori*, whether they made the correct decisions: analysing the performance in terms of yield or product quality may cast doubts on the choices made and result in changes to the crop rotation, the varieties used or the fertilizer application dates. Information flows may lead to other stakeholders such as consumers, food processors and public authorities having an indirect influence on cropping systems through contracts, quality labelling and regulations (Fig. 5).

Some of the criteria commonly applied by farmers to select their practices are related to soil biodiversity. For example, the presence of weeds or insect pests in a field may trigger a pesticide treatment but, if aphids are being controlled by a beneficial insect, a farmer may decide not to intervene. Farmers' observations can also influence strategic decisions. For example, a change in crop sequence can be the result of an increase in the weed population or an increased crop damage caused by soil fungi, such as fusarium or aphanomyces. In rainfed paddy fields in southern Thailand, farmers assess the extent of wild rice infestation during the fallow period right at the beginning of the rainy season by looking for red rice grains in the ground. If infestation is high, they will change their planting method from direct sowing to transplanting which makes it easier to control weeds (Trébuil and Thungwa 2002).

Farmers build up their cropping systems by collecting information on their fields and using it to select their practices: each farming practice used depends on the effects of previous practices and the expected effects of subsequent practices. They build up their knowledge from these observations, improving their perception of the functioning of the ecosystem they have to manage and their expertise in managing the available resources. However, incomplete information may lead to bias. This was the case, for example, in the intensive banana cropping systems of Guadeloupe: farmers observed that nematodes had a harmful impact on production and decided to control them using nematicides. These farmers probably did not realise that the build-up of the harmful population of nematodes was related to the reduction in soil biodiversity caused by tillage (Clermont-Dauphin et al. 2004). Meynard et al. (2002) showed that farmers found it much easier to assess the economic performance of their production systems than their environmental performance. The environmental impacts of practices are often expressed on large geographical scales (catchment area, landscape) and long time scales (several years or even decades) that make it difficult to attribute them clearly to the individual practices of a given year. In northeast Thailand, for instance, it is suspected, although this has still not been confirmed, that the increased salinity in the lowland paddy fields may be related to the deforestation of the uplands for annual crop production (Clermont-Dauphin et al. 2010). Because farmers cannot evaluate the ecological consequences of their decisions, it is difficult for them to take account of such consequences to improve their practices and for policy makers to define regulations that would promote the development of sustainable agriculture. Agronomists and ecologists must provide farmers with easily accessible indicators, at field or farm scale, that are correlated with the ecological impacts of practices so that they can take account of parameters other than short term economic impacts. This is discussed below in the section on the development of biodiversity indicators.

The Relationship of Cropping Systems to the Role of Stakeholders Other than Farmers

Agricultural practices are not defined solely by farmers. They may also be influenced by the large number of advisors, customers or authorities with whom they have contact: technical advisors, farm suppliers that provide services related to their sales of inputs, food and feed processors who include specifications in their contracts and authorities who define “good practices”. In a study on constraints on crop diversification, Meynard et al. (2013) showed that the simplification and shortening of crop rotations in French agriculture is not decided by farmers alone. It is the result of interrelated decisions taken by cooperatives, agricultural processing businesses, seed companies, advisory services, etc. The authors concluded that if the authorities wish to reduce the harmful effects of this crop specialization, – in this case over-use of pesticides, uniformity of landscape mosaics, etc. – and promote crop diversification, they should seek to influence the strategies of those driving the move towards specialisation. It would not be efficient to focusing exclusively on decisions made by farmers. In northeast Thailand, the rapid expansion of rubber in smallholdings was made possible by the conjunction of high rubber prices, experience gained by many farmers in this region who had worked as tappers in the rubber plantations of the south, substantial government involvement at various levels of the rubber sector, subsidised inputs and loans to farmers during the first 6 years of the immature phase of rubber trees, technical support programs, research into clonal selection, expansion of both private and government-owned agribusinesses and the development and maintenance of transportation routes.

Conclusion 1

The strong relationships between farming practices and between cropping systems and soil biodiversity are far more complex than might be expected a priori. Different farming practices affect the soil biodiversity through processes which are now beginning to be relatively well understood. The perception that a particular practice may have a harmful effect on soil biodiversity may lead farmers to adapt their cropping systems. These changes in strategy may make it difficult to determine the causes of poor soil biodiversity. For instance, in the case of the Antillean intensive banana cropping systems described above, it was not easy for scientists to determine whether poor soil biodiversity was caused by the use of pesticides or by the tillage that had made the pesticides necessary.

All aspects of the relationship between cropping systems, farming strategies and the environment must be taken into account when considering how practices can be improved. Any innovative technology is likely to result in the modification of several other practices. It is essential to study how innovation fits in with the whole cropping system, and their interactions with other stakeholders. Trade-offs between various objectives and processes should be considered for developing innovative cropping systems. Advances in agricultural system design approaches, which are discussed in the final section of this paper, will play a vital role in improving practices.

Relationships Between Cropping Systems, Soil Biodiversity, Functions and Services: State of the Art

Relationship Between Soil Biodiversity and Ecosystem Services

Soil Biodiversity

Soil biodiversity can be defined as the variety of life in the soil, from genetic variability to the range of communities, and the variety of soil habitats, from micro-aggregates to whole landscapes (Turbé et al. 2010). Soils are among the most species-rich habitats of terrestrial ecosystems as they are host to extensive biodiversity, in terms of abundance, number of species and functions of organisms (Wolters 2001; Decaëns 2010; Pulleman et al. 2012). Most animals in terrestrial ecosystems spend at least part of their life cycle in the soil (Wolters 2001; Decaëns et al. 2006). More than a quarter of the described species of terrestrial invertebrates and vertebrates are strictly soil or litter inhabitants (Decaëns et al. 2006).

Soil organisms and the interactions between them drive many soil processes that provide essential services such as nutrient cycling, soil formation, primary production, regulation of atmospheric composition and climate, water quantity and quality and pest and disease control in agricultural and natural ecosystems (Brussaard et al. 1997; Daily et al. 1997; McNeely 1994a, b; Turbé et al. 2010).

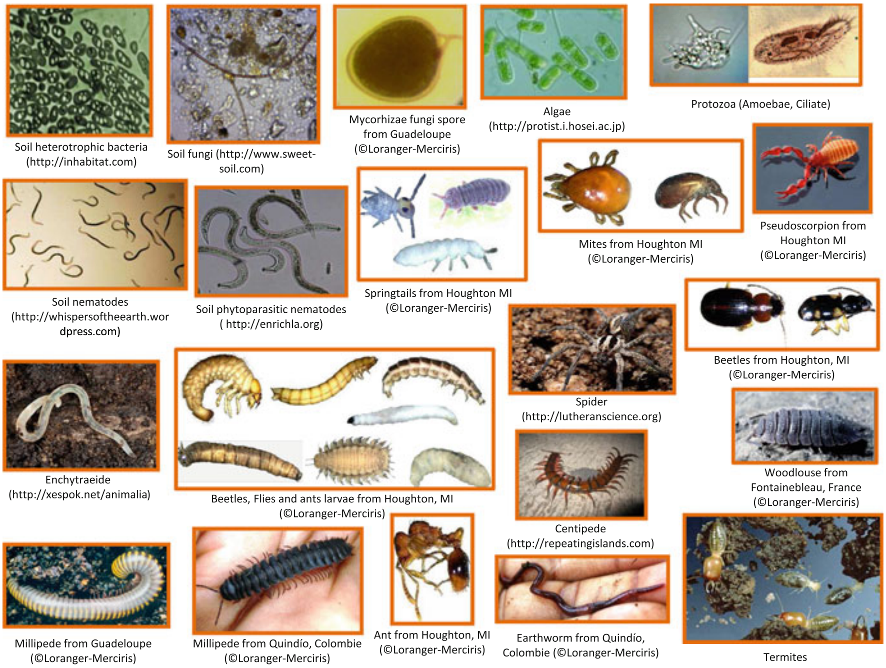


Fig. 6 Soils comprise a wide variety of different sized organisms: microorganisms (bacteria, fungi, algae), microfauna (protozoa, nematodes), mesofauna (springtails, mites, pseudoscorpions, enchytraeids, etc.), and macrofauna (insects larvae, spiders, beetles, millipedes, ants, centipedes, earthworms, woodlice, termites, etc.)

Micro-organisms such as bacteria, fungi and algae constitute 80 % of the living biomass in soils. Soils also comprise a large variety of animals. Most of the phyla such as protozoa, nematodes, annelid oligochaeta and arthropods are represented in soil and litter fauna (Fig. 6). Soil fauna abundance, biomass and diversity vary significantly depending on the climate, soil characteristics, type of vegetation, land use and biological interactions (Gobat et al. 1998; Lavelle and Spain 2001).

Measuring soil biodiversity is a challenge. Most soil organisms are not visible to the naked eye and many microbial and animal species are still unknown (Turbé et al. 2010). For example, it is estimated that more than 99 % of bacterial and nematode species are unknown (Wall and Virginia 2000). The identification of soil fauna requires efficient sampling and extraction processing and the expertise of several taxonomists for visual recognition. It is very difficult to measure soil microbial biodiversity. Until now, less than 1 % of micro-organisms has been cultured and/or characterised (Torsvik and Ovreas 2002). Genetic methods (DNA or phospholipid analyses) which partly replace the morphological identification of species under the microscope characterise whole communities rather than single species (Turbé et al. 2010).

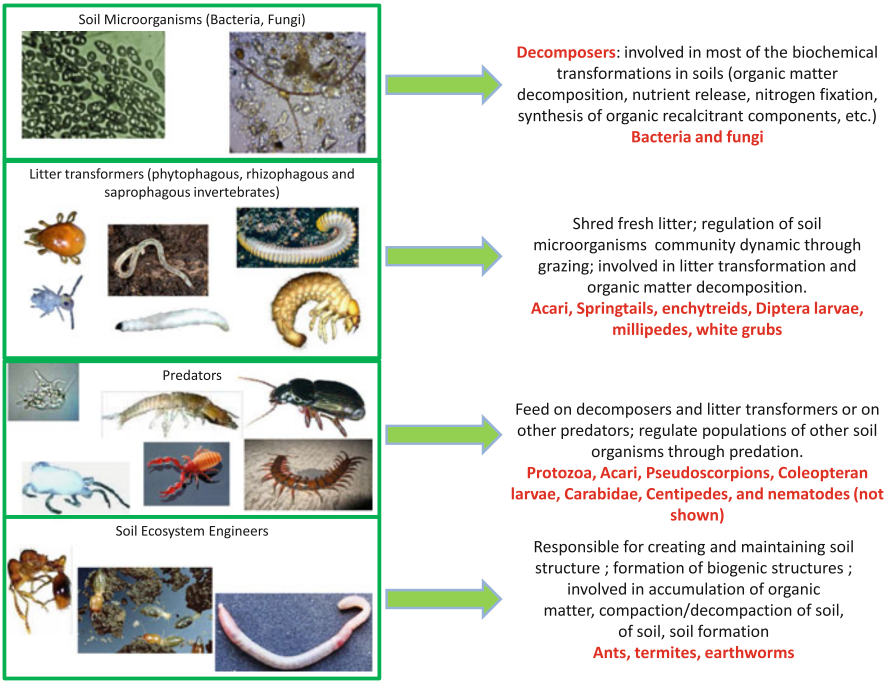


Fig. 7 Classification of soil functions into four main groups performing three essential ecosystem functions: transformation and decomposition, biological regulation, and soil engineering

Soil Functional Groups

Soil biodiversity may be better measured by considering functional groups. Several functional classifications have been proposed by soil ecologists based, for example, on soil organism size, alimentation or localisation in the soil profile. One of the most interesting classifies groups of soil organisms according to the three major ecosystem functions they fulfil (Fig. 7): transformation and decomposition, biological regulation and soil engineering (Lavelle 1997; Brussaard 1998; Turbé et al. 2010).

The first group comprises **soil micro-organisms** which act as **chemical engineers** or **chemical decomposers**. Bacteria and fungi are the main representatives of this functional group. They are involved in most biochemical transformations in soils. Chemical decomposers are involved in the transformation and mineralisation of complex organic compounds (such as sugars, cellulose, phenols and lignin) into nutrients available for plants. They are also involved in humification (formation of stable complex organic molecules included in humus) and in several other major biological processes such as nitrogen fixation, methanogenesis, nitrification and ammonification.

The litter transformer group includes phytophagous, rhizophagous and saprophagous invertebrates. They feed on decaying organic matter associated with bacteria and fungi. This group comprises invertebrates ranging from microfauna

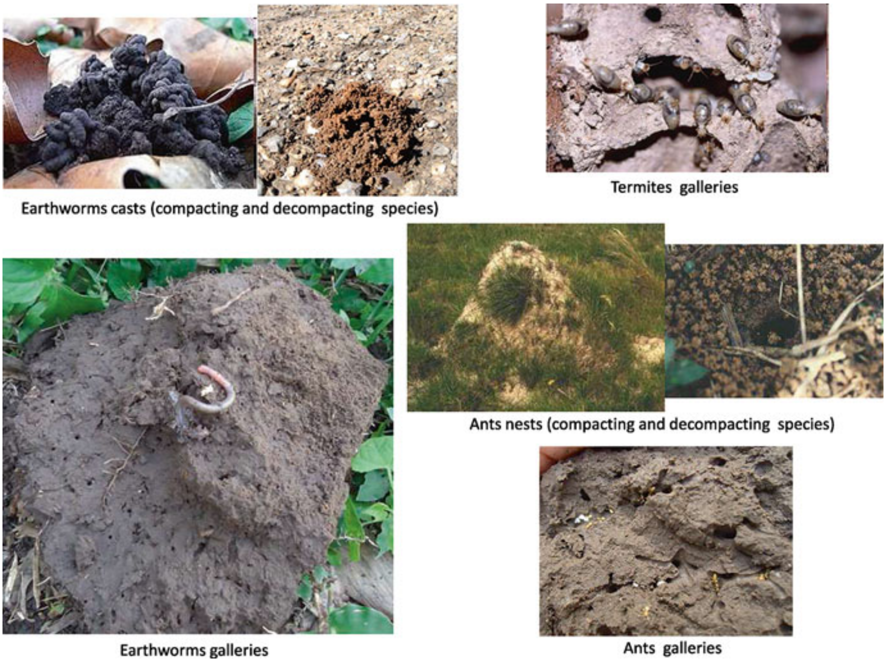


Fig. 8 Soil ecosystem engineers biogenic structures

(<200 μm) to macrofauna (>2 mm). They are involved in the **decomposition** function directly by shredding and digestion and also through the facilitating/stimulating effect they have on the action of chemical decomposers.

The **Predator** group comprises various invertebrates ranging from micro- to macrofauna. They are present from the top of the profile (litter and organic layers) to organo-mineral layers where they feed on decomposers and litter transformers (first order predators) and other predators (second and third order predators). Predators are responsible for the regulation of the populations on which they prey. Among this group, micropredators (protozoa and nematodes) feed on bacteria and fungi. Litter transformers and predators together perform the function of **biological regulators** because these organisms are responsible for the regulation of populations of other soil organisms, through grazing or predation.

Ecosystem engineers (termites, earthworms, ants, etc.) constitute a fourth group. These organisms can change the physical state of soil by producing biogenic structures (earthworms' burrows and casts, termite or ant mounds, etc.). Bioturbation by soil engineers can modify the nature and/or accessibility of resources for other soil organisms, e.g. nutrient availability for plants, pores for non-burrowing invertebrates (Stork and Eggleton 1992; Jones et al. 1994; Lavelle 1997; Decaëns et al 2001). This group has a major impact on soil functioning mainly by creating soil structures (Fig. 8) and regulating organic matter dynamics.

From Soil Function to Ecosystem Services

Soil functional groups and their interactions maintain soil ecosystem services through the different functions they fulfil in the soils (Brussaard et al. 1997; Daily et al. 1997; Millennium Ecosystem Assessment 2005; Lavelle et al. 2006; Barrios 2007; Turbé et al. 2010). This section considers the major ecosystem services that are of direct interest for agriculture.

The fertility of a soil can be defined as its ability to support plant growth by efficient organic matter decomposition and nutrient cycling. Because of their involvement in biochemical transformation in soils, chemical decomposers are the main group involved in nutrient cycling but in close relation with the other functional groups. Litter transformers such as millipedes stimulate microbial biomass and promote nutrient leaching (Kaneko 1999; Toyota et al. 2006). Soil engineers are known to stimulate microbial activities and to improve nutrient availability. Soil microbial activities, N availability, C mineralization rate and functional diversity are higher in ant mounds (Dauber and Wolters 2000; Dauber et al. 2001; Amador and Görres 2007). Microbial activities and mineral nutrient (NO_3^-, NH_4^+, P) release are also higher in termite mounds (Holt 1998; Jouquet et al. 2004; López-Hernández 2001). Several studies showed that soil microbial activities and nutrient availability were higher in earthworm casts and burrows. These biogenic structures are specific soil habitats which host specific soil functional microbial communities and have a higher mineral nutrient content than the bulk soil (Parkin and Berry 1999; Lavelle et al. 2004; Le Bayon and Binet 2006; Chapuis-Lardy et al. 2010; Bernard et al. 2012; Loranger-Merciris et al. 2012).

Water infiltration rates and water storage capacity are mainly affected by bioturbation by earthworms, ants and termites. In a fallow in the Sahelian zone of Senegal, Sarr et al. (2001) showed that water infiltration rates were significantly lower in plots without termites than in plots with termites. The impact of earthworms on water infiltration depends on the ecological group. In a 2-year experiment conducted in a humid savanna in the Ivory Coast, Blanchart et al. (1997) showed that the water retention capacity was increased by the activity of *Millsonia anomala*, a species which significantly increased soil macroporosity, while small Eudrilid earthworms tended to destroy large aggregates and form smaller ones.

In natural ecosystems, biological pest control is mainly carried out by predators. In an agro-ecosystem, low diversity is associated with a greater vulnerability to pests, as the natural regulation of these pests is disturbed (Turbé et al. 2010). In agro-ecosystems with high biodiversity, species tend to fill all ecological nests and use all available resources (Elton 1958). This state of equilibrium limits pest development (Altieri 1999). For example, in Senegal, millet is attacked by two main nematode species, *Tylenchorhynchus gladiolatus* and *Scutellonema cavenessi*. These two species represent more than 95 % of the nematode community of these agroecosystems. When millet fields were left fallow, the abundance of both nematodes decreased and there was a marked increase in the abundance of other nematodes. Interestingly, the amount of damage caused by the two main pest nematode species was reduced when they were associated with other plant-feeding nematodes

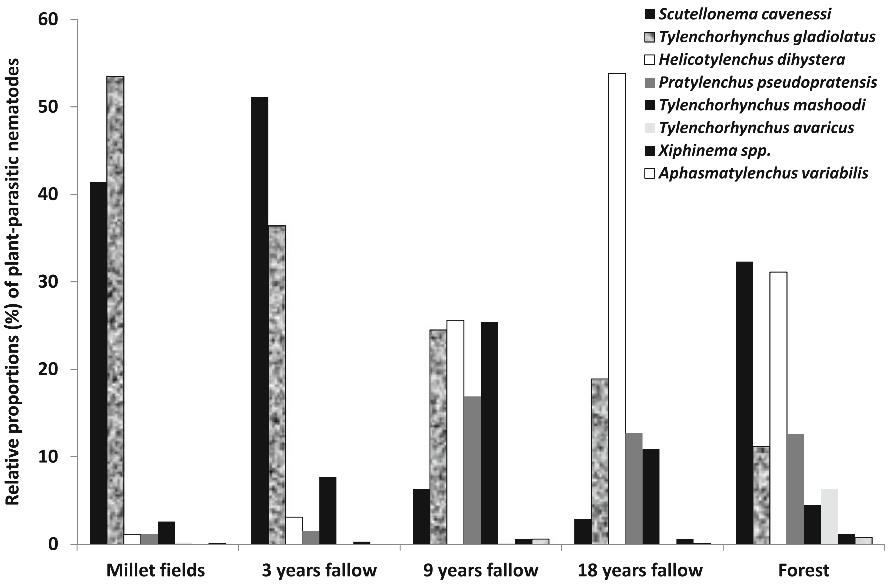


Fig. 9 Relative proportions (%) of the main plant-parasitic nematodes in millet fields, fallows of various durations and in forests, in the Sudanese-Sahelian region of Senegal (Adapted from Cadet and Floret 1999; Cadet et al. 2002; Villenave and Cadet 1998)

such as one of those whose abundance was increased when fields were left fallow (*Helicotylenchus dihystera* (Fig. 9) (Villenave and Cadet 1998; Cadet and Floret 1999; Cadet et al. 2002).

Soil functional groups have a significant impact on primary production through their role in various plant growth-supporting ecosystem functions : (i) biochemical transformations (chemical decomposers); (ii) organic matter fragmentation (litter transformers); (iii) stimulation of nutrient availability (ecosystem "engineers"); (iv) activation of mutualistic organisms (ecosystem "engineers"); (v) water infiltration and storage via bioturbation (ecosystem "engineers") and vi) pest and decomposer population control (predators). Several studies showed that interactions between functional groups also had a significant effect on primary production. In a microcosm experiment, Förster et al. (2006) showed that, in a soil amended with fecal pellets from millipedes and woodlice (litter transformers), the growth of rice plants was stimulated as the microbial activity was higher than in a soil without fecal pellets. These results show that litter transformers have clear positive effect on the release of nutrients by soil microorganisms and consequently on plant growth. In a recent study, Loranger-Merciris et al. (2012) showed that growth of banana plants was significantly increased in the presence of the earthworm *Pontoscolex corethrurus*. This was probably due to soil bioturbation by earthworms. In the aggregates derived from casts, the pore structure was rebuilt with a shift from mesobiotic pores (3–300 μm) to microbiotic pores (0.3–3 μm), improving the physical habitat for microorganisms. Bioturbation, therefore, helped to increase a microbial community which in turn increased P mineralization, as suggested by the greater P availability in the earthworm casts. The greater availability of P in the presence of earthworms resulted in higher P content in banana plants and in better plant growth. Several studies showed that earthworms have an indirect impact on plant-parasitic nematodes. These effects are mainly due to physical and chemical changes in the soil properties induced by earthworm activities. As a consequence, plants may have a better tolerance to plant-feeding nematodes or defend themselves against them more effectively in the presence of earthworms and consequently grow better (Blouin et al. 2005; Lafont et al. 2007; Wurst 2010; Loranger-Merciris et al. 2012).

Because of their importance and their position in the hierarchy, the disappearance or disturbance of soil ecosystem engineers can have a significant impact on other soil organisms and ecosystem services (Lavelle et al. 1993). In Brazilian Amazonian pastures, a decrease in soil fauna biodiversity leading to the dominance of *Pontoscolex corethrurus* significantly reduced soil porosity and affected water regulation (Chauvel et al. 1999; Barros et al. 2001), preventing a variety of biological functions from operating satisfactorily. Brussaard et al. (2007) showed that soil biodiversity had a stabilising effect on stress and disturbance although this appeared to depend on the kind of stress and disturbance and on the combination of their effects. For example, (i) soil microbial diversity provided protection against soil-borne disease, (ii) mycorrhizal diversity had a positive effect on nutrient and, possibly, water use efficiency and (iii) soil fauna diversity contributed indirectly to nutrient and water use efficiency through its effects on soil structure.

The examples described above show that the functional group approach, focusing on soil engineers appears to be one of the best ways of determining the relationship between biodiversity and soil functioning in agro-ecosystems.

Relationship Between Cropping Systems and Soil Biodiversity and Services

This review summarizes current knowledge on the effects of tillage, chemical and organic fertilization, crop rotation and intercropping and the use of pesticides on the dynamics of various soil biodiversity components and the interactions between components.

Tillage

Soil macrofauna, particularly earthworms, are generally affected in the long term by conventional tillage. This was reported by Kladivko et al. (1997); El Titi and Ipach (1989); Legrand et al. (2011) based on field experiments in temperate areas and by De Leon-Gonzales et al. (2012) based on a review of studies in tropical areas. Tillage causes direct physical damage to worms by exposing them to predators, frost or

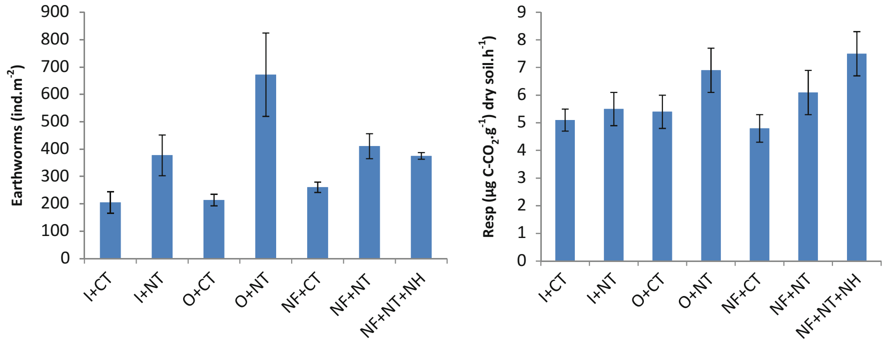


Fig. 10 Impact of various practices on earthworm density and microbial biomass 1 month after planting in a field experiment in northern Spain. I=Inorganic fertiliser, O=Organic fertiliser, NF=No fertiliser, CT=Conventional tillage, NT=No-till, NH=No herbicides. Note that the impact of no-till on earthworm density and microbial biomass depends on the use of organic amendment. Moreover, microbial activity is particularly affected by the application of herbicides (Adapted from Mijangos et al. 2006)

dryness and by destroying their casts (House and Parmelee 1985; Chan 2001; Clapperton et al. 1997). Tillage could also have an indirectly harmful effect on earthworm populations by soil compaction (Hansen and Engelstad 1999; Capowiez et al. 2009), by burying the surface residues that protect them from extreme changes of weather and by encouraging rapid mineralisation of the soil organic materials on which earthworms feed (Chan 2001; Doube et al. 1994; Kladivko 2001; Spedding et al. 2004). Conventional tillage practices affect different species of earthworm in different ways: the most affected are anecic species which move the soil vertically within the soil profile and epigeic species which inhabit the litter layer on the soil surface. Endogeic species which acquire a greater proportion of their food from the soil rather than surface litter are less affected by soil tillage (Edwards and Lofty 1982; Holland 2004; Kladivko et al. 1997). In cropping systems in Norway where the earthworm community is mainly composed of endogeic species, Pommeresche and Loes (2009) compared various soils tilled annually or not tilled and found that earthworm density and biomass were not significantly affected by tillage but rather by the presence or absence of legumes in the crop rotations and by the incorporation of animal manure into the soil. Their conclusions would probably have been different if the soil earthworm community had been dominated by epigeic and anecic species. Based on a field experiment in a clay loam soil in northern Spain, Mijangos et al. (2006) showed that the impact of tillage on the earthworm community varied according to organic matter management methods: tillage reduced earthworm abundance more where organic matter was applied, i.e. in situations where high food availability for earthworms, may allow a high rate of growth for the community. When no organic matter was applied tillage had little effect on earthworm abundance (Fig. 10). Manetti et al. (2010) in Argentina also found that tillage had little effect on soil macrofauma and attributed this to the fact that tillage had little effect on the soil content in organic matter. Tillage is more harmful to earthworm abundance in coarse-textured soils than in clay soils, as a higher proportion of soil organic matter is mineralised after tillage of coarse-textured soil (Rosas-Medina et al. 2010). Similarly, because chisel-disks loosen the soil more than rotary harrows, they do more damage to earthworms (Kladivko 2001). The impact of tillage on earthworm communities may also depend on the date of tillage which determines the weather conditions at the time of tillage, and therefore the risk of earthworms' exposure to cold or to high temperature (Pelosi et al. 2008). Few studies have been carried out to determine how tillage affects the various development stages of earthworm communities. It is generally assumed that adult earthworms are the most affected by tillage because they are larger (Kladivko 2001).

Soil microbial activity is generally adversely affected in the long term by conventional tillage, in comparison to reduced tillage or no-till (Angers et al. 1992; Carter 1986; Asuming-Brempong et al. 2008; Spedding et al. 2004; Fuentes et al. 2009). Mijangos et al. (2006) showed that that tillage had the greatest impact on soil microbial respiration in amended soils (Fig. 10). However, greater soil microbial activity may be observed directly after tillage and incorporation of residue (Logan et al. 1991). Based on a meta-analysis of the effects of the conversion to no till in Brazilian ecosystems, Kaschuk et al. (2010) reported that microbial biomass increased by 58 % in 10–15 years and remained stable up to 25 years. Soil microbial biomass is reported as being an earlier indicator of soil disturbance than organic carbon, soil physical and chemical properties and even crop productivity (Mijangos et al. 2006; Hungria et al. 2009; Kaschuk et al 2010). Many studies have shown that burying residues with conventional tillage led to higher organic matter decomposition rates which promote bacteria (Simmons and Coleman 2008; Spedding et al. 2004), whereas no-till systems tend to be dominated by fungi. Mycorrhizal hyphae which often account for about 25 % of the soil microbial biomass (Spedding et al. 2004) are damaged by tillage (Beauchamp and Hume 1997). Sisti et al. (2004) showed that higher soil organic matter mineralization due to tillage resulted in higher soil N availability and lower biological N fixation. Melero et al. (2009) and Spedding et al. (2004) suggested that the negative effect of tillage on N fixation depended on the soil texture: Tillage had a greater effect on clay soils than on sandy soils, as more nitrogen was released from high clay content soils during tillage. There are also some cases where agricultural practices may not be the main drivers of soil microbial activity: the results of Feng et al. (2003); Bossio et al. (1998); Hungria et al. (2009); Shi et al. (2013) suggested that changes in microbial biomass owing to management regimes such as tillage, inputs of manure, cover crops and mineral fertilizers for a given soil were less significant than variations owing to the climatic conditions.

Zhang et al. (2012) showed that 4 years of no-till had no significant effect on the abundance and biomass of total nematodes although the effect depended on the genus. Stirling et al. (2010) and Zhang et al. (2012) showed that straw cover explained more variations in soil nematode abundance than tillage. Some recent studies suggest that the detrimental direct effect of tillage on larger soil organisms that prey on nematodes could lead to the short term increase of populations of plant-parasitic nematodes. For instance, Stirling et al. (2010) showed that in sugarcane

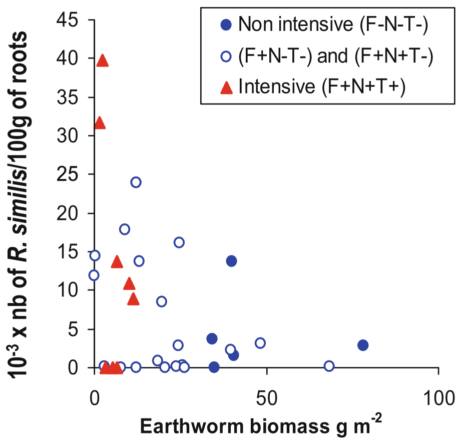


Fig. 11 Mean earthworm biomass and *Radopholus similis* abundance per 100 g of roots in banana plantations in Guadeloupe. Each point represents a farmer's field. F-N-T- means No fertilizer, No Nematicide, No-Till; F+N+T+ means that intensive fertilizer, Nematicide and Tillage were applied

plantations the populations of *Pratylenchus zeae and Meloidogyne javanica* were higher in the first sugarcane cropping cycle following tillage than in the successive ratoon crops. This was related to the decline in the population of the natural enemies of these nematodes in the first year after tillage and their gradual increase in the following years. DuPont et al. (2009) and Ferris and Matute (2003) suggested that C inputs from crop residues encouraged the development of a soil food web capable of limiting populations of plant-parasitic nematodes. In a survey comparing various banana cropping systems with and without tillage in Guadeloupe, Clermont-Dauphin et al. (2004) showed that tillage reduced earthworm abundance, reduced the population of the nematode *Helicotylenchus multicinctus* and decreased soil organic matter in the 0–10 cm layer as well as microbial respiration. At the same time the population of the parasitic nematode *Radopholus similis* increased (Fig. 11). However, the negative correlation between earthworm abundance and *R. similis* infestation suggested by the field survey was not confirmed in a greenhouse experiment, probably because of the short duration of this study and the reduced number of nematodes species introduced into the pots (Lafont et al. 2007).

From the various studies reviewed above, it appears that a higher abundance of many organisms or greater biomass is found in no-till than in tilled systems. Many different processes may be involved, and their magnitude depends to a great extent on the soil and climate characteristics as well as on interactions between the various components of the management system.

Mineral and Organic Fertilizers

Mineral N fertilizers may have a short term negative impact on soil biodiversity through soil acidification. This was shown by Edward and Lofty (1982), Hansen and Engelstad (1999) for earthworm populations and by Beauchamp and Hume (1997) for microbial populations. However, mineral fertilizer amendment generally has a beneficial long term effect on soil microbial biomass and activity with increased crop yields and root biomass and, therefore, increased organic matter returning to the soil (Edwards and Lofty 1982; Beauchamp and Hume 1997; Spedding et al. 2004). In a sandy soil where soluble N was rapidly leached and the soil P content was not limiting, Krumins et al. (2009) showed that strong pulses of nitrogen increased bacterial communities but did not increase fungi. N fertilizer may inhibit biological N fixation (Giller and Cadisch 1995; Kahindi et al. 1997) and mycorrhizal functions (Dighton et al. 2004; Lilleskov et al. 2002). On the other hand, P fertilizer was shown to stimulate biological N fixation (Hogh-Jensen et al. 2002).

Pommeresche and Loes (2009) and Rousseau et al. (2010) reported that organic residues increased soil biodiversity. These effects may vary with the C:N ratio and the content of polysaccharides and proteins of these residues (Leroy et al. 2008). Based on a meta-analysis of studies conducted in Brazilian ecosystems, Kaschuk et al. (2010) reported that several industrial residues were shown to stimulate microbial biomass. They stressed that this effect depended on the type of residue, the dose applied and the soil texture. Much attention has recently been paid to vermicomposting, the composting of organic waste with earthworms under mesophilic conditions. Vermicomposting has been shown to convert organic waste into an organic product containing a significant amount of nutrients and microbial matter and with stabilised humic substances. This manure was found to improve biological regulation of various plant parasitic nematodes (Arancon et al. 2003, 2007). Many studies have focused recently on biochar, the product of thermal degradation of organic materials in the absence of air. However, more attention has been paid to its effects on soil physical and chemical properties rather than to its impact on soil biodiversity. Lehmann et al. (2011) reported that sorption phenomena, pH and physical properties of biochars such as pore structure, surface area and mineral matter may play important roles in determining how different biochars may affect soil biodiversity.

Crop Rotations and Intercropping

Some studies suggest that crop diversity has a positive effect on soil biodiversity. In a greenhouse experiment Chen et al. (2008) showed significant differences in soil microbial community composition between a legume and a grass. This difference was related to their respective root exudation compositions. They showed that intercropping legumes and grasses increased the bacterial and fungal biomass in the soil compared to grass grown as a monoculture. Boswell et al. (1998) showed that introducing a winter wheat into a maize rotation resulted in significantly higher root colonisation by mycorrhizae both in tillage and no-till systems. In natural grasslands, arbuscular mycorrhizal (AM) fungi were found to play a role in determining the plant community composition and dynamics (Allen et al. 2002). Conversely, because plants differ in their response to a single AM fungus or to several AM fungi, multiple cropping systems producing two or more crops in the same field each year may help to maintain high AM fungi biodiversity (Hart and Klironomos 2002). Monocultures tend to select one species which is not necessarily the most efficient

(Johnson et al. 1992). Fewer attacks of pests and diseases in intercropping and rotation systems compared to monoculture have often been reported as the result of the build-up of a biological control (Cadet and Floret 1999; Cadet et al. 2002). In intensive banana plantations in Guadeloupe, it is likely that the decrease of plant diversity in comparison to perennial plantations was a contributing factor in reducing the biodiversity of the nematode community which, in turn, encouraged the development of the most harmful nematode, *Radopholus similis* (Clermont-Dauphin et al. 2004; Lafont et al. 2007). Plenchette et al. (2005) reported that in some areas with deep soils of the Paris basin in France, farmers grow crops such as potatoes, peas, beans and alfalfa which are favourable for AM fungi, especially when Integrated Pest Management (IPM) systems have been adopted, reducing fungicide treatments. In other areas with dry summers and shallow soils, the crop rotations mainly include cereals and oilseed rape, which are very hostile to mycorrhizae, particularly as the high frequency of wheat crops makes it difficult to reduce fungicide treatments.

However, other studies have suggested that the correlation between plant diversity and soil biodiversity is not always significant, probably because certain plant species have less impact on the soil microbial structure than others (Marschner et al. 2001; Johnson et al. 2003). As already pointed out by Kennedy et al. (2005), the diversity of plant species is probably less significant than the diversity of their functional traits.

Chemical Pest Control

The impacts of pesticides on soil communities may vary according to the type of pesticide, the period of application and the amount applied (Edwards and Bohlen 1996). For instance, Plenchette et al. (2005) reported that the effects of fungicides are often harmful to AM fungi but vary depending on the active ingredient and the rate of application. It was also demonstrated that some fungicides such as fosetyl-Al, metalaxyl and promamocarb do not have a negative effect, and sometimes have a positive effect, on AM fungi. Fungicides applied as seed coating would probably inhibit AM development more than fungicides applied when plants are already mycorrhized (Plenchette and Perrin 1992).

In conventional agriculture, chemical pest control is often associated with other practices, such as mechanical tillage, mineral fertilisers and monoculture. All these practices are well known to be potentially harmful for soil biodiversity. It is not possible to draw conclusions on the direct effects of pesticides by simple comparisons between fields that are treated with pesticides and those that are not. For instance, a comparison of banana plantations under intensive and traditional non intensive cropping systems in Guadeloupe showed that the use of nematicides increased the dependency of the banana yield on nematicides (Clermont-Dauphin et al. 2004). Tillage practices favoured the development of nematode populations and reduced the populations of earthworms which regulated nematode population (Fig. 11). Nematicides applied by farmers to control the harmful populations of *Radopholus* *similis* appeared to have a more harmful effect on earthworms and auxiliary nematode species than on the pest itself and, as the farmers noticed increasing nematode damage, they increased the frequency of nematicide applications. A few years after planting, this vicious circle resulted in excessive populations of nematodes and a new plantation had to be prepared. In this example, where a particular farming practice increased the population of parasites, the farmer responded by changing to another practice, which itself disturbed the biological balance even more, and so on. Dependence on pesticides can be both a cause and a consequence of the decline in biodiversity.

Conclusion 2

There has been much discussion about the extent to which conventional farming practices reduce soil biodiversity. However, some studies have also shown that the effects of these practices vary significantly depending on soil and climatic conditions. They have shown that there may be significant interactions between different types of operations. The results from one set of conditions cannot readily be extrapolated to other situations. For instance, the impact of tillage on soil biodiversity may vary according to the soil texture, the soil water status and temperature at the time of tillage, the type of tool, the crop rotation, the crop residue management system, the organic amendment practices, etc. This suggests that cropping systems should be considered as a whole when analysing the impacts of a particular practice on soil biodiversity and services, and that agro-ecological cropping systems should be designed in a site-specific approach.

Cropping systems affect directly both the soil biodiversity and the availability of environmental resources required to achieve the expected crop production. Soil biodiversity also contributes to crop production through functions or processes. It is often more convenient to determine the soil biodiversity functions in greenhouse experiments, but the impacts of cropping systems on soil biodiversity and the services it provides need to be determined at field scale. Field and greenhouse studies appear to be complementary. However, more research should be carried out into defining methodologies for combining the information gleaned from greenhouse and field experiments and ensuring that the two approaches are complementary.

Most of these studies remain academic and unrelated to the objectives and the socio-economic situation of farmers. Little research is being carried out into farmers' field conditions, and farmers' participation in identifying the possible compromises is often not required. However, as seen in section "The Cropping System Concept: Consequences for Ecological Intensification of Agriculture", there is some evidence that farmers are taking account of soil biodiversity services and that they have built up their own knowledge basis for making the best use of the soil biodiversity.

Taking Account of Soil Biodiversity and Its Services in the Design of Agro-ecological Cropping Systems

Developing Agro-ecological Cropping Systems for Farmers with Farmers

It is difficult to define the aims for redesigning current cropping systems. What criteria can be used to assess whether innovative systems respond well to new challenges? How can the importance of these criteria be prioritised? How can these criteria and priorities be defined with all stakeholders? These questions raise two problems.

Firstly, there is uncertainty about future developments. Apart from general trends such as increased emphasis on the management of environmental resources, it is difficult to predict how the international economic situation, government policies, public opinion and power relationships between pressure groups will change over the next 10–15 years. Similarly, although the reality of climate change is generally accepted, its local implications remain uncertain. The relative importance of issues and criteria needs to be established in order to design or evaluate innovative systems that will be appropriate for the future.

Secondly, not all stakeholders have the same objectives and interests – these vary from small farmers to large scale agri-businesses, from advisory services to government authorities, from agri-supply industries to food processing industries. A new technique may be considered to be a step forward or a step backwards depending on the point of view. What is acceptable for one may be considered by another to be inappropriate or harmful.

The diversity of actors, the variety of future scenarios and local situations create a large number of permutations and combinations that need to be taken into account when redesigning cropping systems. Agronomists and agro-ecologists must recognize that farmers, businesses and organisations all have different priorities and that these depend on where they are. They have to do more than recommend an "ideal cropping system". They should aim to help farmers to find their own solutions rather than trying to define a universal cropping system. With this in mind, considerable methodological work has been carried out since the 1980s. Meynard et al. (2012) identified two approaches for designing innovative cropping and farming systems: the "de novo" design and the step-by-step design.

The "**de novo**" **design** aims to determine effective systems without worrying, at least initially, about the transition from the current system to the new system. What is essential is to invent something that marks a break. The use of crop models, which give a dynamic simulation of the performances of crops subjected to various different practices, is a highly effective method of *de novo* design, as shown for example by De Wit et al. (1988); Rossing et al. (1997); Keating and McCown (2001); Bergez et al. (2010). They enable a very wide exploration of combinations of practices that can be carried out, going well beyond the level of current knowledge, and they provide predictions of the long-term impacts of the system that is being designed and on the probable effects of climate change. They can be used to identify which cropping system from the multitude of possible combinations of techniques, best meets the economic, social and environmental criteria. However, although using models is still the most frequently chosen approach for de novo design, some researchers have worked on prototyping without models (Lançon et al. 2008; Reau et al. 2012).

Step-by-step design focuses not on the target system but on the management of change. An existing system is taken as the starting point and is gradually modified to arrive at a new system which was not known in advance. The design work begins with a diagnosis. Do the present cropping systems meet the farmers' expectations? What are the ecosystem functions that cause unsatisfactory performance? Which farming practices should be changed (Doré et al. 1997, 2008)? On the basis of this diagnosis, changes to the farming systems are designed and implemented. After 1 or more years, another diagnosis is made. New changes are made to the systems, forming a loop of continuous improvement (Meynard 2012). This design method benefits from progress made in recent years in "on farm" analysis, which makes it easy to carry out precise, reliable diagnoses. Examples of step-by-step design are given by Coquil et al. (2009) and Mischler et al. (2009). Mischler et al. (2009) for example, studied arable cropping systems in the Paris Basin, France. The major problem identified by the initial diagnosis was excessive use of pesticides in short crop rotations. After 6 years, by diversifying crop rotations and adopting IPM techniques, the farmers had reduced the use of pesticides by half, without reducing profits.

These two design approaches have complementary benefits (Meynard et al. 2012): in "step-by-step design" the exploration is more cautious but has the advantage of adapting easily to the specific constraints of each farming situation. The farmer perfects his new system year by year. At the same time, he learns to control it, becomes convinced of its relevance and gradually reorganizes his work and his means of production. Step-by-step design encourages farmers to play an active role and apply their knowledge to the design process. "*De novo* design" gives free rein to creativity and, in this way, can provide highly innovative sources of inspiration for farmers engaged in step-by-step design (Table 1). Scientists generally prefer model-based design, which makes good use of scientific knowledge in the form of crop models. However, as pointed out by Passioura (1996), a complex model designed to incorporate an increasing amount of scientific knowledge becomes more difficult to use, requiring more input variables and estimated parameters. As a consequence, increasing complexity may result in loss of precision. Many research models are still unsuitable for use by grassroots players: the input variables are too complex to collect, the formalisms used are not easily understood, the effects of certain practices are not defined, the scope of validity is unknown, etc. Models built by researchers are still difficult to use by people other than those who designed them. There is still a gap between the research sector which devotes considerable effort to modelling and the development sector which still does not feel implicated. The needs and constraints of potential users should be incorporated into the models and cropping system designers should be associated with their construction more frequently than is currently the case (Prost et al. 2012).

Table 1 Comparison between the two general approaches for designing innovative cropping and farming systems

	De novo approach	Step by step approach
Focus	Invention of a system that marks a break with the present ones	Progressive evolution of current systems
Management of the transition	No	Yes
Methods	Model based explorations; design workshops, …	Diagnosis of current systems' failures, and loop of continuous improvement
Advantages	Exploration of very innovative solutions; source of inspiration for step-by-step design	Progressive learning for farmers; easy adaptation to specific constraints of a farm
Risks	Low realism	Conservatism

Fig. 12 Experiment on the effect of different endemic and introduced earthworm species on soil enzymatic activities in Madagascar

Improving Knowledge of the Relationships Between Agricultural Systems, Biodiversity, Functions and Services: Priorities

Interactions Between Laboratory and Field Studies

Experiments carried out in the laboratory are appropriate for describing the processes and roles played by various organisms (Fig. 12). However, generally only a limited number of functions are examined. The quantification of the provision of ecosystem services from this kind of experiment cannot be extrapolated to field conditions where various mechanisms may interfere. Experiments carried out at "field" scale would have the advantage of incorporating the impacts of practices on the various organisms and their interactions and of quantifying the various services under a given management option. However, in field experiments, it is difficult to establish causal relationships between cropping practices, soil biodiversity and services. Each farming practice may affect various components of the agrosystem, not only soil biodiversity. For instance, as tillage may affect not only the soil biodiversity but also the soil-water dynamics, the nutrient distribution in soil, the weed infestation and the plant root distribution, differences in crop performances with till and no-till systems may be at least partially due to one or more of these changes rather than to the change in soil biodiversity. In a study carried out in Brazil, after many years, no-till cropping systems led to higher biomass of chafer grubs and higher soil carbon stocks in the upper horizons (Blanchart et al. 2007). However, it was impossible to determine whether the larvae had a significant positive influence on carbon storage or, on the contrary, whether carbon storage affected the development of chafer grubs. It is also well known that earthworms increase the mineralisation of soil organic matter in the short term but may prevent organic matter from mineralisation in the long term (Coq et al. 2007; Martin 1991). However, it is difficult to predict whether an increase in the earthworm populations in agro-ecological systems will improve the storage of organic matter in soil. The same question is raised regarding the impact of earthworms on greenhouse gas (GHG) emissions: it is difficult to determine how they contribute to GHG emissions in the field whereas it has been clearly established in the laboratory that earthworms are major emitters of GHG in the short term (Lubbers et al. 2013).

More effort needs to be made to drawing on knowledge from different sources: (i) laboratory studies focusing on the ecological functions of soil biodiversity which lead to ecological models, (ii) field experiments using an agronomic diagnosis approach to identify and rank the farming practices and processes that should be included in site-specific models and (iii) on-station experiments to test certain hypotheses and acquire additional reference material.

The agronomic diagnosis approach is based on a study of the cropping practices, the crop and the environment, including soil biodiversity, within a network of farmers' fields, as described by Doré et al. (1997) in order to identify the variables and processes which are the most involved in fulfilling the expected ecosystem services. This approach was adopted to identify the main problems affecting plantain (*Musa paradisiaca*) performance in various Caribbean regions and provide agro-ecological alternatives. In Guadeloupe, this approach was carried out in 23 plantations and showed that the main constraints affecting the cropping systems were (i) the high level of pesticides which reduced natural pest regulation and (ii) the planting of contaminated plant material. The diagnosis was also used to create biological indicators for the main functional groups affected by the conventional cropping systems (Loranger-Merciris et al. unpublished data). In a study of the causes of variation in the quality of barley grain for malting, Le Bail and Meynard (2003) show the role of water stress as well as that of a soil-borne disease, caused by a parasitic fungus, whose frequency and severity are increased by short rotations with high frequency of cereal crops.

Modelling the impact of biodiversity on soil functioning is a challenge as it involves a large number of processes and organisms which act over different space and time scales. Most ecological models have tended to focus on one functional group. For instance, the SWORM model describes the action of earthworms on soil structure through bioturbation and estimates the fate of soil organic matter and soil structure at soil profile scale (Blanchart et al. 2009). This model is being developed to give a better description of the interactions between earthworms and microorganisms

Fig. 13 Farmers sowing rice in the residues of a previous covercrop *Stylosanthes guianensis* in mid west Madagascar

in order to predict their impact on nutrient availability to plants and, consequently, on plant growth. As already reported by Anderson (1995) further research is required to establish the links between (i) ecological processes involving interactions between soil properties, microbial and soil engineering activities, studied in the laboratory at detailed temporal and spatial scales and (ii) ecosystem services operating on large scales, studied and characterized in field stations.

Reconciling Short and Long Term Effects of Agro-ecological Practices

Agro-ecological practices may have a significant negative impact on crop production in the short term. For instance, in sub-Saharan Africa, Kihara et al. (2012) showed that, because of the crusting of the soil, at least six seasons were required for maize yields under no-till to match those under conventional tillage. In many areas of Madagascar, the introduction of no-till required the use of chemical inputs such as fertilizers, insecticides and herbicides, in order to maintain the previous yield levels (Husson et al. 2012). Despite actions to provide information and soft financing, most farmers preferred to reserve these soil conservation systems for their most degraded soils without using the high levels of chemical inputs recommended by the advisory services.

New options or strategies, involving more research, may be needed to manage the short term negative impacts of new agro-ecological practices and encourage their adoption. A few questions are already being raised, such as how can the risk of pest development due to the mulch in no-till systems be controlled without significantly affecting the rate of regeneration of the desired soil biodiversity (Fig. 13)? How can

Fig. 14 Harvest of *Phaseolus vulgaris* in intercropping with a maize crop in Haiti. © Eric Auguste

the best varieties be selected for sustainable agricultural intensification (Séguy et al. 1998)? How can soil surface acidification under no-till (Fox and Bandel 1986) or the risk of NH_3 loss to the atmosphere be managed? In temperate areas, how can the soil warming in spring be managed under conservation agriculture etc.?

Reconciling Services

It is probably impossible to achieve the optimum level for all the desired services. There may even be conflicting relationships between services (Roger-Estrade et al. 2010). For instance, when a crop species provides the service of natural pest control for the companion crop at the same time as it competes for water (Fig. 14), or when tillage controls weeds but increases soil erosion risks. The thresholds of soil biodiversity below which each expected service is severely affected should be determined in order to adapt farming practices. For instance rather than comparing till and no-till in a caricatural or dogmatic way, it would be more relevant to identify tillage options targeted on precise functions (Roger-Estrade et al. 2010). Tillage at a specific period of the year could prove to be a good compromise between the need to preserve the services of soil structure maintenance and the need to control a specific weed population. Attention should be paid to how soil biodiversity and ecosystem services change with time, as some studies have suggested that this relationship may be quite complex. For instance, Spain et al. (1992), in the Ivory Coast, showed that the relationship between earthworm biomass and the growth of *Panicum maximum* was not linear: plant growth first increased rapidly with earthworm biomass and then decreased. The authors suggested that the high earthworm biomass compacted the soil and decreased the water-holding capacity.

Building Indicators for Evaluating and Designing Agro-ecological Cropping Systems

The notion of bioindicators, or biological indicators, is strongly linked to that of soil quality. The first reference to the "soil quality" of agricultural soils dates from 1977 (Warkentin and Fletcher 1977) but it was only in the 1990s that the term was defined and scientific studies of soil quality were carried out (Doran et al. 1994). The definition evolved progressively from an indicator of "crop production" potential to a multifunctional indicator of the quality of agro-ecosystems. Soil quality or soil health takes account not only of crop production but also the impact that soil management has on the quality of the environment, human and animal health and food safety and quality (Karlen et al. 2003). Karlen et al. (1997) defined soil quality as the "capacity of a soil to function" implying that soil management should "sustain plant and animal productivity, maintain or enhance water and air quality and support human health and habitation". Soil quality could now be defined as the ability of a soil to provide ecosystem goods and services. Soil quality can also be used as an indicator of sustainable use of the soil and therefore sustainability applied to soils is the capacity of a soil to maintain or improve its quality with time.

There are no tools for measuring soil quality directly as it is composite and context-dependent. The assessment of soil quality should not be limited to the measurement of degradation, such as decrease in fertility, erosion, compaction, etc. it is also necessary to analyse the functions and processes that cause such degradation. Soil quality indicators are measurable soil or plant properties, which help to understand the soil functioning. They are generally physical, chemical or biological properties. Considerable scientific work has been carried out to find good indicators of soil quality. For example, an indirect indicator, such as pH-Eh-resistivity, proposed by Husson (2013), may be an appropriate for characterising the overall interactions between soil, plants and microorganisms to characterise the productivity, resistance of crops to pathogens or bioavailability of nutrients. This section, however, focuses on bioindicators.

If soil quality is defined as the capacity of a soil to provide ecosystem services, what indicators can be used to assess it? Can all ecosystem services be included in a single indicator, i.e. what is included in the concept of "soil multifunctionality"? Soil multifunctionality is of major importance for agriculture, where a soil that provides all expected ecosystem services is preferable to a soil that provides only a few services. The question of trade-off between services is rarely applied to agricultural soils because agricultural soils are increasingly expected to deliver all of a wide range of ecosystem services at the same time: producing food while avoiding erosion and soil and environmental pollution, preserving biodiversity, encouraging carbon sequestration, providing attractive landscapes, etc. The quality of a cropped soil is extremely difficult to assess and considerable research has been carried out on this subject (Karlen et al. 2003; Bispo et al. 2011; Kibblewhite et al. 2008).

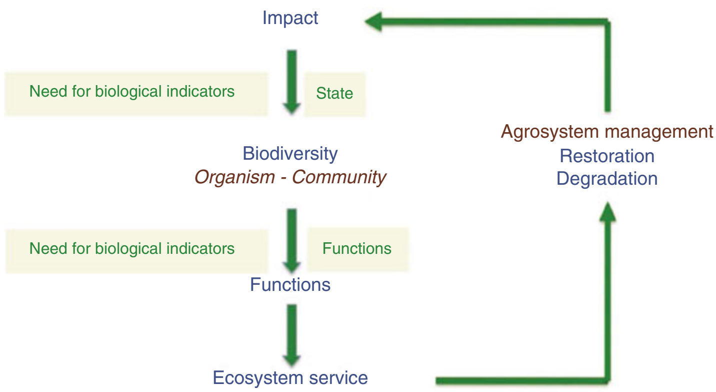


Fig. 15 Distinction between bioindicators which assess the state of the ecosystem to evaluate the effect of a farming practice or management system on soil biodiversity and bioindicators which describe or predict the provision of ecosystem functions and services depending on the management system

Organisms as Indicators

Soil users, farmers in particular, have defined their own indicators empirically. A survey conducted in France in 2011 (Vian et al. 2009) showed that the most common bioindicator used by farmers is earthworm density, because earthworms are known to affect soil structure and the decomposition and burying of organic matter (Pérès et al. (2011). Some farmers also pay great attention to the number of earthworm casts on the surface of the soil. However, there are still differences between earthworm sampling methods and there is still no standardised method which would enable effective debate among those concerned by sustainable intensification of agriculture. Pelosi et al. (2009) attempted to define a standard method by comparing the efficiency of three chemical expellants using or not using hand-sorting. Other biological indicators that could be used by farmers are microbial biomass which depends on the decomposition of organic matter and the abundance of certain macro invertebrates such as slugs as pests or carabid beetles as pest predators but these are rarely used. Scientific studies have shown that earthworm populations and microbial biomass change rapidly when a farmer shifts from a conventional system to another system that is considered to be more sustainable, such as conservation agriculture, organic farming and low pesticide use (Ruiz-Camacho et al. 2009; Pérès et al. 2011).

Many scientific works propose indicators for describing soil biological properties (Fig. 15). Research has been carried out in France to provide reference data for the species/taxa found in specific areas and the density and biomass measured for a wide range of climate conditions, soils and agricultural practices (Coll et al. 2011; Cluzeau et al. 2012). These values are of great importance but can they be used as indicators of sustainable soil use? The main issue is the link between biological properties and ecosystem services. The most important property of soil biodiversity is the organisation of soil organisms into functional groups rather than species richness, density or biomass. One approach is to define the activity of organisms in fulfilling the four main aggregated soil functions and the ecosystem services they provide (Kibblewhite et al. 2008).

Functional Roles of Soil Organisms as Biological Indicators

It is not easy to attribute functions to soil organisms because our knowledge of the biology of soil taxa is still limited. This is at the core of various research programs which aim to attribute functional traits to species. Functional traits are morphological, anatomical, physiological and behavioural characteristics, which define the consequences of the activity of a given organism on its environment and on other organisms. This approach has long been applied to soil nematofauna. Nematodes are currently classified into trophic guilds: bacterial-feeders, fungal-feeders, omnivores, predators, facultative or obligate plant-feeders (Bongers and Bongers 1998). The nematode inventory shows the parasitism pressure on plants and the functioning of soil micro-foodwebs: do bacteria or fungi play a greater role in the decomposition of organic matter (Djigal et al. 2012)? The structure of nematode communities appears to be a very good indicator of soil functioning. This approach was also applied to other soil organisms such as springtails, classified according to their trophic diet. It was applied to earthworms which were classified into ecological categories based on demographic, behavioural and functional properties. The roles played by epigeic, anecic and endogeic earthworm species on soil functioning are so different that they are generally studied separately. The microbial compartment has been generally well evaluated, especially when considered as a whole. The most common microbial indicators are microbial biomass, DNA and RNA concentrations, 16S and 18S gene richness and total heterotrophic respiration. Genetic tools are also used for gene coding the various enzymes to describe the density of functional groups of micro-organisms, especially those involved in the nitrogen cycle and in functions such as ammonification, nitrification, denitrification, etc. However, almost nothing is known about the micro-organisms involved in the phosphorus cycle. This shows that it is essential to carry out studies to determine the relationship between organisms and functions before proposing biological indicators for the provision of ecosystem services.

Interactions between organisms may be another line of research. A soil that is characterized by great biodiversity and by numerous, complex trophic and non-trophic interactions is considered to be more stable and more resilient (Bengtsson 1998; Loreau and Thébault 2006). It indicates an environment with available trophic resources and a diversity of habitats. It might be possible to produce a Global Biological Index similar to the Biological Index of Soil Quality IBQS (Ruiz-Camacho et al. 2009) which takes account of all macroinvertebrates at a given site. Such an index could deal simultaneously with all functional groups (decomposers, detritivores, trophic regulators, engineers, etc.). This would represent the diversity of interactions in a soil and could help to assess the services provided by soil.

Ecological Functions as Indicators

Four aggregate ecological functions fundamental to ecosystem services have also been studied as potential indicators of soil functioning: (i) for carbon transformation: the dynamics of organic matter decomposition, soil respiration, amount and forms of organic matter; (ii) nutrient cycling: pH, nitrogen mineralization; (iii) soil structure maintenance: bulk density, porosity, structural stability and (iv) biological population regulation: plant damage (Kibblewhite et al. 2008).

Conclusion 3

Including soil biodiversity in the design of cropping systems is still very difficult as soil biodiversity has not been sufficiently well modelled for incorporation into crop models. It is still difficult to find articles in the scientific literature on quantitative causal models linking biological parameters, functions and services. Even when there are clear stable correlations, it is often very difficult to identify the underlying causalities.

Research needs to be carried out to improve our understanding how soil organisms respond to disturbance or restorative practices, taking account of the spatial and temporal variability of biological parameters. Only then will it be possible to build indicators for evaluating and designing agro-ecological cropping systems. Many more genetic approaches such as microgenomics, metagenomics, barcoding, etc., should be developed to characterize biological parameters. Much research remains to be undertaken to define functional traits and response traits for soil organisms. Little attention has been paid to taxa such as protozoa and archaea although their functional roles seem very important. It is essential to analyse functional groups, soil biological parameters and ecosystem services at the same time and in the same site to increase the reference frame for the indicators.

Current studies rarely move towards developing indicators that can be used by farmers, or more generally, grassroots players. This lack of suitable soil biodiversity indicators remains a serious obstacle for the improvement of agro-ecological systems using a step-by-step design approach.

General Conclusion

Throughout this article, attention has been drawn to the gulf between cropping system design approaches that have been developed in agronomy and the extensive pool of knowledge that has been developed by ecologists on soil biodiversity. More extensive knowledge of the effects of cropping systems on soil biodiversity and associated ecosystem services is required to develop models for anticipating the impacts of farming practices on soil biodiversity and ecosystem services and to develop easily measured soil biodiversity indicators that can be used by farmers and field technicians. Such progress can only be achieved by increasing collaboration between agronomists and soil ecologists, to move from laboratory to field scale, and incorporating the "cropping system" concept into soil biodiversity studies.

When bringing together agronomy and ecology sciences, the knowledge and experience of farmers are essential for determining work schedules, the effects of waterlogging and particular characteristics of local soils, etc. Moreover, farmers' expertise in managing the trade-off between various services must surely be a source of inspiration for scientists when designing options for sustainable intensification of agriculture. As underlined by Altieri (1999, 2002) or Meynard et al. (2012), the development of innovative cropping systems based on agro-ecology relies on an increase in scientific knowledge together with the recognition of local knowledge held by farmers. Just as in the past, the cropping systems of the future will not be built by ecologists and agronomists alone. Agro-ecology stands at the crossroads between disciplines where many fascinating avenues remain to be explored.

Acknowledgements The authors thank Laurent Cournac, Nicolas Dauphin and Harry Ozier-Lafontaine for the helpful discussions on a previous draft of this paper.

References

Allen MF, Lansing J, Allen EB (2002) The role of mycorrhizal fungi in the composition and dynamics of plant communities: a scaling issue. In: Esser K et al (eds) Progress in botany. Springer, Berlin, pp 344–367

Altieri MA (1999) The ecological role of biodiversity in agroecosystems. Agric Ecosyst Environ 74:19–31. doi:10.1016/S0167-8809(99)00028-6

Altieri MA (2002) Agroecology: the science of natural resource management for poor farmers in marginal environments. Agric Ecosyst Environ 93:1–24. doi:10.1016/S0167-8809(02)00085-3

Altieri MA, Funes-Monzote FR, Petersen P (2012) Agroecologically efficient agricultural systems for smallholder farmers: contributions to food sovereignty. Agron Sustain Dev 32:1–13. doi:10.1007/s13593-011-0065-6

Amador JA, Görres JH (2007) Microbiological characterization of the structures built by earthworms and ants in an agricultural field. Soil Biol Biochem 39:2070–2077. doi:10.1016/j.soilbio.2007.03.010

Anderson JM (1995) Soil organisms as engineers: microsite modulation of macroscale processes. In: Jones CG, Lawton JH (eds) Linking species and ecosystems. Chapman & Hall, London, pp 94–106

Angers DA, Pesant A, Vigneux J (1992) Early cropping-induced changes in soil aggregation, organic matter and microbial biomass. Soil Sci Soc Am J 56:115–119. doi:10.2136/sssaj1992.03615995005600010018x

Arancon NQ, Galvis P, Edwards CA, Yardim EN (2003) The trophic diversity of nematode communities in soils treated with vermicompost. Pedobiologia 47:736–740. doi:10.1016/S0031-4056(04)70261-9

Arancon NQ, Edwards CA, Yardim EN et al (2007) Suppression of two-spotted spider mite (*tetranychus urticae*), mealybugs (*pseudococcus*) and aphid (*myzus persicae*) populations and damage by vermicomposts. Crop Prot 26:26–39. doi:10.1016/j.cropro.2006.03.013

Asuming-Brempong S, Gantner S, Adiku SGK et al (2008) Changes in the biodiversity of microbial populations in tropical soils under different fallow treatments. Soil Biol Biochem 40:2811–2818. doi:10.1016/j.soilbio.2008.08.010

Barrios E (2007) Soil biota, ecosystem services and land productivity. Ecol Econ 64:269–285. doi:10.1016/j.ecolecon.2007.03.004

Barros E, Curmi P, Hallaire V (2001) The role of macrofauna in the transformation and reversibility of soil structure of an oxisol in the process of forest to pasture conversion. Geoderma 100:193–213. doi:10.1016/S0016-7061(00)00086-0

Beauchamp EG, Hume DJ (1997) Agricultural soil manipulation: the use of bacteria, manuring, and ploughing. In: Van Elsas JD (ed) Modern soil microbiology. Marcel Dekker, New York, pp 643–664

Bellande A, Paul JL, Cabidoche YM (1994) Paysans, systèmes et crise: travaux sur l'agraire haïtien. Tome 3 : dynamique de l'exploitation paysanne. SACAD/FAMV, Pointe à Pitre/Port Au Prince, 476 pp

Bengtsson J (1998) Which species? What kind of diversity? Which ecosystem function? Some problems in studies of relations between biodiversity and ecosystem function. Appl Soil Ecol 10:191–199. doi:10.1016/S0929-1393(98)00120-6

Bergez JE, Colbach N, Crespo O et al (2010) Designing crop management systems by simulation. Eur J Agron 32:3–9. doi:10.1016/j.eja.2009.06.001

Bernard L, Chapuis-Lardy L, Razafimbelo T et al (2012) Endogeic earthworms shape bacterial functional communities and affect organic matter mineralization in a tropical soil. ISME J 6:213–222. doi:10.1038/ismej.2011.87

Bispo A, Blanchart E, Delmas AB, Laval K (2011) Indicateurs de la qualité des sols. In: Girard MC et al (eds) Sols et environnement, 2nd edn. Dunod, Paris, pp 509–527

Blanchart E, Lavelle P, Braudeau E et al (1997) Regulation of soil structure by geophagous earthworm activities in humid savannas of Côte d'Ivoire. Soil Biol Biochem 29:431–439. doi:10.1016/S0038-0717(96)00042-9

Blanchart E, Bernoux M, Sarda X et al (2007) Effect of direct seeding mulch-based systems on soil carbon storage and macrofauna in Central Brazil. Agric Conspec Sci 72:81–87

Blanchart E, Marilleau N, Chotte JL et al (2009) SWORM: an agent-based model to simulate the effect of earthworms on soil structure. Eur J Soil Sci 60:13–21. doi:10.1111/j.1365-2389.2008.01091.x

Blouin M, Zuily-Fodil Y, Pham-Thi AT et al (2005) Belowground organism activities affect plant aboveground phenotype, inducing plant tolerance to parasites. Ecol Lett 8:202–208. doi:10.1111/j.1461-0248.2004.00711.x

Bongers T, Bongers M (1998) Functional diversity of nematodes. Appl Soil Ecol 10:239–251. doi:10.1016/S0929-1393(98)00123-1

Bossio DA, Scow KM, Gunapala N et al (1998) Determinants of soil microbial communities: effects of agricultural management, season, and soil type on phospholipid fatty acid profiles. Microb Ecol 36:1–12. doi:10.1007/s002489900087

Boswell EP, Koide RT, Shumway DL et al (1998) Winter wheat cover cropping, VA mycorrhizal fungi and maize growth and yield. Agric Ecosyst Environ 67:55–65. doi:10.1016/S0167-8809(97)00094-7

Brussaard L (1998) Soil fauna, guilds, functional groups and ecosystem processes. Appl Soil Ecol 9:123–135. doi:10.1016/S0929-1393(98)00066-3

Brussaard L, Behan-Pelletier VM, Bignell DE et al (1997) Biodiversity and ecosystem functioning in soil. AMBIO 26:563–570

Brussaard L, de Ruiter PC, Brown GG (2007) Soil biodiversity for agricultural sustainability. Agric Ecosyst Environ 121:233–244. doi:10.1016/j.agee.2006.12.013

Cadet P, Floret C (1999) Effect of plant parasitic nematodes on the sustainability of a natural fellow cultural system in the Sudano-Sahelian area in Senegal. Eur J Soil Biol 35:91–97. doi:10.1016/S1164-5563(99)00208-3

Cadet P, Spaull VW, McArthur DG (2002) Role of plant parasitic nematodes and abiotic soil factors in growth heterogeneity of sugarcane on a sandy soil in South Africa. Plant Soil 246:259–271. doi:10.1023/A:1020624114434

Cairns J (2000) Setting ecological restoration goals for technical feasibility and scientific validity. Ecol Eng 15:171–180. doi:10.1016/S0925-8574(00)00068-9

Capowiez Y, Cadoux S, Bouchant P et al (2009) The effect of tillage type and cropping system on earthworm communities, macroporosity and water infiltration. Soil Tillage Res 105:209–216. doi:10.1016/j.still.2009.09.002

Carter MR (1986) Microbial biomass as an index for tillage-induced changes in soil biological properties. Soil Tillage Res 7:29–40. doi:10.1016/0167-1987(86)90005-X

Chan KY (2001) An overview of some tillage impacts on earthworm population and diversity–implications for functioning in soils. Soil Tillage Res 57:179–191. doi:10.1016/S0167-1987(00)00173-2

Chapuis-Lardy L, Brauman A, Bernard L et al (2010) Effect of the endogeic earthworm *pontoscolex corethrurus* on the microbial structure and activity related to CO_2 and N_2O fluxes from a tropical soil (Madagascar). Appl Soil Ecol 45:201–208. doi:10.1016/j.apsoil.2010.04.006

Chauvel A, Grimaldi M, Barros E et al (1999) Pasture damage by an Amazonian earthworm. Nature 398:32–33. doi:10.1038/17946

Chen M, Chen B, Marschner P (2008) Plant growth and soil microbial community structure of legumes and grasses grown in monoculture or mixture. J Environ Sci 20:1231–1237. doi:10.1016/S1001-0742(08)62214-7

Clapperton MJ, Miller JJ, Larney FJ et al (1997) Earthworm populations as affected by longterm tillage practices in southern Alberta, Canada. Soil Biol Biochem 29:631–633

Clermont-Dauphin C, Meynard JM, Cabidoche YM (2003) Devising fertiliser recommendations for diverse cropping systems in a region: the case of bean maize intercropping in a tropical highland of Haiti. Agronomie 23:673–681. doi:10.1051/agro:2003046

Clermont-Dauphin C, Cabidoche YM, Meynard JM (2004) Effects of intensive monocropping of bananas on properties of volcanic soils in the uplands of the French West Indies. Soil Use Manag 20:105–113. doi:10.1079/SUM2003231

Clermont-Dauphin C, Cabidoche YM, Meynard JM (2005) Diagnosis on the sustainability of an upland cropping system of southern Haiti. Agric Ecosyst Environ 105:221–234. doi:10.1016/j.agee.2004.03.008

Clermont-Dauphin C, Suwannang N, Grünberger O, Hammecker C, Maeght JL (2010) Yield of rice under water and soil salinity risks in farmers' fields in northeast Thailand. Field Crop Res 118:289–296. doi:10.1016/j.fcr.2010.06.009

Clermont-Dauphin C, Suvannang N, Hammecker C, Cheylan V, Pongwichian P, Do FC (2013) Unexpected absence of control of rubber tree growth by soil water shortage in dry subhumid climate. Agron Sustain Dev 33:531–538. doi:10.1007/s13593-012-0129-2

Cluzeau D, Guernion M, Chaussod R et al (2012) Integration of biodiversity in soil quality monitoring: baselines for microbial and soil fauna parameters for different land-use types. Eur J Soil Biol 49:63–72. doi:10.1016/j.ejsobi.2011.11.003

Colbach N, Meynard JM (1995) Soil tillage and eyespot – influence of crop residue distribution on disease development and infection cycles. Eur J Plant Pathol 101:601–611. doi:10.1007/BF01874864

Coll P, Le Cadre E, Blanchart E, Hinsinger P et al (2011) Organic viticulture and soil quality: a long-term study in southern France. Appl Soil Ecol 50:37–44. doi:10.1016/j.apsoil.2011.07.013

Coq S, Barthès BG, Oliver R et al (2007) Earthworm activity affects soil aggregation and soil organic matter dynamics according to the quality and localization of crop residues – an experimental study (Madagascar). Soil Biol Biochem 39:2119–2128. doi:10.1016/j.soilbio.2007.03.019

Coquil X, Blouet A, Fiorelli JL et al (2009) Conception de systèmes laitiers en agriculture biologique: une entrée agronomique. INRA Prod Anim 22:221–234

Daily GC, Alexander S, Ehrlich PR et al (1997) Ecosystem services: benefits supplied to human society by natural ecosystems. Issues Ecol 2:1–16

Dauber J, Wolters V (2000) Microbial activity and functional diversity in the mounds of three different ant species. Soil Biol Biochem 32:93–99. doi:10.1016/S0038-0717(99)00135-2

Dauber J, Schroeter D, Wolters V (2001) Species specific effects of ants on microbial activity and N-availability in the soil of an old-field. Eur J Soil Biol 37:259–261. doi:10.1016/S1164-5563(01)01094-9

De Leon-Gonzales F, Fuentes-Ponce M, Payán-Zelaya F (2012) Earthworms and agricultural systems management: emphasis on the Latin American region. Dyn Soil Dyn Plant 6(SI 1):14–25
De Wit CT, Van Keulen H, Seligman NG et al (1988) Application of interactive multiple goal programming techniques for analysis and planning of regional agricultural development. Agric Syst 26:211–230. doi:10.1016/0308-521X(88)90012-1
Decaëns T (2010) Macroecological patterns in soil communities. Global Ecol Biogeogr 19:287–302. doi:10.1111/j.1466-8238.2009.00517.x
Decaëns T, Galvin JH, Amezquita E (2001) Propriétés des structures produites par les ingénieurs écologiques à la surface du sol d'une savane colombienne. CR Acad Sci Biol 324:465–478
Decaëns T, Jiménez JJ, Gioia C et al (2006) The values of soil animals for conservation biology. Eur J Soil Biol 42:S23–S38. doi:10.1016/j.ejsobi.2006.07.001
Derpsch R (2008) No-tillage and conservation agriculture: a progress report agricultural. In: Goddard T et al (eds) No-till farming systems. WASWC, Bangkok, pp 7–39
Dighton J, Tuininga AR, Gray DM et al (2004) Impacts of atmospheric deposition on New Jersey pine barrens forest soils and communities of ectomycorrhizae. For Ecol Manag 201:131–144. doi:10.1016/j.foreco.2004.07.038
Djigal D, Saj S, Rabary B et al (2012) Mulch type affects soil biological functioning and crop yield of conservation agriculture systems in a long-term experiment in Madagascar. Soil Tillage Res 118:11–21. doi:10.1016/j.still.2011.10.008
Doran JW, Coleman DC, Bezdicek DF et al (1994) Defining soil quality for a sustainable environment. Soil Science Society of America Spec Publ n° 35, Soil Sci Soc Am Inc and Am Soc Agron Inc, Madison
Doré T, Meynard JM, Sebillotte M (1997) A diagnostic method for assessing regional variations in crop yield. Agric Syst 54:169–188. doi:10.1016/S0308-521X(96)00084-4
Doré T, Clermont-Dauphin C, Crozat Y et al (2008) Methodological progress in on-farm regional agronomic diagnosis. A review. Agron Sustain Dev 28:151–161. doi:10.1051/agro:2007031
Doube BM, Buckerfield JC, Kirkegaard JA (1994) Short-term effects of tillage and stubble management on earthworm populations in cropping systems in southern New South Wales. Aust J Agric Res 45:1587–1600. doi:10.1071/AR9941587
DuPont ST, Ferris H, Van Horn M (2009) Effects of cover crop quality and quantity on nematode-based soil food webs and nutrient cycling. Appl Soil Ecol 41:157–167. doi:10.1016/j.apsoil.2008.10.004
Edwards CA, Bohlen PJ (1996) Biology and ecology of earthworms, 3rd edn. Chapman & Hall, London
Edwards CA, Lofty JR (1982) The effects of direct drilling and minimal cultivation on earthworm populations. J Appl Ecol 19:723–734. doi:10.2307/2403277
El Titi A, Ipach A (1989) Soil fauna in sustainable agriculture: results of an integrated farming system at Lautenbach, FRG. Agric Ecosyst Environ 27:561–572. doi:10.1016/0167-8809(89)90117-5
Elton CS (1958) The ecology of invasions by animals and plants. Methuen, London
Feng Y, Motta AC, Reeves DW et al (2003) Soil microbial communities under conventional-till and no-till continuous cotton systems. Soil Biol Biochem 35:1693–1703. doi:10.1016/j.soilbio.2003.08.016
Ferris H, Matute MM (2003) Structural and functional succession in the nematode fauna of a soil food web. Appl Soil Ecol 23:93–110. doi:10.1016/S0929-1393(03)00044-1
Förster B, Muroya K, Garcia M (2006) Plant growth and microbial activity in a tropical soil amended with faecal pellets from millipedes and woodlice. Pedobiologia 50:281–290. doi:10.1016/j.pedobi.2006.03.001
Fox RH, Bandel VA (1986) Nitrogen utilization with no-tillage. In: Sprague MA, Triplett GB (eds) No-tillage and surface-tillage agriculture: the tillage revolution. Wiley, New York, pp 117–148
Fuentes M, Govaerts B, De Leon F et al (2009) Fourteen years of applying zero and conventional tillage, crop rotation and residue management systems and its effect on physical and chemical soil quality. Eur J Agron 30:228–237. doi:10.1016/j.eja.2008.10.005

Giller KE, Cadisch G (1995) Future benefits from biological nitrogen fixation: an ecological approach to agriculture. Plant Soil 174:255–277. doi:10.1007/BF00032251

Gobat JM, Aragno M, Matthey W (1998) Le sol vivant: bases de pédologie, biologie des sols. Collection gérer l'environnement, Presses Polytechniques et Universitaires Romandes, Lausanne

Hansen S, Engelstad F (1999) Earthworm populations in a cool and wet district as affected by tractor traffic and fertilization. Appl Soil Ecol 13:237–250. doi:10.1016/S0929-1393(99)00037-2

Hart MM, Klironomos JN (2002) Diversity of arbuscular mycorrhizal fungi and ecosystem functioning. In: Van der Heijden MGA, Sanders I (eds) Ecological studies. Springer, Berlin, pp 226–242

Hénin S, Gras R, Monnier G (1969) Le profil cultural: l'état physique du sol et ses conséquences agronomiques. Masson et Cie, Paris

Hogh-Jensen H, Schjoerring JK, Soussana JF (2002) The influence of phosphorous deficiency on growth and nitrogen fixation of white clover plants. Ann Bot 90:745–753. doi:10.1093/aob/mcf260

Holland JM (2004) The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agric Ecosyst Environ 103:1–25. doi:10.1016/j.agee.2003.12.018

Holt JA (1998) Microbial activity in the mounds of some Australian termites. Appl Soil Ecol 9:183–187. doi:10.1016/S0929-1393(98)00073-0

House GJ, Parmelee RW (1985) Comparison of soil arthropods and earthworms from conventional and no-tillage agroecosystems. Soil Tillage Res 5:351–360. doi:10.1016/S0167-1987(85)80003–9

Hungria M, Franchini JC, Osvaldino BJ et al (2009) Soil microbial activity and crop sustainability in a long-term experiment with three soil-tillage and two crop-rotation systems. Appl Soil Ecol 42:288–296. doi:10.1016/j.apsoil.2009.05.005

Husson O (2013) Redox potential (Eh) and pH as drivers of soil/plant/microorganism systems: a transdisciplinary overview pointing to integrative opportunities for agronomy. Plant Soil 362:389–417. doi:10.1007/s11104-012-1429-7

Husson O, Charpentier H, Raharison T et al (2012) Climat de moyenne altitude (600–1100 m) avec longue saison sèche (> 6 mois) Lac Alaotra et Moyen Ouest. In: CIRAD (ed) Manuel pratique du semis direct à Madagascar -Volume IV-, Cirad, Antananarivo, pp 4–60

Johnson NC, Copeland PJ, Crookston RK et al (1992) Mycorrhizae: possible explanation for yield decline with continuous corn and soybean. Agron J 84:387–390

Johnson D, Booth RE, Whiteley AS et al (2003) Plant community composition affects the biomass, activity and diversity of microorganisms in limestone grassland soil. Eur J Soil Biol 54:671–677. doi:10.1046/j.1365-2389.2003.00562.x

Jones CG, Lawton JH, Shachak M (1994) Organisms as ecosystem engineers. Oikos 69:373–386. doi:10.2307/3545850

Jouquet P, Tessier D, Lepage M (2004) The soil structural stability of termite nests: role of clays in *macrotermes bellicosus* (isoptera, macrotermitinae) mound soils. Eur J Soil Biol 40:23–29. doi:10.1016/j.ejsobi.2004.01.006

Kahindi JHP, Woomer P, George T et al (1997) Agricultural intensification, soil biodiversity and ecosystem function: the role of nitrogen fixing bacteria. Appl Soil Ecol 6:55–76. doi:10.1016/S0929-1393(96)00151-5

Kaneko N (1999) Effect of millipede *parafontaria tonominea* attems (diplopoda: xystomidae) adult on soil biological activities: microcosm experiment. Ecol Res 14:271–279. doi:10.1046/j.1440-1703.1999.143302.x

Karlen DL, Mausbach MJ, Doran JW et al (1997) Soil quality: a concept, definition, and framework for evaluation. Soil Sci Soc Am J 61:4–10

Karlen DL, Ditzler CA, Andrews S (2003) Soil quality: why and how? Geoderma 114:145–156. doi:10.1016/S0016-7061(03)00039-9

Kaschuk G, Alberton O, Hungria M (2010) Three decades of soil microbial biomass studies in Brazilian ecosystems: lessons learned about soil quality and indications for improving sustainability. Soil Biol Biochem 42:1–13. doi:10.1016/j.soilbio.2009.08.020

Keating A, McCown RL (2001) Advances in farming systems analysis and intervention. Agric Syst 70:555–579. doi:10.1016/S0308-521X(01)00059-2
Kennedy N, Edwards S, Clipson N (2005) Soil bacterial and fungal community structure across a range of unimproved and semi-improved upland grasslands. Microb Ecol 50:463–473. doi:10.1007/s00248-005-0256-2
Kibblewhite MG, Ritz K, Swift MJ (2008) Soil health in agricultural systems. Philos Trans R Soc B 363:685–701. doi:10.1098/rstb.2007.2178
Kihara J, Bationo A, Waswa B (2012) Effect of reduced tillage and mineral fertilizer application on maize and soybean productivity. Exp Agric 48:159–175. doi:10.1017/S0014479711000895
Kladivko EJ (2001) Tillage systems and soil ecology. Soil Tillage Res 61:61–76. doi:10.1016/S0167-1987(01)00179-9
Kladivko EJ, Akhouri NM, Weesies G (1997) Earthworm populations and species distributions under no-till and conventional tillage in Indiana and Illinois. Soil Biol Biochem 29:613–615. doi:10.1016/S0038-0717(96)00187-3
Krumins JA, Dighton J, Gray D et al (2009) Soil microbial community response to nitrogen enrichment in two scrub oak forests. For Ecol Manag 258:1383–1390. doi:10.1016/j.foreco.2009.06.046
Lafont A, Risède JM, Loranger-Merciris G et al (2007) Effects of the earthworm *pontoscolex corethrurus* on banana plants infected with the plant-parasitic nematode *radopholus similis*. Pedobiologia 51:311–318. doi:10.1016/j.pedobi.2007.05.004
Lançon J, Reau R, Cariolle M et al (2008) Elaboration à dire d'experts de systèmes de culture innovants. In: Reau R, Doré T (eds) Systèmes de culture innovants et durables: quelles méthodes pour les mettre au point et les évaluer. Educagri, Dijon, pp 91–108
Lavelle P (1997) Faunal activities and soil processes: adaptive strategies that determine ecosystem function. Adv Ecol Res 27:93–132. doi:10.1016/S0065-2504(08)60007-0
Lavelle P, Spain AV (2001) Soil ecology. Kluwer Scientific, Amsterdam, 654p
Lavelle P, Blanchart E, Martin A et al (1993) A hierarchical model for decomposition in terrestrial ecosystems: application to soils of the humid tropics. Biotropica 25:130–150. doi:10.2307/2389178
Lavelle P, Blouin M, Boyer J et al (2004) Plant parasite control and soil fauna diversity. CR Acad Sci Biol 327:629–638. doi:10.1016/j.crvi.2004.05.004
Lavelle P, Decaëns T, Aubert M et al (2006) Soil invertebrates and ecosystem services. Eur J Soil Biol 42:S3–S15. doi:10.1016/j.ejsobi.2006.10.002
Le Bail M, Meynard JM (2003) Yield and protein concentration of spring malting barley: the effects of cropping systems in the Paris basin (France). Agronomie 23:13–27. doi:10.1051/agro:2002029
Le Bayon RC, Binet F (2006) Earthworms change the distribution and availability of phosphorus in organic substrates. Soil Biol Biochem 38:235–246. doi:10.1016/j.soilbio.2005.05.013
Le Roux X, Barbault R, Baudry J et al (2008) Agriculture et Biodiversité Valoriser les synergies. Synthèse du rapport d'expertise – 2ème partie. Expertise scientifique collective, INRA, Paris, pp 38–113
Legrand A, Gaucherel C, Baudry J et al (2011) Long term effects of organic, conventional and integrated crop systems on carabids. Agron Sustain Dev 31:515–524. doi:10.1007/s13593-011-0007-3
Lehmann J, Rillig MC, Thies J et al (2011) Biochar effects on soil biota – a review. Soil Biol Biochem 43:1812–1836. doi:10.1016/j.soilbio.2011.04.022
Leroy BLM, Schmidt O, van den Bossche A et al (2008) Earthworm population dynamics as influenced by the quality of exogenous organic matter. Pedobiologia 52:139–150. doi:10.1016/j.pedobi.2008.07.001
Lilleskov EA, Fahey TJ, Horton TR et al (2002) Belowground ectomycorrhizal fungal community change over a nitrogen deposition gradient in Alaska. Ecology 83:104–115. doi:10.2307/2680124
Logan TJ, Lal R, Dick WA (1991) Tillage systems and soil properties in North-America. Soil Tillage Res 20:241–270. doi:10.1016/0167-1987(91)90042-V

López-Hernández D (2001) Nutrient dynamics (C, N and P) in termite mounds of *nasutitermes ephratae* from savannas of the Orinoco llanos (Venezuela). Soil Biol Biochem 33:747–753. doi:10.1016/S0038-0717(00)00220-0

Loranger-Merciris G, Cabidoche YM, Deloné B et al (2012) How earthworm activities affect banana plant response to nematode parasitism. Appl Soil Ecol 52:1–8. doi:10.1016/j.apsoil.2011.10.003

Loreau M, Thébault E (2006) Food webs and the relationship between biodiversity and ecosystem functioning. In: de Ruiter P, Wolters W, Moore JC (eds) Dynamic food webs. Elsevier, Amsterdam, pp 270–282

Lubbers IM, van Groeningen KJ, Fonte SJ et al (2013) Greenhouse-gas emissions from soils increased by earthworms. Nat Clim Change. doi:10.1038/NCLIMATE1692

Manetti PL, Lopez AN, Clemente NL et al (2010) Tillage system does not affect soil macrofauna in southeastern Buenos Aires province, Argentina. Span J Agric Res 8:377–384

Marschner P, Yang CH, Lieberei R (2001) Soil and plant specific effects on bacterial community composition in the rhizosphere. Soil Biol Biochem 33:1437–144. doi:10.1016/S0038-0717(01)00052-9

Martin A (1991) Short- and long-term effects of the endogeic earthworm *millonia anomala* (megassolecidae, oligochaeta) of tropical savannas, on soil organic matter. Biol Fertil Soil 11:234–238. doi:10.1007/BF00335774

McNeely JA (1994a) Lessons from the past: forest and biodiversity. Biodivers Conserv 3:3–20. doi:10.1007/BF00115329

McNeely JA (1994b) Protected areas for 21st century: working to provide benefits to society. Biodivers Conserv 3:390–405. doi:10.1007/BF00057797

Melero S, López-Garrido R, Madejón E et al (2009) Long-term effects of conservation tillage on organic fractions in two soils in southwest of Spain. Agric Ecosyst Environ 133:68–74. doi:10.1016/j.agee.2009.05.004

Meynard JM (2012) Innovating in cropping and farming systems. In: Coudel E et al (eds) Renewing innovation systems in agriculture and food: how to go towards more sustainability? Wageningen Academic, Wageningen, pp 89–108

Meynard JM, Doré T, Habib R (2001) L'évaluation et la conception de systèmes de culture pour une agriculture durable. Dossier établi pour les responsables du département environnement et agronomie. CR Acad Agric Fr 87:223–236

Meynard JM, Cerf M, Guichard L et al (2002) Which decision support tools for the environmental management of nitrogen? Agronomie 22:817–829. doi:10.1051/agro:2002064

Meynard JM, Dedieu B, Bos AP (2012) Re-design and co-design of farming systems. An overview of methods and practices. In: Darnhofer I, Gibon D, Dedieu B (eds) Farming systems research into the 21st century: the new dynamic. Springer, Dordrecht, pp 407–432

Meynard JM, Messéan A, Charlier A et al (2013) Freins et leviers à la diversification des cultures. Etude au niveau des exploitations agricoles et des filières. Synthèse du rapport d'étude, INRA, 52p. http://institut.inra.fr/Missions/Eclairer-decisions/Etudes/Toutes-les-actualites/Diversification-des-cultures

Mijangos I, Perez R, Albizu I et al (2006) Effects of fertilization and tillage on soil biological parameters. Enzym Microb Technol 40:100–106. doi:10.1016/j.enzmictec.2005.10.043

Millennium Ecosystem Assessment (2005) Ecosystems and human well-being: policy responses. Island Press, Washington, DC

Mischler P, Lheureux S, Dumoulin F et al (2009) Huit fermes de Grande culture engagées en production intégrée réduisent les pesticides sans baisse de Marge. Le Courrier de l'Environnement 57:73–91

Parkin TB, Berry EC (1999) Microbial nitrogen transformations in earthworms burrows. Soil Biol Biochem 31:1765–1771. doi:10.1016/S0038-0717(99)00085-1

Passioura JB (1996) Simulation models: science, snake oil, education or engineering? Agron J 88:690–694

Pelosi C, Bertrand M, Makowski D et al (2008) WORMDYN: a model of *lumbricus terrestris* population dynamics in agricultural fields. Ecol Model 218:219–234. doi:10.1016/j.ecolmodel.2008.07.002

Pelosi C, Bertrand M, Capowiez Y et al (2009) Earthworm collection from agricultural fields: comparisons of selected expellants in presence/absence of hand-sorting. Eur J Soil Biol 45:176–183. doi:10.1016/j.ejsobi.2008.09.013

Pérès G, Vandenbulcke F, Guernion M et al (2011) Earthworm indicators as tools for soil monitoring, characterization and risk assessment. An example from the national bioindicator programme (France). Pedobiologia 54:S77–S87. doi:10.1016/j.pedobi.2011.09.015

Plenchette C, Perrin R (1992) Evaluation of the greenhouse of the effects of fungicides on the development of mycorrhiza on leek and wheat. Mycorrhiza 1:59–62. doi:10.1007/BF00206137

Plenchette C, Clermont-Dauphin C, Meynard JM, Fortin A (2005) Management of arbuscular mycorrhizal fungi in cropping systems. Can J Plant Sci 85:31–40

Pommeresche R, Loes AK (2009) Relations between agronomic practice and earthworms in Norwegian arable soils. Dyn Soil Dyn Plant 3(SI 2):129–142

Prost L, Cerf M, Jeuffroy MH (2012) Lack of consideration for end-users during the design of agronomic models – a review. Agron Sustain Dev 32:581–594. doi:10.1007/s13593-011-0059-4

Pulleman M, Creamer R, Hamer U et al (2012) Soil biodiversity, biological indicators and soil ecosystem services-an overview of European approaches. Curr Opin Environ Sustain 4:529–538. doi:10.1016/j.cosust.2012.10.009

Queinnec M (2013) Caractérisation et typologie des exploitations agricoles du Moyen Ouest du Vakinankaratra, Madagascar. MSc thesis Supagro Montpellier, Paris, 58 p

Reau R, Monnot LA, Schaub A et al (2012) Les ateliers de conception de systèmes de culture pour construire, évaluer et identifier des prototypes prometteurs. Innov Agron 20:5–33

Roger-Estrade J, Anger C, Bertrand M et al (2010) Tillage and soil ecology: partners for sustainable agriculture. Soil Tillage Res 111:33–40. doi:10.1016/j.still.2010.08.010

Rosas-Medina AM, de Leon-Gonzalez F, Flores-Macias A et al (2010) Effects of tillage, sampling date and soil depth on earthworm population on maize monoculture with continuous Stover restitutions. Soil Tillage Res 108:37–42. doi:10.1016/j.still.2010.03.008

Rossing WAH, Meynard JM, van Ittersum MK (1997) Model-based explorations to support development of sustainable farming systems: case studies from France and the Netherlands. Eur J Agron 7:271–283. doi:10.1016/S1161-0301(97)00042-7

Rousseau GX, Silva PRS, Carvalho CJR (2010) Earthworms, ants and other arthropods as soil health indicators in traditional and no-fire agro-ecosystems from eastern Brazilian Amazonia. Acta Zool Mex 2:117–134

Ruiz-Camacho N, Velasquez E, Pando A (2009) Indicateurs synthétiques de la qualité du sol. Etude et Gestion des Sols 16:323–338

Sarr M, Agbogba C, Russel-Smith A (2001) Effects of soil faunal activity and woody shrub on water infiltration rates in a semi-arid fallow of Senegal. Appl Soil Ecol 16:283–290. doi:10.1016/S0929-1393(00)00126-8

Schneider A, Flénet F, Dumans P et al (2010) Diversifier les rotations céréalières notamment avec du pois et du colza –données récentes d'expérimentations et d'études. OCL Ol Corps Gras Li 17:301–311

Sebillotte M (1974) Agronomie et agriculture: essai d'analyse des tâches de l'agronome. Cahiers ORSTOM, série Biologie 24:3–25

Sebillotte M (1980) Rôles de la prairie dans la succession culturale. Fourrages 83:79–124

Séguy L, Bouzinac S, Maeda N et al (1998) Semis direct du cotonnier en Grande culture motorisée. Agric Dév 17:4–22

Serpantié G (2009) L'agriculture de conservation à la croisée des chemins (afrique, Madagascar). VertigO 9(3):1–21

Shi Y, Lalande R, Hamel C et al (2013) Seasonal variation of microbial biomass, activity, and community structure in soil under different tillage and phosphorus management practices. Biol Fertil Soils 49:803–818. doi:10.1007/s00374-013-0773-y

Simmons BL, Coleman DC (2008) Microbial community response to transition from conventional to conservation tillage in cotton fields. Appl Soil Ecol 40:518–528. doi:10.1016/j.apsoil.2008.08.003

Sisti CPJ, dos Santos H, Kohhann R et al (2004) Change in carbon and nitrogen stocks in soil under 13 years of conventional or zero tillage in southern Brazil. Soil Tillage Res 76:39–58. doi:10.1016/j.still.2003.08.007

Spain AV, Lavelle P, Mariotti A (1992) Stimulation of plant growth by tropical earthworms. Soil Biol Biochem 24:1629–1633. doi:10.1016/0038-0717(92)90161-P

Spedding CRW (1979) An introduction to agricultural systems. Applied Science Publishers, London, 189pp

Spedding TA, Hamel C, Mehuys GR et al (2004) Soil microbial dynamics in maize-growing soil under different tillage and residue management systems. Soil Biol Biochem 36:499–512. doi:10.1016/j.soilbio.2003.10.026

Stirling GR, Cox MC, Ogden-Brown J (2010) Resistance to plant-parasitic nematodes (*pratylenchus zeae* and *meloidogyne javanica*) in erianthus and crosses between erianthus and sugarcane. Int Sugar J 114:30–36

Stork NE, Eggleton P (1992) Invertebrates as determinants and indicators of soil quality. Am J Altern Agric 7:38–45

Tilman D (1999) Global environmental impacts of agricultural expansion: the need for sustainable and efficient practices. Proc Natl Acad Sci U S A 96:5995–6000. doi:10.1073/pnas.96.11.5995

Torsvik V, Ovreas L (2002) Microbial diversity and function in soil: from genes to ecosystems. Curr Opin Microbiol 5:240–245. doi:10.1016/S1369-5274(02)00324-7

Toyota A, Kaneko N, Ito MT (2006) Soil ecosystem engineering by the train millipede *parafontaria laminata* in a Japanese larch forest. Soil Biol Biochem 38:1840–1850. doi:10.1016/j.soilbio.2005.12.015

Trébuil G, Thungwa S (2002) Farmers' Direct sowing practices in rainfed lowland rice in southern Thailand: improving a traditional system. In: Pandey S et al (eds) Direct seeding: research strategies and opportunities, proceedings of the international workshop on direct seeding in Asian rice systems. International Rice Research Institute, Los Baños, pp 99–115

Turbé A, De Toni A, Benito P, Lavelle P, Ruiz N, Van der Putten WH, Labouze E, Mudgal S (2010) Soil biodiversity: functions, threats and tools for policy makers. Bio Intelligence Service, IRD, and NIOO Technical Report 2010–049 for European Commission (DG Environment), Paris

Vian JF, Peigné J, Chaussod R et al (2009) Effects of four tillage systems on soil structure and soil microbial biomass in organic farming. Soil Use Manag 25:1–10. doi:10.1111/j.1475-2743.2008.00176.x

Villemaine R (2011) Eléments d'analyse du dispositif d'innovation autour des SCV dans la région du lac Alaotra, Madagascar. MSc thesis, AgroParisTech, Paris, France, 77 p

Villenave C, Cadet P (1998) Interaction of *helicotylenchus dihystera*, *pratylenchus pseudopratensis* and *tylenchorhynchus gladiotus* on two plants from the Sudano-Sahelian zone of West Africa. Nematropica 28:31–39

Wall DH, Virginia RA (2000) The world beneath our feet: soil biodiversity and ecosystem functioning. In: Raven PR, Williams T (eds) Nature and human society: the quest for a sustainable world. National Academy of Sciences and National Research Council, Washington, DC, pp 225–241

Warkentin BP, Fletcher HF (1977) Soil quality for intensive agriculture. In: Proceedings of the international seminar on soil environment and fertilization management; Intensive Agriculture Society of Science, Soil and Manure; National Institute of Agricultural Science, Tokyo, pp 594–598

Wezel A, Bellon S, Dore T et al (2009) Agroecology as a science, a movement and a practice. A review. Agron Sustain Dev 29:503–515. doi:10.1051/agro/2009004

Wolters V (2001) Biodiversity of soil animals and its function. Eur J Soil Biol 37:221–227. doi:10.1016/S1164-5563(01)01088-3

Wurst S (2010) Effects of earthworms on above- and belowground herbivores. Appl Soil Ecol 45:123–130. doi:10.1016/j.apsoil.2010.04.005

Zhang X, Li Q, Zhu A et al (2012) Effects of tillage and residue management on soil nematode communities in north China. Ecol Indic 13:75–81. doi:10.1016/j.ecolind.2011.05.009

Agroecology and Grassland Intensification in the Caribbean

Maryline Boval, Stéphane Bellon, and Gisele Alexandre

Abstracts Grasslands are a major ecosystem covering about a quarter of earth surface. Grasslands have essential functions including providing high quality food from animal products. Moreover grasslands generally do not compete with crop land and land for other human activities. Grasslands also support the livelihoods of many small holders, a variety of social and cultural services and an important role facing of economic or seasonal food shortages. At the same time, the intensification of livestock production is essential to meet the growing demand for animal products, whereas the expansion of agricultural areas is not unlimited and that it's necessary to promote positive interactions with grazing, the environment and biodiversity. Therefore grasslands represent a major alternative, and should be intensified other than what had conventionally been done so far. The concepts of agroecology provide scientific, methodological and technological basis to design the intensification of pastures. As a science, agroecology can integrate environmental, social and economic dimensions in the management of grassland systems. Considered practical, agroecology promotes traditional and indigenous knowledge and encourages appropriation by most of farmers.

Here two case-studies from the Caribbean and involving different animal species show that there are potential strategies for agroecological management, and how they can be valued for sustainable intensification of grasslands. The first example concerns the mixed grazing goats with heifers, and was considered according to an approach of research bottom-up. The act of mixing goats with heifers has provided

M. Boval (✉) • G. Alexandre
INRA, UR143, Unité de Recherches Zootechniques, Petit-Bourg 97170, Guadeloupe
e-mail: Maryline.boval@antilles.inra.fr; Gisele.alexandre@antilles.inra.fr

S. Bellon
UR0767, Unité de recherche Écodéveloppement, Avignon Cedex 9, France

INRA, UR0767, Unité de recherche Écodéveloppement. Ecodeveloppement, Centre de recherche d'Avignon, Avignon, France
e-mail: Stephane.bellon@avignon.inra.fr

H. Ozier-Lafontaine and M. Lesueur-Jannoyer (eds.), *Sustainable Agriculture Reviews 14: Agroecology and Global Change*, Sustainable Agriculture Reviews 14,
DOI 10.1007/978-3-319-06016-3_6,

a higher performance by 40 % compared to goats reared alone. This gain is explained by a better feeding complementarity between the animal species, combined with a better resilience of goats against parasitism. The non-use of fertilizers and of anthelmintic, the role of heifers to limit theft of goats, are all assets, for a more agro-ecological management of natural pastures. It comes now how to transfer to breeders.

The second case study concerns a widespread traditional practice locally, like in other tropical areas, which has been studied in experimental farms according to an approach of research top-down. It is the tethering practice, for which surveys have revealed a wide variety of technical itineraries. Some itineraries are particularly suited to satisfying performance by about 750 g per day at lower cost and with an equivalent gross margin, to more conventional systems. The use of race and local food resources in various contexts, including the slopes and close crop is possible with a limited investment and use of family labor. All these aspects make this practice agro-ecological and very contemporary, and can be supported by various innovations to sustainably intensify natural pastures.

Keywords Grassland • Natural • Management • Performance • Goat • Cattle • Sustainable

Introduction

In the current context, the need to attain food security is crucial and there is a need for intensification or for expansion of agricultural land. However this latter expansion is no more possible, except considering some biomes, such as woodlands and some natural grassland, also very important for other functions. Grasslands represent 26 % of global land with up to 80 % which are still natural (Fig. 1).

There is potential to better exploit these biomes in order to increase animal production per unit area, but at the same time, this intensification should meet several objectives derived from inter alia, from previous experiences and of the current context of climate change. This grassland intensification should ensure animal products, while continuing providing various other essential functions. Intensification should also be better shared among various production systems and smallholders and be consistent with environment stakes, in order to be sustainable.

“Agroecology” laid the foundations of “how to sustainably intensify” and we have examined how agro-ecological principles are well suited to grasslands, their diversity as well as their multi functions. Based on these premises, we show that agroecological intensification appears as a relevant option for a large part of so-called natural areas.

Case studies of management of tropical grassland in the Caribbean are then valued to confront such premises with research and practical experiences. They appear as consistent with major agro-ecological principles, either from a scientific process, or from practices transmitted, perpetuated and innovated over generations of farmers. These experiences give tangibility to a possible agro-ecological intensification and

Fig. 1 In Guadeloupe, a French island in the Caribbean, various small natural areas are used, as here back mangrove to raise cattle during the dry season. During the wet season, these spaces are no longer usable because of flooding, but other pastures then produce more forage

provide generic elements, which can be a source of innovation. These experiences go beyond theory and they give tangibility to the agro-ecological concepts and to a possible and thus sustainable intensification of grasslands.

After outlining some elements illustrating the best use of grasslands in the current context and interest of agro-ecological principles to get there, this paper aims to show that strategies do exist, like in the case of the Caribbean, to actually achieve an agro-ecological intensification of natural pastures. Furthermore Research need still progress, in order to provide, (i) additional technical options, (ii) more or less long-term tools for decision support to help farmers to adjust their management in their everyday life, (iii) indicators of a sustainable agro-ecological intensification.

Importance of Grasslands Intensification

Grasslands, a Major Biome Still Natural and Available

Pastures are a major biome representing 26 % of global land with up to 80 % still natural. The major part of grasslands is in tropical and developing regions, to meet unprecedented demands on agriculture (FAO 2012). Indeed global demand for agricultural products such as food, feed, and fuel is now a major driver of croplands and

Fig. 2 In Guyana, natural pastures installed after deforestation are an important way to raise cattle. It is better to intensify these existing fields, which also contribute to carbon storage root level to limit deforestation

of pasture expansion, and particularly across much of the developing world. Worldwide demand for agricultural products is expected to increase by 50 % by 2050 (Gibbs et al. 2010) and according to the projection of FAO, global agricultural areas are likely to expand substantially, by about 280 M ha by 2030.

There has been an expansion of 9.6 % in the world's agricultural area over the last 50 years, in arable land, permanent crops and permanent meadows and pastures (O'Mara 2012). But since 1991, the total area has been static and with discrepancies among various countries of the world. While in developed countries the agricultural land area, decreased by more than – 34 % between 1995 and 2007 (by 412 million ha, including pastures and permanent cropland), developing countries saw increases of nearly +17.1 % (by 400 million ha, Gibbs et al. 2010).

At the same time, there is a consensus to say that increasing yields on existing agricultural land is a key component of food security, without additional expansion (Wirsenius et al. 2010). Therefore, there is a need to improve productivity from the existing land, since the conversion of additional poorer quality land to agricultural uses may lead to an overall decline in existing agricultural land productivity (O'Mara 2012). This suggests that if trends in agricultural expansion for 1980–2000 persist and in order to meet the growing demand for food, feed and fuel, areas of arable land, as existing in most tropical areas, will be concerned, as well as intact forests cleared for grazing (Gibbs et al. 2010; Letourneau et al. 2012, Fig. 2.).

Grasslands Contribute to Livelihood and to Many Other Functions

Grasslands should be better used particularly in developing countries, where they contribute directly to the livelihoods of over 800 million people (Reynolds et al. 2005). In addition, it is an essential way to maintain the population in some areas, while providing income and insuring socio-cultural needs for many small holders. It has been estimated that about 70 % of the 1.4 billion people around the world in "extreme poverty" survives from livestock grazing (FAO 2009). Furthermore, the statistics often underestimate the contribution of livestock to regional or national economic development, since often, disregarding many non-food livestock outputs (Sansoucy et al. 1995; Thomas and Rangnekar 2004). Apart from marketable livestock products, grasslands also provide a variety of social and economic goods, and cultural services. These latter are quite often more important, more varied and more multi-purpose, in developing economies than in developed ones, and constitute an important component of the agricultural economy (McDermott et al. 2010; Thornton and Herrero 2010). Livestock reared on grasslands contribute also to the social status of the breeder and play a crucial role in social protection for the poor to cope with the uncertainties and constraints, such as crop failures and other disasters (FAO 2009). They also have a cultural dimension, since cattle animals are the foundation of many religious rituals (Alexandre et al. 2008).

Moreover, grasslands offer various products often non-arable areas for crops, and/or without competition with other human activities, while having a low dependence on external inputs (i.e. fossil energy). Therefore, different products can be cheaply obtained, and as a bonus, with the added value of quality. More and more consumers are willing to pay indeed much more for livestock products perceived as having been obtained in a natural environment without impact on the latter (Gracia et al. 2011; Gracia and Zeballos 2011). Grasslands are able to make use all-year round of solar radiation and support livestock which can alleviate seasonal food variability and availability and contribute to food security. For example in Northwest India where droughts are frequent, the contribution of livestock to family income can then reach 90 % (Thomas and Rangnekar 2004). Therefore, in addition to the factors of production such as all possible products, livestock, capital and labor (Fig. 3), other inputs such as natural ecosystem characteristics, biomass, and even energy (solar energy) and fuels possible in some cases (Wirsenius et al. 2010), are all elements to consider for better utilization of grasslands.

Grasslands to Facilitate Most Widely Shared Intensification

Appropriate grassland utilization can help address against inequalities in access to food and other products. While today the world produces sufficient food to feed its population, there still remain more than one billion people who suffer from food insecurity and malnutrition (Pretty et al. 2010). A winning strategy over the long

Fig. 3 In Guadeloupe, steers traditionally pulled carts loaded with sugar cane to the distilleries. And at the end of the period of sugar, they participated in competitions of steers pulling. Currently, these meetings often organized on Sundays, have increasingly been successful, and are the opportunity for many bets to large public gatherings

term is to help develop efficiently the largest number of production systems, including for/with small holders. However, priority has long been given to increasing the maximum efficiency of a small number of conventional production systems (Bonny 2011). In fact, given their importance in terms of areas, their geographical diversity and variety of possible production systems (Suttie et al. 2005), grasslands represent a very flexible agro ecosystems, which may allow different ways of intensification more or less suitable for different contexts. While extensive pastoral systems occupy regions where agricultural production is generally marginal, confined to a small proportion of the landscape, mixed crop-livestock systems are associated with high population density regions (Bouwman et al. 2005). All these systems based on the utilization of grazing areas, may be improved differently depending on local needs and constraints. Grasslands can then be used with cattle, sheep and goats, or horses, raised alone or in combination, more or less intensely, partly inside building with more or less long grazing periods.

Thus, the better valorization of this ecosystem is crucial, considered all the functions performed, while being delicate. Because most of grasslands are still semi-natural and marginal, representing around 47 % and 36 % of total grasslands respectively (Kruska et al. 2003; Bouwman et al. 2005; van Asselen and Verburg 2012), the issue is not only to rethink the idea of intensification, but also to innovate, while taking into account previous experiences. The stakes are therefore high, given the roles of natural areas in the current global context.

Importance of Agro-ecological Concepts for Intensification of Grassland

The concept of sustainability of agriculture was supported by Agroecology, defined as a way to protect natural resources, with guidelines to design and manage sustainable agro ecosystems (Altieri 1989; Wezel et al. 2009). The term of agroecology is currently used with quite different meanings, as a science or as practices. Agroecology may also be a movement, as in Latin America or USA (Wezel et al. 2009). According to Bonny (2011) the main difference between agroecology and ecological intensification refers to the concept of intensification, which is more pronounced in the second case (Powers et al. 2011), and also some different approaches at the socio-technical and economic levels. Agroecology is providing the scientific, methodological and technological basis for new "agrarian revolution" worldwide (Altieri et al. 2012) and is essential to consider it as a science as well as a practice for intensification of this ecosystem.

Agroecology as a Science

Although agroecology as a Science presents a large diversity of approaches and definitions in different countries of the world, one of the broadest provided (Francis et al. 2003) is "the integrative study of the ecology of the entire food systems, encompassing, ecological, economic and social dimensions", or more simply "the ecology of food systems".

Agriculture should be based on ecological processes that enhance ecosystem services, i.e. carbon storage, biodiversity, leaching and others. First of all, intensification need to (i) improve biomass turnover, (ii) ensure favorable soil conditions for plant growth, particularly by managing organic matter, soil cover and improving soil biological activity, (iii) minimize losses in solar energy, air and water management microclimate recovery water and soil management through increased soil cover, (iv) promote genetic diversification and agro-ecosystem species in time and space (v) enhance beneficial biological interactions and synergies between elements from biodiversity, to highlight the processes and key ecological services (Wezel et al. 2009).

To be effective, the intensification must also be consistent with the social contexts and interests of producers and smallholders, including the analysis of their attitudes and practices. According to Altieri and Tolledo (2011) promotion of an agroecological development paradigm based on the revitalization of small farms, which emphasizes social processes that value community participation and empowerment, proves to be perhaps one of the only viable options to meet present and future food needs. One of the basic elements of sustainable agricultural systems is the use of the recognition and conservation of agricultural heritage that enables social cohesion, promotes a sense of pride and belonging (Koohafkan et al. 2012) (Fig. 4).

Fig. 4 In this natural grassland, we can imagine the link between the farmer and the animal, the sense of belonging and pride of the farmer, the source of his motivation to find the best options to feed their animals and ensure their best condition and their growth

On the economic point of view, agroecological principles can help feed the world and provide a more radical move towards a new type of eco-economy. Economic factors have become the predominant forces in the food system (Altieri 1989), and the relationship between agricultural intensification, natural resources management and socioeconomic development is complex. There is a need for rethinking market mechanisms and organizations, and for a more innovative institutional flexibility at different spatial scales, combined with active farmers and consumer's participation (Abreu et al. 2012). Today, the increasing emphasis on the environment suggests development of a global market economy towards a "sustainable market economy" or a "social market economy and sustainable". This type of economy consists in reducing costs by reducing external dependencies, the inputs, energy or improved techniques. There is also the issue of certification and recognition by the market as Ecovida in Brazil. Thus, to move forward, a more sustainable animal protein economy, the change must first occur at the three levels of production, distribution, and consumption (Gliessman 2009).

Agroecology as a Practice

Considered as a practice, agroecology aims at improving the traditional or indigenous agriculture in developing countries. It helps to make agriculture more environmentally friendly, ecological, organic or alternative, and should help better ownership by producers (Wezel et al. 2009).

Taking into account the traditional practices can be a way around the barriers to intensification. A significant change in practice requires various conditions, including to have enough producers that make up a critical mass for the intensification and to have a pretty good acceptance by society. There is also the need of searching for farmer's autonomy, with a balance between a reuse of old practices and the use of scientific and technological innovations (Horlings and Marsden 2011).

Moreover, traditional practices are an important crucible for innovation (Pretty et al. 2010), as they result from a collection of many precious observations and experiences over time. It is not a mere return to tradition, which also includes important elements of environmental unsustainability (overgrazing, over-exploitation of some soils, deforestation, poor health status of livestock, etc.). Traditional knowledge resulting from many observations "the eye of the farmer" and the use of various sensors more or less complex may allow more appropriate local interventions and more fine adjustments. This accumulation of knowledge, tacit or codified, more or less enriched with technical knowledge (Alexandre et al. 2013), concerns the needs of plants and animals in nutrients, their management, detection and treatment of diseases, as well as information on the environment or the state of livestock and crops (Doré et al. 2011).

Agroecology Well Suited for Grasslands Intensification

The principles of agroecology appear well suited to better value grasslands, surely more than other agricultural sectors, mainly due to the multifunction of grasslands that can then effectively be addressed adequately. Thus, from an ecologically viewpoint, grasslands are precisely ecosystems having a strong link between herbivores and floral diversity for instance (Gliessman 2009) and provides it is well managed, can be a tool for ecological and regulating services, notably to maintain and restore biodiversity of the open landscape (Ma and Swinton 2011; Metera et al. 2013). Moreover grasslands can potentially offset a significant proportion of global greenhouse gases emissions and the extent of storage is depending of appropriate strategies of management, such as stocking rate and grazing pressure or application of nitrogen fertilization (Allard et al. 2007; Ammann et al. 2007; Soussana et al. 2013). Essential actor on regrowth of grass, animals contribute to improving the quality of the cover, an essential tool in soil erosion and the watershed processes of infiltration and water retention (Gliessman 2009). Thus, pastoral nomadism, a complex set of practices and knowledge, ensures the long-term maintenance of a sophisticated "triangle of sustainability" which includes plants, animals and people (Koocheki and Gliessman 2009).

Beyond the ecological services, natural resources and landscapes may provide numerous social, cultural, recreational, and aesthetic services which satisfy human need and well-being (Boval and Dixon 2012; Ma and Swinton 2011; Zhang et al. 2007). In this sense, most traditional agroecosystems have remarkable characteristics regulated by strong cultural values and collective forms of social organization, including customary institutions for agro-ecological management, normative arrangements for resource access and benefit sharing, value systems, rituals, etc. (Altieri and Toledo 2011). The livestock production systems based on grasslands therefore has great potential for social equity, the poverty alleviation, risk reduction and gender equality (Gliessamn 2009). These services must be considered and the agro-ecological concepts can really support that.

Also, beyond the provisioning services of animal products, via a good exploitation of arable land and an efficient conversion of biomass plant into animal protein (Gliessman 2009) the ecosystemic services may be source of income (Ma and Swinton 2011). Moreover production systems based on grasslands enhance short circuits, reducing the cost of food distribution. The development of local food chains seems in addition allowing renewal of the meaning of farm work and of the social links between city and country, and has an impact on energy consumption (Mundler and Rumpus 2012). These important services in the context of the exploitation of grassland eco-economic factors are properly taken into account in the agro-ecological concepts.

Case Studies of Some Agroecological Management Strategies of Grassland

To achieve the agroecological intensification of grasslands, considering the principles developed above, concrete management strategies are required. Some strategies already are known (Boval and Dixon 2012) and may be more or less in consistence with the agro-ecological principles. These strategies which should help to better adjust the grassland production and the use and consumption by animals, may be considered at two levels.

Firstly elementary interventions, may act at one level or on one component of the production systems, on grass or on the animal and its management. At the grass level for example, such strategy will focus on the choice of the stage of regrowth, or the height at the exit of the animals, frequently used in various contexts, (Lemaire et al. 2009), the fertilization level or the addition of other feeding supplements, like it is often the case in mixed system (Herrero et al. 2009). The elementary strategies at the animal level will include the choice of herbage allowance or of the area to be grazed by animals, or more generally the stocking rate, being average or instantaneous, the duration of grazing, continuously or in rotation, including or not nocturnal grazing, or by the mixing of animal species (d'Alexis et al. 2013). Moreover, these interventions interact with others concerning animal adaptation: fertility and reproductive performance, disease resistance, adaptation to the constraints of grazing (Dumont et al. 2013).

Otherwise, global strategies may be implemented at an overall level, acting on many or all components of the production system. These strategies, contrary to elementary interventions, focus on various components, at various levels of the production system. They are more representative of actual practice by a farmer, as it integrates all the interventions performed.

In the Caribbean, existing overall strategies of natural pastures, a priori consistent with many agro-ecological principles, have been the subject of research programs.

The aim was to assess these strategies and check that they actually generate a satisfactory animal performance. Two examples have been developed below, illustrating approaches for intensification and for different animal species. The first example is based on assumptions and knowledge of published scientific studies in temperate and tropical contexts, which have been tested in experimental stations, and which will be transferred to the goat herders. The second is a traditional strategy, widely used by owners of local cattle, which persisted, and once studied and once studied in a framework of a research program, really shows great potential for agro-ecological exploitation of grazing areas.

Mixed Grazing with Goats and Cattle

Description

In Guadeloupe, French Caribbean, there is a strong demand for local goat meat with a high purchase price, while production is insufficient (Alexandre et al. 2008). By another way, goat production is more widely spread in the tropics (over 90 % of 921 million goats in the world are located in developing countries (FAO 2012), and projections to 2030 indicate a marked increase in goats and sheep by 32 % (560 million), when the increase for hogs and cattle would be 22 % and 24 % respectively (190 and 360 million).

Even if the production of conventional intensive farms has increased six times faster than the traditional systems, they are important components to meet the growing demand of consumers to favor production methods more "natural" and more respectful of their environment (Godfray et al. 2010; Gracia and Zeballos 2011). But the high vulnerability of goats to gastro-intestinal nematodes (and their resistance to anthelmintics) adversely affect production, prompting research into sustainable methods to overcome this problem (Hoste et al. 2010).

Mixed grazing system of various species has been proposed as an appropriate strategy to increase meat production at pasture while reducing parasitism through the dilution of gastro intestinal nematodes between the two species (Hoste et al. 2010). The association of sheep and cattle has been studied for a long time in temperate and tropical areas and several types of association have been studied based on various options in the choice of the species associated, of the space and time scales (d'Alexis et al. 2012; Nolan and Connolly 1977; Nolan et al. 1989, Fig. 5). The species can be reared in rotation, one species after another, or being put to graze together. In this case they can graze also continuously the same paddock.

Benefits of This Strategy for Goat Production

This promising strategy has been evaluated in French Caribbean to offer alternatives to farmers to improve performances of their goat herds. First, it was checked that the strongyles, affecting the Creole goats could be diluted by association with Creole

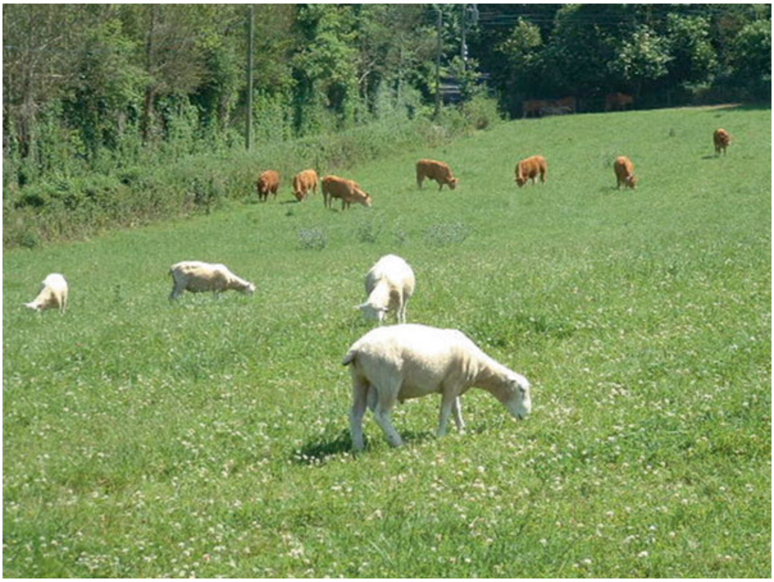


Fig. 5 The rationale for mixed species grazing, as it is practiced in temperate or tropical areas, is based on the principle that animals have different grazing preferences and dietary overlap is minimal in a diverse sward

heifers (d'Alexis et al. 2009). Secondly, experiments were conducted to evaluate the usefulness of mixed grazing on goat performances, for which the knowledge in the literature is really scarce, compared to sheep.

Goats continuously grazing, and mixed with cattle (M) were compared with goats reared alone (C). This pattern was replicated in space (two set of four subplots), and in time with six successive cohorts of animals, during two successive years. The average daily gains of goats in mixed grazing was higher than in controls irrespective of gastro-intestinal nematode status, while the biomass was lower (Fig. 6).

The value of 32 g is close to previous values reported (Alexandre et al. 1997) for Creole goats, but treated with anthelminthics and on fertilized pastures (37 g/day). For daily live weight gain calculated per kg DM, and per ha, mixed grazing also yielded better results than the controls (Fig. 7). Therefore, we confirmed that mixed goats with heifers may offer an alternative to individual, as an overall production, by summing the live weight of goats and cattle. The effect of mixed grazing on dilution of gastro intestinal nematodes on pasture was not demonstrated in our experiment, driven in situ on natural grassland, but this method may help to obviate use of anthelmintics and obtain high performances. The live weight gain measured was associated with lower biomass available to the animals, suggesting better use of pasture. Thus, concerning the two components accounting for the impact of mixing (i.e., feeding and health), it appears that feeding is the most important, as this is what determines the benefit of mixed grazing, as often been pointed out in other studies. Further experiments need to be conducted on pasture feeding to gain a better understanding of how this live weight gain occurs in mixed pastures.

Fig. 6 You can see the difference between grazed plots with only goats, *top right* and *bottom left*, compared with those managed mixed. We can clearly see the heterogeneity of grazed plots with only goats, for which high biomass were measured

Agro-ecological Interest

This study aimed to promote innovative practice to local farmers which do not practice yet this kind of management. We do hope that by having tested these strategies in situ conditions, close to normal grazing conditions considering seasonal variability, and having obtained satisfying results, that the appropriation by local breeders will be real. The feeding was improved without any supplement or any anthelmintic, and with small risk to have chemical residues in the meat. The continuous grazing also has the advantage of reducing the costs of closing, important for rotational grazing, which is most widely practiced in the local farms. The presence of cattle is also an important factor for farmers who are often powerless against many thefts of their animals and dog attacks (Fig. 8).

Thus, this strategy has acted at different levels, for health and improved nutrition status of the goats, to better manage residual biomass (Fig. 7b), well known in very intensive systems (Alexandre et al. 1997; Ortega-Jimenez et al. 2005), and appears consistent with the environment constraints, i.e.no fertilizer, no anthelminthics and use of natural grassland.

Besides, from a breeder's economic point of view for a breeder, the mixed system would reduce expenses for anthelmintics, since as we showed, mixed grazing allows for equivalent performance compared to infected young goats treated with anthelmintics. Furthermore, in terms of carcass yield animal output, earnings would be

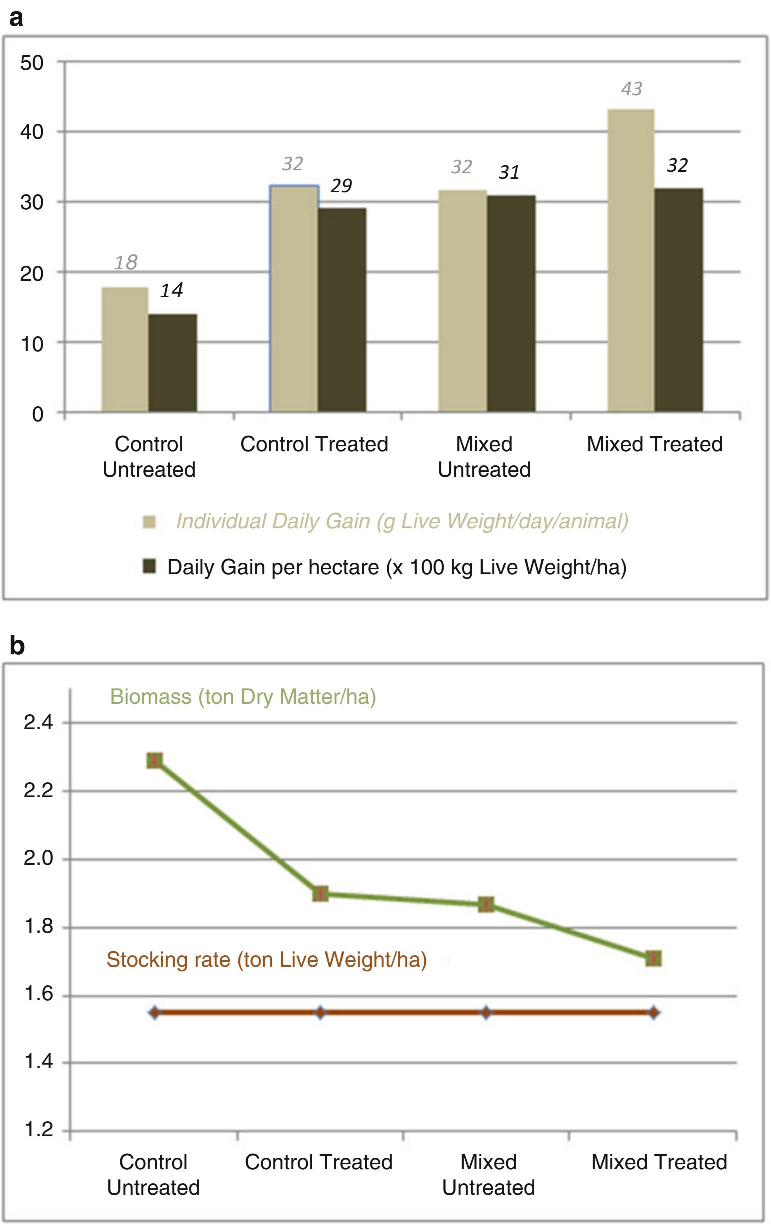


Fig. 7 (**a**) Measurements of daily gains per animal or per ha, for control goats reared alone, being either treated with anthelminthics or not, compared to Mixed goats grazing with heifers, being either treated or not. (**b**) Measurements of biomass and stocking rate on the paddocks grazed by the control goats reared alone, being either treated with anthelmintics or not, and on the paddocks grazed by Mixed goats grazing with heifers, being either treated or not

Fig. 8 The presence of heifers with goats, may limit attack by the dogs, as well as thefts. These attacks are fairly common for small ruminants on pastures, and almost not observed for cattle, even for young animals

provided by the sale of cattle on foot. Expenditures are needed to make fencing, but not as much as for rotational grazing, and mixed grazing could remain profitable for a farmer. Complementary economic approaches are currently underway.

Traditional Tethering Practice of Cattle in French Caribbean

Description of the Practice

Creole cattle are mainly reared tethered in Guadeloupe, in natural pastures based on *Dichanthium spp*, at roadsides, near sugar cane crops or houses (Fig. 9). The "tethering practice" is well established and concerns about 90 % of cattle holders and 60 % of goat farmers (Alexandre et al. 2008; Boval et al. 2012; Gunia et al. 2010). Beyond the Caribbean, this type of farming is also practiced in other latitudes such as in Ghana, Ethiopia, Uganda or Sahel (Ayantunde et al. 2008; Duku et al. 2010; Kugonza et al. 2001; Senbeto et al. 2013) in India (Das and Hema 2008) or North America (Heredia-Nava et al. 2007; Patra et al. 2008) and even in Europe (Corsica and Normandy, personal communication).

Face to the persistency of this practice, and despite the promotion of other conventional managements to the local farmers, surveys of about 250 farmers using this practice were realized in order to better comprise and understand this practice (Boval 1994). The information collected showed a great variety of practices, with no less than five different types, identified according to different interventions: the average length of the chain, the number of daily moves, the time of return to the

Fig. 9 Cattle are often attached near pieces of sugarcane in Guadeloupe and in particular during the dry season to supplement the animals. The tethering practice, which requires per animal, a chain and an iron piquet or a trunk in place, allow to move the animals from one place to another, for a better use of different forage resources, at a lower cost. The animals frequently in contact with the farmers are generally quite manageable

same location, the frequency of drinking, and, finally, the practice of tethering "dorm place", the animals are grouped for the night in a reserved area, still tethered to grouped pickets, in order to keep the manure (Boval et al. 2012).

All the interventions reflect some generic zootechnical bases, valuable for all grazing livestock and defining key parameters such as the surface and duration for grazing, the frequency of moving and the stage of regrowth, which determine the grass traits.

The size of herds reared tethered can go from two to five heads for 24 % of the surveyed, till 15–46 heads for larger holders i.e. for 18 % of respondents. These livestock farmers also have surfaces of sugar cane and food crops that they irrigate and fertilize, and also use by-products to supplement their animals during the dry season. The distribution of supplements is actually easier at the tethering point, sugar cane leaves are commonly used by 75 % of surveyed before mowing various other possible fodders, like it is the case for 27 % of respondents. Farmers carrying out a particular tethering practice are not particularly distinguished by their means of production, social status, or their marketing arrangements.

The diversity of these practices seems to depend on the geographic area and of the local agro-ecological context. Thus, one of the five practices identified, based on only one daily move and watering regardless of the season (Fig. 10), is widespread in the clay suburban plains of the western part of the island (1,500–2,000 mm year)

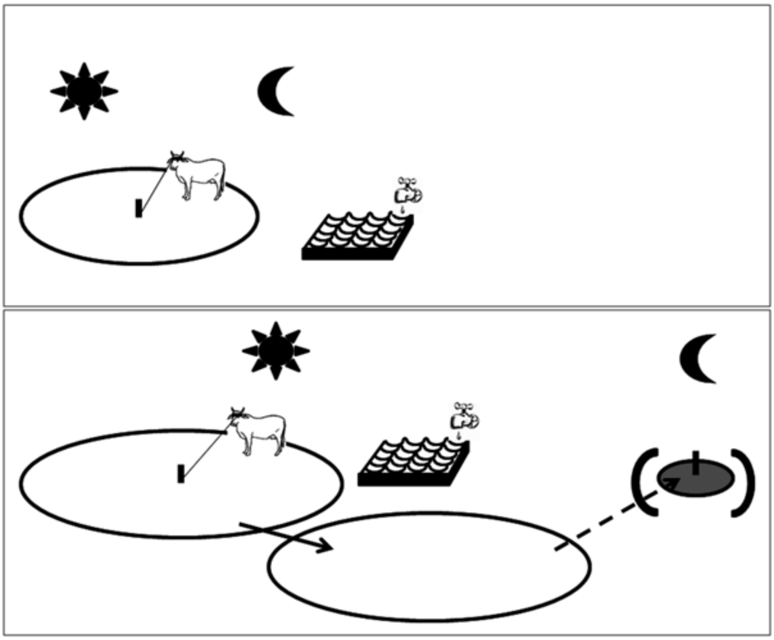


Fig. 10 Two practical examples of "tethering" practices for Creole cattle in traditional farms: **Type 1** (25 % surveyed): 1 displacement/day, 1 watering/day, 14 days of regrowth whatever the season. **Type 5** (25 % surveyed): 2 displacements/day and a Dorm place at night, 1 watering/day, the regrowth stage depends of season

where productive cropping and grazing dominate, like for 48 % of respondents. However, another practice identified, with very long chains is mostly carried out by 46 8 % of the surveyed, in the Northern area of the great limestone plateau (1,000–1,250 mm/year) where coexist growing sugarcane, and natural grasslands. Otherwise, it could be a simple diffusion of specific practices in micro-regions, perpetuated over time, not subsequently affected by structural changes of the farms or financial needs of farmers.

Technical Benefits

The statements of farmers surveyed constituted an intrinsic knowledge of this traditional practice, from which a research project was set up to really assess the livestock performance obtained, what had never been done before. However, until then, the poor performance of tethered animals was reported by various agricultural institutions, compared to more conventional management strategies. The objective was to validate the importance of these various practices and seek to innovate thereafter from what was observed empirically by several generations of traditional breeders.

The average daily gain measured with tethered Creole heifers on indigenous grasslands, was from 400 to 750 g/day (Fig. 11), without other addition of supplement,

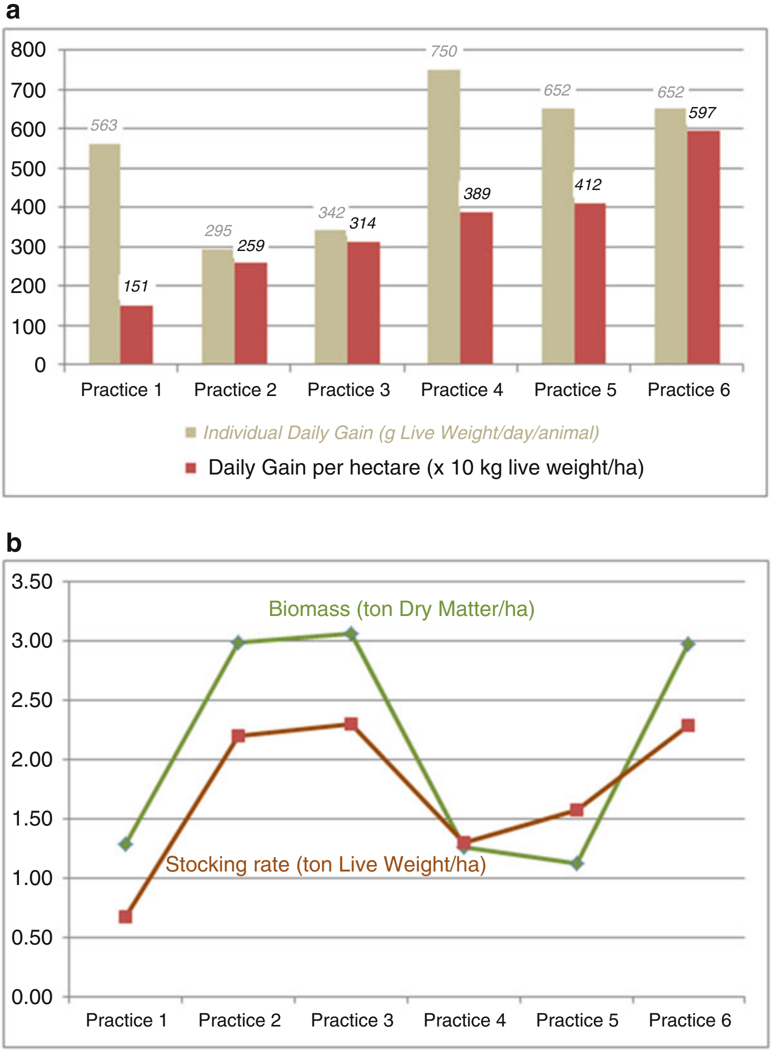


Fig. 11 (**a**) Measurements of daily gains per animal or per ha, for different tethering practices for Creole heifers on natural pastures. (**b**) Measurements of biomass and stocking rate for different tethering practices for Creole heifers on natural pastures
Practice 1: 7 m chain, grazing on 24 h, 21 days of regrowth, fertilization 2.38kgN/ha
Practice 2: 2 surfaces/d with 4 m chain, daytime grazing for 12, 14 days of regrowth, 1.42 kg N/ha
Practice 3: 1 4 m surface channel, 12 h daytime grazing, 14 days of regrowth, 1.42 kg N/ha
Practice 4: 5.6 m chain, grazing on 24 h, 21 days of regrowth, 2.38 kg N/ha
Practice 5: 4 m chain, grazing on 24 h, 28 days of regrowth, 0 kg N/ha
Practice 6: 4 m chain, grazing on 24 h, 14 days of regrowth, 1.4 kgN/ha

with various modalities of moving, of chain lengths, of stages of grass regrowth and various levels of fertilizer added (Boval et al. 2000, 2002, 2007a, b). The average daily gains values are entirely satisfactory, given previous values obtained for Creole cattle also fed with fresh grass, but with a distribution of supplements (Naves 2003).

This practice, which allows measurements of feeding and grass for grazing animals on an individualized area, has also enabled a better understanding of the Herbage-Animal relationships and identified the intrinsic grass characteristics that would make “good” grassland, to optimize feeding of grazing ruminants in real situation (Boval et al. 2007a, b). We have highlighted the importance of the physical characteristics of the grassland, that affect the amount of removed forage and animal performance (Boval et al. 2007b). This practice has also been very useful to develop methodological tools to measure animal feeding in situ, from fecal samples collected on the individualized surfaces with the chain. These faecal samples represent indeed reliable indicators of the selection of grass, which is actually consumed by grazing ruminants (Boval et al. 2003, 2004; Fanchone et al. 2007, 2009).

Traditional Practice, Contemporary and Agro-ecological

In-depth study of this practice a priori trivial, helped to better assess its variability and describe the various technical interventions it includes, as well as the various alternatives and benefits it provides, beyond the negative a priori and major drawbacks long time decried. This bottom-up approach, from the tradition of livestock holders, to scientific experiments, also allowed to progress on knowledge of feeding of grazing ruminants in tropical areas, allowing individual measurements in situ, as well as major methodological progress (Boval and Dixon 2012). Therefore, it was revealed that the practice of tethering, well managed can truly have a key role, from an ecological and environmental perspective and from a societal and economic perspective, of course.

Besides animal performance which can be achieved with certain modalities, this practice makes better use of natural areas as well as additional surfaces more or less regularly grazed: fallow or communal ownership, the rear of mangroves during the dry season, too steep or rocky areas to be cultivated. Beyond the tradition, 75 % of farmers surveyed emphasize indeed first, real strengths of this practice, which appears as a management tool, allowing an intensive, flexible and rational use of agricultural land. By driving the animals, the adjustments of stocking rate may be really precise according to the status of the animal or of the grass, by changing the grazing time or area allowed, and allow preventing any risk of overgrazing. At the same time, the individual moving allows detection of any health problem and anoestrus.

Therefore, the time required for the tethering practice appears important and has been long time denounced as a major constraint. Nevertheless, it is not rare to have up to 40 animals tethered together, the average daily time per animal being estimated to be 10–15 min. It is to put in balance with other advantages like the low cost of material required without additional cost to fences, the flexibility of the practice, to allow the use of various grazing surfaces. Furthermore, this might appear to be a major constraint which is suitable for the organization of farmers, with cheap family labor. Moreover, this practice contributes to a number of specific ecosystem services on the basis of those considered by the MEA (2005), in addition to grazing component (Table 1). It is possible in fact to use uncultivable areas, like mangroves or

Table 1 Classification of ecosystem services, adapted from MEA (2005) and De Groot et al. (2002)

Regulations services	**Cultural services**
Regulation/water purification (controlled watering stations)	Recreation and ecotourism
Pollination	Ecological wellness
Biodiversity	***Cultural heritage***
Climate regulation	***Family activity***
Storage/carbon sinks	***Patrimonial value of natural ecosystems***
Erosion control by maintaining grazing in areas sensitive to erosion (steep areas)	
Disease regulation by individual monitoring	
Provisioning services	**Auto-maintenance services**
Food	Composition of soils
Freshwater	Development of nutrient cycling
Fibre	***Primary production and maintenance of uncultivable areas, of wasteland***
Centralized production of manure	
Subsistence farming on a small scale	

In bold and italic, services more specific of tethering practices

wastelands, to produce manure for cultivation of other vegetable products and therefore to contribute to subsistence of the family, cheaply, beyond the breeding.

From an economic point of view, this practice provides an income with little investment, according to 12 % of surveyed and allowing access to a wide range of farmers, i.e. multi-active retirees, young dynamic operators, having herds from 5 to 45 heads, on widely varying surfaces, more or less homogeneous. This practice meets the objectives of livestock holders that may diversify their agricultural production, especially with sugar cane. This diversification is a factor of security that allows a stable income and a whole production system flexible, autonomous and resilient to market fluctuations.

Tethered livestock is not less profitable and the calculation of gross margins for various livestock tethered, or for free intensive grazing, give values quite close, respectively of € 792/ha and € 938/ha (Diman et al. 2002). Required funding is reduced, as well as the level of risk, shown by the difference between the maximum and minimum gross margins being about 364 €/ha and 538 €/ha, respectively for tethered and free animals. Incomes generated by the sale of animals are to be regarded with the sale of manure, which is more Profitable.

Implications of Case Studies

Given the urgent need for better use of grasslands, which provides many other features, Research must still invest, for studies of efficient and portable strategies for sustainable agro-ecological management. The Caribbean experiences described above illustrate that there is scope to better use the tropical natural grasslands by cattle and small ruminants for instance, and that there are efficient management strategies, implying lower inputs and leading to satisfying animal performances. Considering at the same time the biomass and its better use (i.e. the lower residual biomass in mixed systems or the diversity of lands used with tethering practices), it is a demonstration that agro-ecological approaches may contribute to intensification and food security, while assuring other functions.

"*That agro-ecological approaches can contribute to the future demand for food production, especially in developing countries*" it is in fact a central issue illustrated by various examples (Altieri and Toledo 2011; Horlings and Marsden 2011). However, there are still few studies describing examples of livestock on pasture, studied and reported in the literature from tropical environments, where most of the intensification is expected (Fernando Gomez et al. 2013). Moreover, there are still few examples of direct investment of scientists and of research program developed with farmers, while this may play a major facilitating role for technological innovation (Altieri and Toledo 2011; Altieri et al. 2012). Beyond theory, the scientific approach invested here, allow to provide tangible results at different levels, including for social and economic dimensions that are currently being deepened. This requires multidisciplinary approaches, which while not being easy to implement, were mandatory, involving animal scientists, agronomists, economists, encouraged by local pressure of livestock holders.

These case studies thus show how traditional practices can be useful to improve the complex production systems, in which researchers have the problem of not knowing "where differences make a difference" for farmers (Kaufmann 2011). Thus, understanding why pastoralist do what they do, and learning about the constraints they face when regulating production processes, are prerequisite to identify viable improvement possibilities and help for appropriation and adoption.

Also the contextual conditions of these case studies may be representative of other tropical locations, give some tangibility of these results and let imagine possible transfer of some technical options. In fact the soil and climatic conditions of these case studies are close to a tropical humid climate "Aw" according to Köppen classification (Peel et al. 2007) that can be found in the outside margin of the tropics, including also the Caribbean, Brazil, Mexico, Indonesia, India, Niger, Kenya, Australia, and sometimes intra-tropical areas such as Colombia.

These examples are illustrative of two approaches highlighted by a process of scientific research, being bottom-up with mixed grazing, and top-down with the traditional practice, and highlighting both the range of technical options to manage pastures. Nevertheless other management options exist for sustainable intensification of grassland, being more or less overall (Boval and Dixon 2012). Ongoing studies focus on organic fertilization of natural pastures with vermicompost, in order to (i) better use manures coming from stall fed animals (ii) increase at lower cost the herbage mass quality and feeding at pasture, that had already been shown with mineral fertilization (Boval et al. 2002), (iii) reduce the impact of gastro-intestinal strongyles for grazing goats, as the strongyles larvae would be controlled by earthworms (d'Alexis et al. 2009; Waghorn et al. 2002).

Research should indeed provide various options and strategies, more or less appropriate and not necessarily a turnkey technical itinerary, from which the breeder will be inspired, according to its constraints, local resources, lifestyle, etc., to implement its own management. To go further, there is a need for more scientific investment in such existing approaches as described in our case studies, in order to innovate within a range of tangible possibilities. Such approaches are very rewarding in order to approach interactions, and to better implement multidisciplinary studies (Alexandre et al. 2002).

To carry out multidisciplinary studies, which are the most appropriate for studying complex systems like pasture use by animals, great methodological steps are required, in order to facilitating parallel development of skills and disciplines and a multi-criteria assessment. Moreover these methodological progresses are the best way to provide support decision tools to livestock holders, to adjust their own daily management that they have adopted and adapted to their context. Thus, a kit for analyzing fecal samples collected in the field, for example, could inform the breeder on the nutritional status of the animals or their health and the quality of his pasture and the need to supplement their animals or not.

Fortunately, advances in recent years are palpable and a number of new technologies can contribute to low-cost acquisition of quantitative data to better understand the interactions between grass and grazing animals, in order to anticipate managing in grassland systems (Boval and Dixon 2012; Decruyenaere et al. 2009; Dixon and Coates 2009; Landau et al. 2006). Development of remote imaging of vegetation, global positioning technology, the diet improved markers, near infrared spectroscopy and modeling provide tools to make decisions based on the knowledge of the constraints of animals grazing-fed animals.

In the same order, research should help to provide some criteria's or indices to policies, in order to better evaluate the level of agro-ecological approaches, usable by various livestock holders, to help promotion, and even certification of such sustainable use of natural grasslands, in the future.

References

Abreu LS, Bellon S, Brandenburg A (2012) Relations between organic agriculture and agroecology: current challenges around the principles of agroecology. Desenvolvimento e Meio Ambiente 26:143–160

Alexandre G, Aumont G, Fleury J, Coppry O, Mulciba P, Népos A (1997) Production semi-intensive au pâturage de caprins à viande en zone tropicale humide: le cas des cabris créoles sur pangola (Digitaria decumbens) en Guadeloupe. INRA Prod Anim 10:43–54

Alexandre G, Archimède H, Boval M, Mahieu M, Aumont G, Xandé A (2002) A holistic approach to the multi-functionality of the grazing systems in the Caribbean. In: 19th general meeting of European Grassland Federation, 1004–05 La Rochelle

Alexandre G, Asselin de Beauville S, Shitalou E, Zebus MF (2008) An overview of the goat meat sector in Guadeloupe: conditions of production, consumer preferences, cultural functions and economic implications. Livest Res Rural Dev 20, Article #14. http://www.cipav.org.co/lrrd/lrrd20/1/alex20014.htm

Alexandre G, Facthum-Sainton J, Angeon V (2013) Tradition and innovation in Caribbean LFS: old rhum in new barrels. In: EAAP. Nantes, 26–30Aout. Wageningen, Academic Publishers
Allard V, Soussana JF, Falcimagne R (2007) The role of grazing management for the net biome productivity and greenhouse gas budget (CO_2, N_2O and CH_4) of semi-natural grassland. Agric Ecosyst Environ 121:47–58
Altieri MA (1989) Agroecology – a new research and development paradigm for world agriculture. Agric Ecosys Environ 27:37–46
Altieri MA, Toledo VM (2011) The agroecological revolution in Latin America: rescuing nature, ensuring food sovereignty and empowering peasants. J Peasant Stud 38:587–612
Altieri MA, Funes-Monzote FR, Petersen P (2012) Agroecologically efficient agricultural systems for smallholder farmers: contributions to food sovereignty. Agron Sust Dev 32:1–13
Ammann C, Flechard CR, Leifeld J, Neftel A, Fuhrer J (2007) The carbon budget of newly established temperate grassland depends on management intensity. Agric Ecosys Environ 121:5–20
Ayantunde AA, Fernandez-Rivera S, Hiernaux PH, Tabo R (2008) Implications of restricted access to grazing by cattle in wet season in the Sahel. J Arid Environ 72:523–533
Bonny S (2011) Ecologically intensive agriculture: nature and challenges. Cahiers Agric 20:451–462
Bouwman AF, Hoek KW, Eickhout VDB, Soenario I (2005) Exploring changes in world ruminant production systems. Agric Syst 84:121–153
Boval M (1994) Tethering practice at pasture of Creole cattle – study of herbage intake. Thesis of the Paris VI University
Boval M, Dixon RM (2012) The importance of grasslands for animal production and other functions: a review on management and methodological progress in the tropics. Animal 6:748–762
Boval M, Cruz P, Peyraud JL, Penning P (2000) The effect of herbage allowance on daily intake by Creole heifers tethered on natural Dichanthium spp. pasture. Grass Forage Sci 55:201–208
Boval M, Cruz P, Ledet JE, Coppry O, Borel H, Archimède H (2002) Effect of nitrogen on intake and digestibility of a tropical grass grazed by Creole heifers. J Agric Sci 138:73–84
Boval M, Archimède H, Fleury J, Xande A (2003) The ability of faecal nitrogen to predict digestibility for goats and sheep fed with tropical herbage. J Agric Sci 140:443–450
Boval M, Coates DB, Lecomte P, Decruyenaere V, Archimède H (2004) Faecal near infrared reflectance spectroscopy (NIRS) to assess chemical composition, in vivo digestibility and intake of tropical grass by Creole cattle. Anim Feed Sci Technol 114:19–29
Boval M, Archimède H, Cruz P, Duru M (2007a) Intake and digestibility in a Dichanthium spp. dominated pasture, at 14 and 28 days of regrowth. Anim Feed Sci Technol 134:18–31
Boval M, Fanchone A, Archimède H, Gibb MJ (2007b) Effect of structure of a tropical pasture on ingestive behaviour, digestibility of diet and daily intake by grazing cattle. Grass Forage Sci 62:44–54
Boval M, Coppry O, Naves M, Alexandre G (2012) L'élevage traditionnel, une source et un support pour l'innovation agro-écologique: la pratique du piquet aux Antilles. Courr Environ INRA 62:87–97
d'Alexis S, Loranger-Merciris G, Mahieu M, Boval M (2009) Influence of earthworms on development of the free-living stages of gastrointestinal nematodes in goat faeces. Vet Parasitol 163:171–174
d'Alexis S, Mahieu M, Jackson F, Boval M (2012) Cross-infection between tropical goats and heifers with Haemonchus contortus. Vet Parasitol 184:384–386
d'Alexis S, Sauvant D, Boval M (2013) Mixed grazing systems to improve gain production at pasture: a quantitative review. J Agric Sci. doi:10.1017/S0021859613000622
Das SK, Hema T (2008) Livestock feeds and feeding practices in rural Sundarbans delta of India. Anim Nutr Feed Technol 8:137–142
De Groot RS, Wilson MA, Boumans RMJ (2002) A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecol Econ 41(3):393–408
Decruyenaere V, Lecomte P, Demarquilly C et al (2009) Evaluation of green forage intake and digestibility in ruminants using near infrared reflectance spectroscopy (NIRS): developing a global calibration. Anim Feed Sci Technol 148:138–156
Diman JL, Naves M, Marquis K, Alexandre G, Zebus MF (2002) Technico-economical differentiation in beef cattle management in Guadeloupe. In: 9 emes Rencontres Recherches Ruminants, 126 Paris, les 4 et 5 Decembre 2002

Dixon R, Coates D (2009) Review: near infrared spectroscopy of faeces to evaluate the nutrition and physiology of herbivores. J Near Infrared Spectrosc 17:1–31
Doré T, Makowski D, Malézieux E, Munier-Jolain N, Tchamitchian M, Tittonell P (2011) Facing up to the paradigm of ecological intensification in agronomy: revisiting methods, concepts and knowledge. Eur J Agron 34:197–210
Duku S, Zijpp AJvd, Howard P (2010) Small ruminant feed systems: perceptions and practices in the transitional zone of Ghana. J Ethnobiol Ethnomed 6:11
Dumont B, Fortun-Lamothe L, Jouven M, Thomas M, Tichit M (2013) Prospects from agroecology and industrial ecology for animal production in the 21st century. Animal 7:1028–1043
Fanchone A, Boval M, Lecomte P, Archimède H (2007) Faecal indices based on near infrared spectroscopy to assess intake, in vivo digestibility and chemical composition of the herbage ingested by sheep (crude protein, fibres and lignin content). J of Near Infrared Spectrosc 15:107–113
Fanchone A, Archimède H, Boval M (2009) Comparison of fecal crude protein and fecal near-infrared reflectance spectroscopy to predict digestibility of fresh grass consumed by sheep. J Anim Sci 87:236–243
FAO (2009) The state of food and agriculture 2009: livestock in the balance. State of Food and Agriculture, Roma
FAO (2012) Developing a global agenda of action for sustainable livestock sector development, 2nd multi-stakeholder platform meeting. State of Food and Agriculture, Roma, 18 pp
Fernando Gomez L, Rios-Osorio L, Eschenhagen ML (2013) Agroecology publications and coloniality of knowledge. Agron Sust Dev 33:355–362
Francis C, Lieblein G, Gliessman S et al (2003) Agroecology: the ecology of food systems. J Sust Agric 22:99–118
Gibbs HK, Ruesch AS, Achard F, Clayton MK, Holmgren P, Ramankutty N, Foley JA (2010) Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. Proc Natl Acad Sci U S A 107:16732–16737
Gliessman SR (2009) Animals in agroecosystems. In: Agroecology: the ecology of sustainable food systems, 2nd edn. CRC Press, Taylor & Francis, New York, 384 p
Godfray HCJ, Beddington JR, Crute IR et al (2010) Food security: the challenge of feeding 9 billion people. Science 327:812–818
Gracia A, Zeballos G (2011) Animal welfare concern and attitudes towards more animal welfare friendly meat products: characterization and segmentation. Itea-Inform Tecnica Econo Agraria 107:33–47
Gracia A, Loureiro ML, Nayga RM (2011) Valuing an EU animal welfare label using experimental auctions. Agric Econ 42:669–677
Gunia M, Mandonnet N, Arquet R et al (2010) Production systems of Creole goat and their implications for a breeding program. Animal 4:2099–2105
Heredia-Nava D, Espinoza-Ortega A, Gonzalez-Esquivel CE, Arriaga-Jordan CM (2007) Feeding strategies for small-scale dairy systems based on perennial (Lolium perenne) or annual (Lolium multiflorum) ryegrass in the central highlands of Mexico. Trop Anim Health Prod 39:179–188
Herrero M, Thornton PK, Notenbaert A et al (2009) An integrated assessment of global changes in crop-livestock systems to 2030: implications for policy development. In: Conference on integrated assessment of agriculture and sustainable development: setting the agenda for science and policy. The Netherlands, pp 22–23, 10–12 Mar 2009
Horlings LG, Marsden TK (2011) Towards the real green revolution? Exploring the conceptual dimensions of a new ecological modernisation of agriculture that could 'feed the world'. Global Environ Change-Hum Pol Dimens 21:441–452
Hoste H, Sotiraki S, Landau SY, Jackson F, Beveridge I (2010) Goat-nematode interactions: think differently. Trends Parasitol 26:376–381
Kaufmann BA (2011) Second-order cybernetics as a tool to understand why pastoralists do what they do. Agric Syst 104:655–665
Koocheki A, Gliessman SR (2009) Pastoral nomadism, a sustainable system for grazing land management in arid areas. J Sust Agric 25:113–131

Koohafkan P, Altieri MA, Gimenez EH (2012) Green agriculture: foundations for biodiverse, resilient and productive agricultural systems. Int J Agric Sustain 10:61–75

Kruska RL, Reid RS, Thornton PK, Henninger N, Kristjanson PM (2003) Mapping livestock-oriented agricultural production systems for the developing world. Agric Syst 77:39–63

Kugonza DR, Bareeba FB, Kirembe G (2001) Characterisation of meat goat management systems in three districts of central Uganda. Muarik Bull 4:26–29

Landau S, Glasser T, Dvash L (2006) Monitoring nutrition in small ruminants with the aid of near infrared reflectance spectroscopy (NIRS) technology: a review. Small Ruminant Res 61:1–11

Lemaire G, Da Silva SC, Agnusdei M, Wade M, Hodgson J (2009) Interactions between leaf lifespan and defoliation frequency in temperate and tropical pastures: a review. Grass Forage Sci 64:341–353

Letourneau A, Verburg PH, Stehfest E (2012) A land-use systems approach to represent land-use dynamics at continental and global scales. Environ Model Software 33:61–79

Ma S, Swinton SM (2011) Valuation of ecosystem services from rural landscapes using agricultural land prices. Ecol Econ 70:1649–1659

McDermott JJ, Staal SJ, Freeman HA, Herrero M, Van de Steeg JA (2010) Sustaining intensification of smallholder livestock systems in the tropics. Livest Sci 130:95–109

Metera E, Sakowski T, Sloniewski K, Romanowicz B (2013) Grazing as a tool to maintain biodiversity of grassland – a review. Anim Sci Pap Rep 28:315–334

Millennium Ecosystem Assessment (MEA) (2005) Ecosystems and human well-being: synthesis. Island Press, Washington, DC. 155 p. http://www.millenniumassessment.org/documents/document.356.aspx.pdf

Mundler P, Rumpus L (2012) The energy efficiency of local food systems: a comparison between different modes of distribution. Food Policy 37:609–615

Naves M (2003) Caractérisation et gestion d'une population bovine locale de la zone tropicale: le bovin Créole de Guadeloupe. Ph.D. thesis, Institut National Agronomique, 444 Paris-Grignon

Nolan T, Connolly J (1977) Mixed stocking by sheep and steers – a review. Herb Abstr 47:367–374

Nolan T, Connolly J, Guillon LM, Sall C, Dieye K, Guerin H (1989) Mixed animal species grazing under temperate and semi-arid conditions. In: 16th Int Grassland Cong, 1102, Versailles/Nice

O'Mara FP (2012) The role of grasslands in food security and climate change. Ann Bot 110:1263–1270

Ortega-Jimenez E, Alexandre G, Boval M, Archimède H, Mahieu M, Xandé A (2005) Intake and milk production of suckling Creole goats reared at pasture in humid tropics according to the post-grazing residue management. Small Ruminant Res 59:217–227

Patra AK, Puchala R, Detweiler C et al (2008) Tethering meat goats grazing forage of high nutritive value and low to moderate mass. Asian-Aust J Anim Sci 21:1252–1261

Peel MC, Finlayson BL, McMahon TA (2007) Updated world map of the Koppen-Geiger climate classification. Hydrol Earth Syst Sci 11:1633–1644

Powers JS, Corre MD, Twine TE, Veldkamp E (2011) Geographic bias of field observations of soil carbon stocks with tropical land-use changes precludes spatial extrapolation. Proc Natl Acad Sci U S A 108:6318–6322

Pretty J, Sutherland WJ, Ashby J et al (2010) The top 100 questions of importance to the future of global agriculture. Int J Agric Sustain 8:219–236

Reynolds SG, Batello C, Baas S, Mack S (2005) Grassland and forage to improve livelihoods and reduce poverty. In: McGilloway DA (ed) 20th international grassland congress, Dublin, FAO, Rome, Italy, pp 323–338

Sansoucy R, Jabbar MA, Ehui S, Fitzhugh H (1995) The contribution of livestock to food security and sustainable development. In: Proceedings of the FAO/ILRI roundtable on livestock development strategies for low income countries. ILRI Addis Ababa, pp 9–21, 27 Feb–2 Mar 1995

Senbeto F, Tegene N, Getahun L (2013) Feed resources and their management systems in Ethiopian highlands: the case of Umbulo Whaco watershed in Southern Ethiopia. Trop Subtrop Agroecosyst 12:47–56

Soussana JF, Tallec T, Blanfort V (2013) Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. Animal 4:334–350

Suttie JM, Reynolds SG, Batello C (2005) Grasslands of the world. In: FAO (ed) Grasslands of the world. Lavoisier Publishing Inc, New York, p xxii, 1514 pp

Thomas D, Rangnekar D (2004) Responding to the increasing global demand for animal products: implications for the livelihoods of livestock producers in developing countries. In: British Society of Animal Science (ed) Responding to the livestock revolution: the role of globalisation and implications for poverty alleviation. British Society of Animal Science Occasional Publication 33, pp 1–36

Thornton PK, Herrero M (2010) Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics. Proc Natl Acad Sci U S A 107:19667–19672

van Asselen S, Verburg PH (2012) A land system representation for global assessments and land-use modeling. Global Change Biol 18:3125–3148

Waghorn TS, Leathwick DM, Chen LY, Gray RAJ, Skipp RA (2002) Influence of nematophagous fungi, earthworms and dung burial on development of the free-living stages of Ostertagia (Teladorsagia) circumcincta in New Zealand. Vet Parisitol 104:119–129

Wezel A, Bellon S, Doré T, Francis C, Vallod D, David C (2009) Agroecology as a science, a movement and a practice. A review. Agron Sist Dev 29:503–515

Wirsenius S, Azar C, Berndes C (2010) How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? Agric Syst 103:621–638

Zhang W, Ricketts TH, Kremen C, Carney K, Swinton SM (2007) Ecosystem services and dis-services to agriculture. Ecol Econ 64:253–260

Ecosystem Services of Multispecific and Multistratified Cropping Systems

Serge Valet and Harry Ozier-Lafontaine

Abstract New cropping alternatives are explored in response to the drawbacks of the Green Revolution. Alternative practices use the ecological regulations of agro-ecosystems, and strengthen and manage agricultural biodiversity. Multi-species cropping systems are good models to seek innovative solutions. Indeed the combination of crops, ranging from simplest forms to complex multi-stage associations, such as agroforests, have allowed many populations to maintain their production conditions, while at the same time overcoming severe shocks such as droughts, epidemics or changes in market prices. An empirical agroecology has thus been created mainly using traditional knowledge. We present the following benefits provided by the ecosystem services of mixed cropping: (1) yields are often higher than in monocultures, (2) the amount of mineral and organic fertilizers is decreased two times, (3) mixed cropping is an effective alternative to pesticides, (4) water and energy is saved, (5) soil quality is preserved, and (6) worktime is better managed. A true agroecological engineering approach, linking scientific and empirical knowledge can thus be designed.

Keywords Agroecology • Agroecological engineering • Ecosystem Services • Multispecies systems • Multi-stratified agroforests • Peasant agriculture • Traditional knowledge

S. Valet
Passerelles Association (loi 1901), 9 rue du Bât d'Argent, 69001 Lyon, France
e-mail: valet.serge2@wanadoo.fr

H. Ozier-Lafontaine (✉)
INRA, UR1321, ASTRO Agrosystèmes Tropicaux, F-97170 Petit-Bourg, France
e-mail: Harry.ozier-lafontaine@antilles.inra.fr

H. Ozier-Lafontaine and M. Lesueur-Jannoyer (eds.), *Sustainable Agriculture Reviews 14: Agroecology and Global Change*, Sustainable Agriculture Reviews 14,
DOI 10.1007/978-3-319-06016-3_7,

Introduction

'*Agronomists have been trained to eradicate ecosystems in order to create an artificial system, simplified and forced by the introduction of a great quantity of fertilizers and pesticides*' Griffon (2006). Climate change, demographic pressure, environmental impacts generated by intensive agriculture -increased erosion, soil, water and human pollution, reduced biodiversity, emission of greenhouse gases -, depletion of fossil fuels and phosphate, rise in fertilizers prices, multinational and "*globalization*" speculation on food products and lands, all this creates a new context which requires a calling into question of the conventional model of agricultural production with high rates of synthetic farm inputs. The admission of failure to enhance food crops monoculture has been highlighted by the overall decline of production conditions such as the collapse of biological and physicochemical components of soil fertility, and of food crop productivity (FAO 2011), made worse by environmental impacts. In response, more and more agronomists agree that *"the reality of the difficulties encountered by the productivist projects born from the green revolution, must force us to consider this perspective as a utopia"*. That is why the Kyoto Protocol recommends the promotion of sustainable conditions for rational agriculture. Recent years have seen renewed interest for the study of mixed cropping in view of the acknowledgement, widely shared, that the conventional specialized farming model has failed (Debar 2013). Mixed-cropping practices are thus well developed in all continents, in contrasted climates, latitudes, altitudes and ecosystems, oasis, sahel, sudan and tropic (Plates 1 and 2). They come in various forms, not only bi or multi-stratified, but also multistage (Baldy 1963; Klee 1980; Brokensha et al. 1980; Mandal et al. 1990; Morelli 2003; Camara et al. 2009, 2010; Camara 2007) (Plates 1 and 2).

They are common across most agrarian civilizations and are representative of agricultural, food, fruit, forest, and industrial production systems still practiced by hundreds millions of farmers (Altieri et al. 1978; Augusseau et al. 2006; Baldy 1963; Charreau and Vidal 1965; Dupriez 1980a, 2006; Eden 1980; Fortmann and Rocheleau 1985; Hullugale 1988; Le Courrier 2002; Li et al. 2007; Malézieux et al. 2001, 2009; Mazoyer 1972; Mbomda 1985; Norman et al. 1984; Okigbo and Greenland 1976; Torquebiau and Penot 2006; Ravignan 1969; Valet 1968, 1974a, b, 1976; Valet and Motelica-Heino 2010).

The cultivated plant species and varieties, as well as their number, vary according to the latitude but also to the altitude, the food habits and the fertility of the soils (Autfray 1985; Ravignan 1969; Valet 1968, 1976). Intercropping contributes significantly to the world food production in North and South America, in Oceania and in Asia. In Africa, it accounts for the largest share in food production which is yielded in association with fodder, fruits and trees (Altieri 1999; Anil et al. 1998; Denevan 1980; Francis 1986; Lithourgidis et al. 2011; Tremblay 2006; Vandermeer 1989).

Having acknowledged the fact that traditional communities could not afford *'risking their own existence with an unbalanced use of their land'* (Dupriez 1980b), many agronomists now consider renewing traditional farming practices to promote the principles of an ecological intensification based on the supply of ecosystemic services (Gliesmann 2001; Griffon 2006; Malézieux and Moustier 2005; Malézieux et al. 2009).

Restoring on-farm biodiversity through diversified farming systems that mimic nature, is considered to be a key strategy for sustainable agriculture (Doré et al. 2006; Jackson et al. 2010). Besides, it has been shown that intensive modern techniques, even the least degrading, are seldom more profitable than mixed cropping, particularly with the sharp increase in the cost of energy, fertilizers, and machines (Jolliffe 1997; Le Buannec 1979; Roose 1983; Valet 2011a; Willey 1979).

Both Dupriez (since 1980) and Hallé (since 2010) have emphasized the multifunctional role of multi-species and multi-terraced intercropping along with successions of species and complementary varieties, useful to human and animal feeding, as well as to industrial and energetic practices (FAO 2011). Most of them are in a position to supply ecosystemic services and build up complex production systems which should be better known and developed. These ecosystem services and the scales (field, landscape, region) from which they would be assessed, have not been sufficiently taken into consideration, studied or conceptualized (Baldy and Stigter 1997; Valet 2007), compared to the volume of research projects aimed at intensive monoculture performances (Altieri 1999).

Studies on mixed-cropping agrosystems for the promotion of ecological development were carried out on a very short period in the 1960s to be undertaken again at the end of the twentieth century (Baldy 1963; Valet 1968; Malézieux et al. 2009). In their review concerning multi-species systems, Malézieux et al. (2009) propose a highly comprehensive generic framework of concepts, tools and methods available for understanding and modeling the operation and management of these systems. However, this synthesis tackles, to a lesser extent, other types of predictive approaches based on the conditions of implementation of the multi-species systems according to soil-climate and land contexts and realities and of the principles which establish the concept of '*innovative traditional ecological intensification*' introduced as early as the 1950s by the farmers. Few researchers have been interested in the processes of small-scale farming innovation (Dugué et al. 2006) concerning the eco-agroforestry and sylvo-pastoral systems so eagerly sought after by agronomists (Baldy and Stigter 1997; Dupriez 1980a; Ducret and Granget 1986; GRET 1982; Léger-Cresson 1989; Tajuddin 1986; Valet 1968, 1974a, b, 1976). This is probably related to the paradigm conveyed by modern technology and widely introduced according to the top-down model in which the mismatch between research findings and farmers' real needs on the ground is strongly enhanced (FAO 2010).

The diversity, of multispecies cropping at the field as well as well as at the hillslope scale, requires further analysis to qualify and quantify their possible contribution to the supply of ecosystem (Millenium Ecosystem Assessment 2005) and economic services which are an essential prerequisite for sustainable development. So here we review the diversity of traditional plant communities and bio physicochemical processes that 'traditional, empirical and innovative ecological intensification' involves. This analysis covers three main areas: (1) diversity and typology of multi-species and multi-terraced intercropping at the field, landscape and territory scale, (2) ecosystem and economic services, (3) considerations on agroecological engineering of mixed/inter cropping systems.

Multi-species Cropping Systems Diversity

Mixed cropping systems cover many modes of spatial distribution – on the surface, above and below the ground level -, and time distribution, in relay with perennial or annual species. They can combine very different plants (grasses, shrubs and trees) in contrasting climate ranges from temperate to tropical environments (Huxley 1983; Papendick et al. 1976; Torquebiau 2000). They are subject to a wide range of analysis and assessment methods (Baldy 1963; Malézieux et al. 2009; Nair 1985). This apparent diversity and even complexity of organizational models may, from a functional point of view, be structured according to nested scales from the field to the territory, in order to deliver ecosystemic services.

Multi-species Space-Time Organization

The terms and conditions of species combinations can be described in five main types (Malézieux et al. 2009; Vandermeer 1986): row intercropping, alley crops or strip intercropping, mixed cropping, mosaic intercropping and relay/sequential crops). These types combine perennial and annual plants in various configurations and for cycles of varying duration and multiple uses in all continents (Barral and Sagnier 1889). Figure 1 shows some possible spatial arrangements of systems with the combination of two crops.

Dupraz and Liagre (2008) describes several forms of incorporation of the species diversity in cropping systems at the field scale through a spatio-temporal interaction gradient conditioning the importance of interspecies competitions. This typology is illustrated in Fig. 2, which distinguishes five main types.

Perennial and annual grass, shrub and tree crops can indeed be combined at various degrees of mixing, according to various spatial and temporal terms and in similar or lower densities than those found in each monoculture.

Different agroforestry models, incorporating trees and shrubs, have been developed in all continents like European and Sudan-Sahelian wooded parks, Indonesian, Indian and Creole forest gardens, oases, mixed cropping in Cameroon,

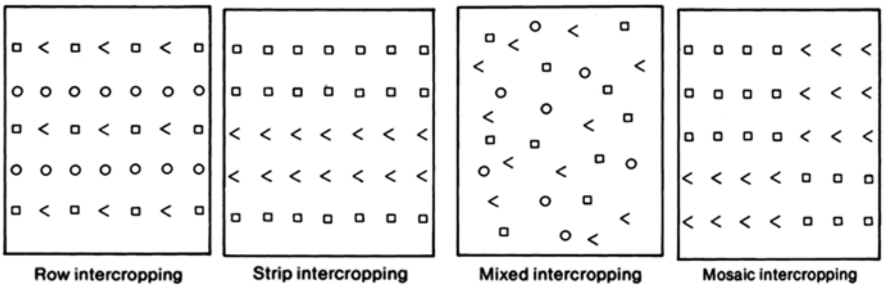


Fig. 1 Some examples of spatial arrangement of mixed cropping

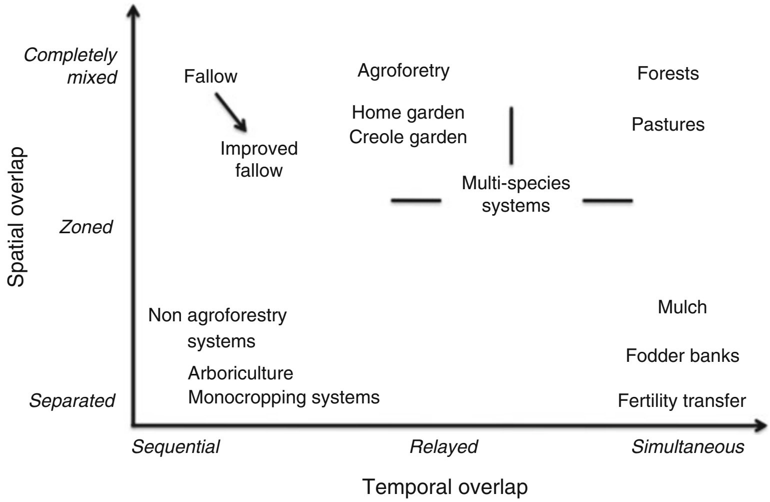


Fig. 2 Classification of multi-species systems according to the degree of spatial and temporal covering of trees and crops (Adapted from Van Noordwijk et al. 1996)

Oceania India, and Asia (Eden 1980; Fortmann and Rocheleau 1985; Klee 1980; Michon 1985; Palapiapan 1988; Nair 1979; Rabot 1982; Steiner 1985; Torquebiau and Penot 2006; Valet 1972). These mixed systems have a high graining rate with a Land Equivalent Ratio (LER), or Equivalent Density Ratio (DER) > 1, in temperate and Sudan-Sahelian areas, and a 1.1–9 arid to in tropical areas (Plate 1a–c). In the garden-forests of Java, 200 plants can be grown, more than 300 in Vera Cruz, and more than 50 trees in Bangladesh (Torquebiau 1992). These results, obtained in the same conditions, comparing mono and mixed crops, were explained by the ability of the mixed systems to provide EcoSystems Services.

According to the oasis model, beneath the canopy of various palm cultivars come the fruit trees level (up to 18 species), then the grasses and vegetable (28) food (3) and forage crops (3) (Battesti 1997). This species abundance can be explained by the fact that the farmer must take a position on different options and strategies of space, regarding the occupation of an irrigated and cultivated area which is not extensive at all, and time.

Since the 1980s, in Mali, Burkina Faso and Niger, in the dune systems of the region of Zinder and Maradi, farmers have used Assisted Natural Regeneration (ANR) on millions of hectares (USAID et al. 2002) (Plate 2a–f). Six main tree species (Gao, palmyra, baobab, néré, zizphus, parkinsonia, Lannea, hibiscus, etc.) are used (20–120 trees per hectare) to ensure the fertility of the soil (Plate 2a), food supplement to be better prepared for famines, various combinations of medicinal species and two growing seasons (Plate 2b–d), firewood and timber, and a feed supplement (Plate 2e) (Larwanou et al. 2006). Traditional irrigation (feeder-screw, watering can, chadouf), greatly improved by the foot pumps, enables to intensify the crop mix and increase its surface, as well as the duration of the growing period (Plate 2f).

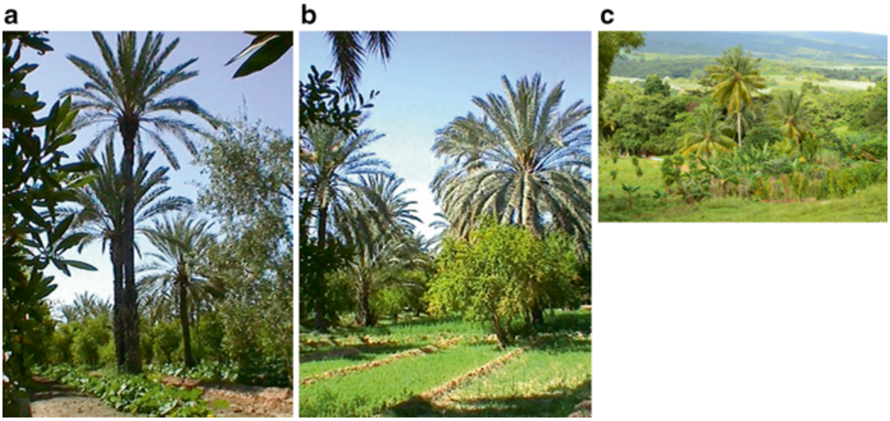


Plate 1 (**a**) Mixed crops three-stratified with palm trees. (**b**) Intercropped horticulture crops with grenadiers (Moussa 2004). (**c**) Creole garden in Guadeloupe (H. Ozier-Lafontaine 2012)

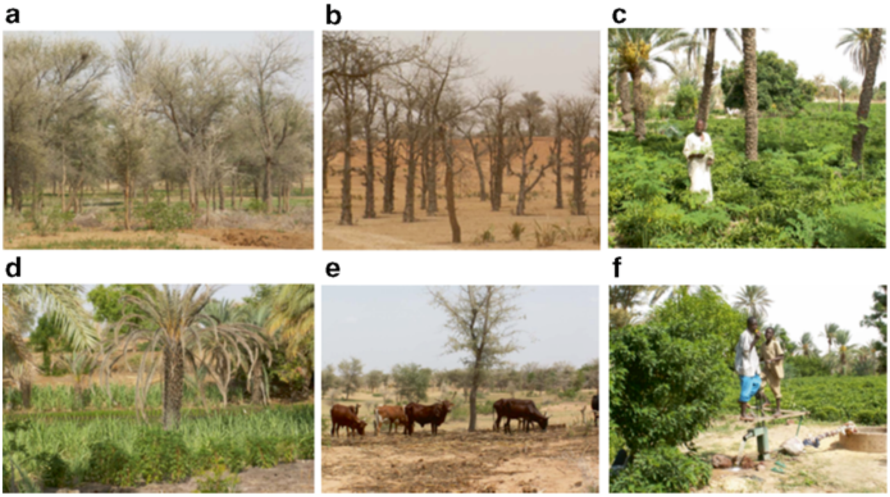


Plate 2 (**a**) Young gao (Faidherbia albida) park presenting a very high density. (**b**) A baobab (*Adansonia digitata*) park. (**c**) A basin planted with date palms, mango trees, cassava, sugar cane and rice, (**d**) palm trees with four crops a year in the fadama, Tassaou, (**e**) crops mixed with livestock and (**f**) the use of a foot pump facilitates irrigation (Chris Reij 2006)

Agroforestry practices, once common in Europe, were gradually abandoned during the twentieth century (Dupraz and Liagre 2008), mainly for reasons related to the intensification and mechanization of agriculture. A form of agroforestry combining rows of trees for timber production with intercropping (silvo-arable agroforestry) is now experiencing renewed interest since it is compatible with crops mechanization (Plate 3a and b). Agroforestry in temperate environments allows

Plate 3 (**a**) Pollarded maples, inserted in the vineyard in the Pyrenean piedmont (S. Guillerme). (**b**) Mechanized agroforestry system combining poplars and wheat on alternate spaced lines in the south of France (LER = 1.3) (Dupraz in Malézieux et al. 2009)

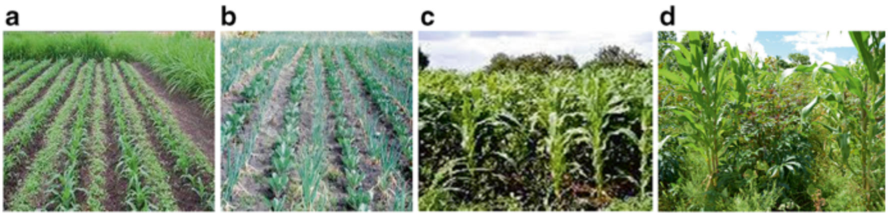


Plate 4 Different annual bispecies combinations: (**a–b–c**) grain/legumes (Séguy et al. 2008) and (**d**) annual plant based multispecies combinations (manihot/maize/cucumber) (Guadeloupe, H. Ozier-Lafontaine et al. 1998)

farm diversification, combining a steady income generated by a continuous crop production with the introduction of standing timber.

Recent studies show that some agroforestry systems could be up to 30 % more productive than crop rotations with agricultural fields on one side, and afforestation of farmland on the other, with food grain and forage production (Anil et al. 1998; Dupraz et al. 2004; Graves et al. 2007: Lithourgidis et al. 2011). Politically, agroforestry is particularly highlighted for its agri-environmental performances. It could be a particularly efficient means to fight against soil erosion, nitrate pollution of rivers and aquifers, standardizing landscapes and biodiversity loss.

From Sahelian to tropical zones, mixed cropping, not including fodder crops, shows an apparent disorder which actually falls within the scope of a sustainable spatial and temporal distribution. It takes into account the different symbiotic services as well as the antagonisms between species (Autfray 1985; Baldy and Stigter 1997; Ahmed et al. 2007; Ducret and Grangeret 1986; Kleitz 1988; Trenbath 1976; Valet 1972, 1976, 1999) as it is illustrated in Plates 4a–d and 5a b.

Thus, under these climate conditions, the constraints resulting from water and soil conditions imprint the types of annual and perennial plant combinations and

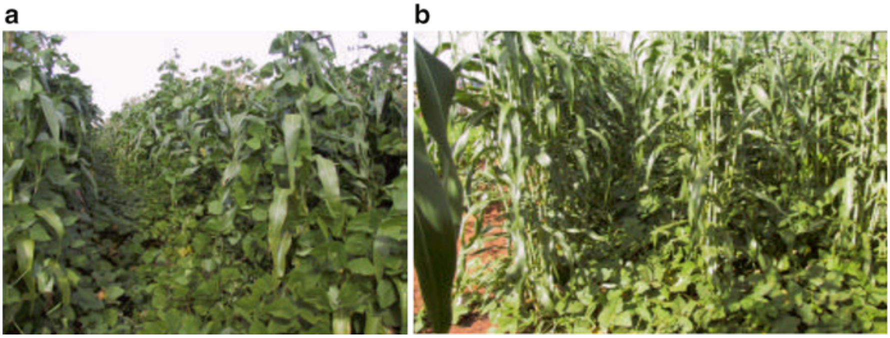


Plate 5 Combination (**a**) maize/cowpea and (**b**) sorghum/beans (vigna), in Madagascar (Photos Séguy 2003)

often provide higher yield than any monoculture even in extremely unfavourable conditions (Dancette 1984).

Criteria for Differentiating the Types at the Field Scale

When two or more crops are growing together, each must have adequate space to maximize cooperation and minimize competition between them using the niche differentiation concept. To achieve this, four criteria need to be considered: (i) spatial arrangement, (ii) plant density, (iii) maturity dates of the crops being grown, and (iv) plant architecture. Even if the possible combinations are endless on a theoretical level, in reality, the degree of complexity of the systems is constrained by parameters depending on the size of the plants, the complementarity or antagonism between species, the microclimate and its variations, the sunlight, the various stress factors, the technical mastery and, to some extents, of the current prices (Ducret and Granget 1986; Dupriez 1980a; Valet 2004).

In the Sudano-Sahelian zone, even in a drought, the land use indices of a bispecies combination millet/cowpea ranged from 0.85 to 1.73 depending on the variety (Dancette 1984; Diagne 1987). The yield of millet is strongly and inversely correlated with the density of *leucaena.* Improvement of indigenous systems is also likely, as there appears to be a response to tile management of the major tree species concerned that enhances their favourable qualities (Charreau 1974; Miche 1986). With the improvement of soil and climatic conditions, the number of crops, typically from bi to tri-species in the temperate and Sudano- Sahelian zones, ranges from 12 to 300 species ha^{-1} in the humid tropical zone.

When the agro-geological context vary from bad to good like in the upper tropical zone of Western Cameroon, 2–46, are specially adapted thanks to the modulation and evolution of density, distribution and species. Their density on the ridge has a

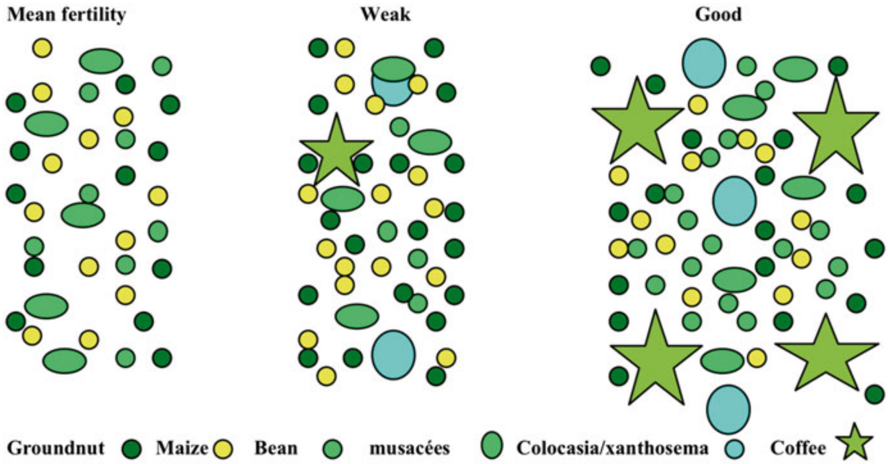


Fig. 3 Evolution of mixed cropping spatial arrangement in first season according to soil fertility (Valet 1972, 1974b)

land use Ratio from one to nine (Autfray 1985, Baldy and Stigter 1997; Kleitz 1988; Leplaideur 1978; Ravignan 1969; Valet 1976, 1999).

The plant disorder attributed to intercropping, being only an appearance, it is interesting to identify the unit cell that can be found in all environmental conditions. This 'unit cell' hinges is defined around the couple maize/groundnut with or without trees (coffee/cocoa and/or others) (Fig. 3).

The typology is very complex because all the geometric forms of combination can be found along the slopes of the different agro-geological landscapes (Kleitz 1988; Valet 1976) (Plate 6a–c). It is possible to identify the dynamics which is a driving factor of multi-cropping systems differentiation (Valet 1968, 1974b).

Fotsing (1993) notes that half a century of scientific popularization was not enough to convince all farmers to abandon traditional techniques. In 1991 only 5.5 % of farmers have adopted the contour ridges. The lush and healthy intercropping, the excellent apparent structural stability of cultivated soils, even on steep slopes, and the healthy eating of the population over centuries, contradicted the agronomists' assertion that *'the Bamileke farmers did anything, anywhere, anyhow'* (J. Praquin, an oral communication 1966) and *'Bamuns practiced a primitive agriculture'* (Tardits 1961). But the study of eight farmer's fields (five in Bamileke country and three in Bamun) under contrasting soil and climate conditions, provides information on this dynamics and the criteria used to identify the different types. Thus, in these fields, the land use Ratio varies from 1.04 to 9 in Bamileke region for identified plants, and from 1.44 to more than 2 in Bamun region for identified plants outside trees (Valet 1968). Comparable DER were measured in Menua with 3.29 (Autfray 1985) and south-central Cameroon with 1.49 (Leplaideur 1978; Ravignan 1969). And the farmers vary quantitatively (DER) and qualitatively (species and varieties) to meet various

Plate 6 (**a**) Agroforestry combination in Bafou. Dry season: trees, sweet banana and plantain, beans (vigna), tubers (dry season) (Photo S. Valet 1999). (**b**) Food crop combination in Foumbot: corn, cocoyams, groundnut, phaseolus, tubers, sweet potatoes, (1,200 m) (Photo S. Valet 1968). (**c**) Food and industrial crop combination, edge of the M'Bos plain. Oil palm, robusta coffee, corn, tubers (850 m) (Cliché S. Valet 1968)

morpho-pedo-hydro-climatic criteria and species tolerances as shown in Fig. 4a, b (Valet 1976, 1999).

But other factors such as the risks of erosion, distance from markets, monetary needs, organoleptic and food needs, changes in local, national and international prices, are taken into account by farmers. Thus the sum total of the land use Ratio

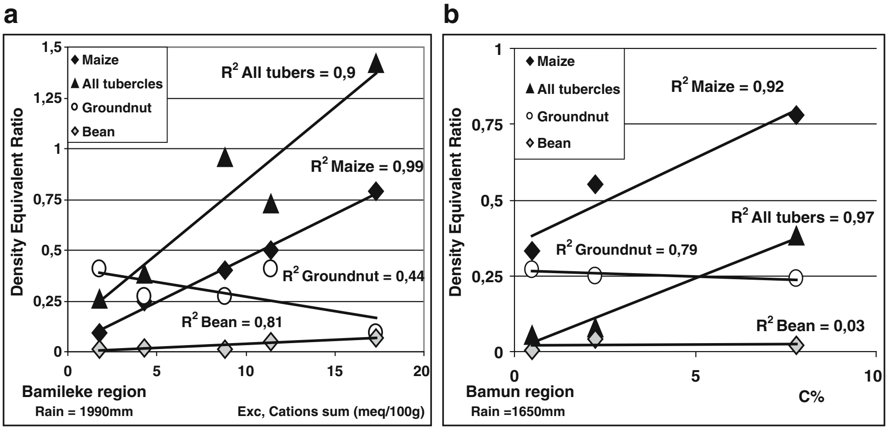


Fig. 4 (**a**) Maize, groundnut, bean, and tubercles DER vs and cations exchange sum (Bamileke region) and (**b**) C% (Bamun region) according to climatic drought risk (Valet 1976, 1999)

gradually moves from the poorest to excessively rich soils, from 1 to 2.9 in Bamileke region and 1.4–2 in Bamun region. In line with the increase in corn density, farmers have reduced that of groundnut and beans (cowpea). But there is an antagonism between bean/maize and groundnut/cowpea. The land use Ratio of the other species does not seem to be dependent on fertility. The corn/bean affinity was confirmed by Autfray (1985) and Kleitz (1988). Both authors identify a corn/bean affinity. Moreover, these authors report a conflict of peanuts with trees, Musaceae, coffee, taro and cocoyam. This incompatibility is also observed between corn/soybean intercropping (Valet 1999). From the first 4 years over 10 years of experimentation, Salez (1990), showed a strong antagonism between the LER for this combination, but with a total LER superior to that of the monocrops (1988) (Fig. 5).

This antagonism, which limits the overall production of the combination, can be explained by the competition for light and its effects on photosynthesis (Clark and Francis 1985). This is one of the reasons why this combination has not been adopted by farmers. A similar repulsion was observed between millet and cowpea in Mali by Hulet (1986) and Klaij et al. (1994), except with a supplement of P, and 21 kg of P ha^{-1}.

Farmers adjust the land use indices to less than 2 and less than 1.5 respectively for the climate and soil drought. After harvesting corn and legumes, farmers sow cabbage, potatoes, eggplant, peppers and beans and leave fields in fallow. Only taro, yam, macabo, sweet potato, banana, pepper, eggplant, sugarcane, remain for several consecutive years. Combinations are not only excessively more complex, but also, regarding the cultivated plants (species and varieties) they evolve very rapidly as a result of the very strong dynamism of the farmers which adds to the existing diversity (Kleitz 1988).

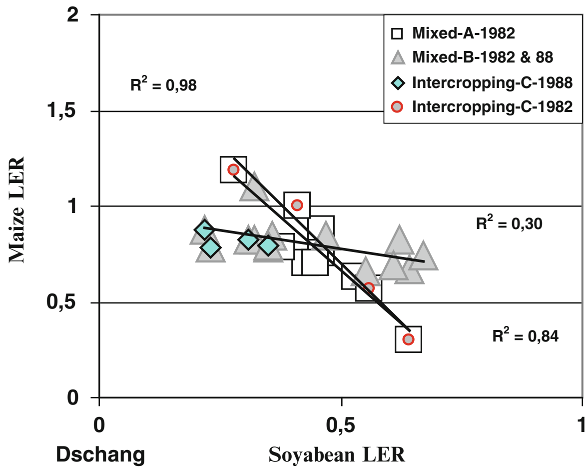


Fig. 5 Alley (C) and mixed (A, B) cropping of maize vs. soyabean LER (1982–1988)

It would be simplistic to limit these combinations to only three types as proposed by Autfray (1985) and Kleitz (1988). Farmers also use all forms of combinations described in Fig. 1, intercropping and relay, similarly taking into account the current soil fertility variation. In the first year, the taros/cocoyams (macabos), which clean the ground, prevail on clearing. In the second year, maize is favoured on rich soil, and groundnut and vouandzu (*voandzeia subterranea*) on poor soil. Both of them are top of the two types of rotations.

Tests conducted in Cameroon on a trispecies combination showed that the best yields were to be observed only in mixed cropping arrangement for maize and cocoyam for high yields, and for taro intercropping in low as in high yield (Fig. 6a–c). In Foumbot, on rich soil, Samson and Autfray (1985) found that the traditional mixed arrangement for a combination maize/soyabean is far preferable to intercropping arrangement. The influence of the spatial arrangement for three plants is obvious but less decisive than for the much more numerous and heterogeneous combinations as demonstrated by Lamanda in Vanuatu (2005). It was also showed that intercropping or mixed arrangement could in turn provide a better yield in grain or straw according to the values of the legume DER under satisfactory rainfall conditions. The small number of sites offset by their choice still allows proposing reliable rational conclusions.

In Brazil and in Madagascar, in small family farms as in field crops, the technique of Permanent Soil Cover Technology (PSCT), based on SeBoTas rice, favours multi-species and varied row and relay combination as recently been practiced: Soya + (Corn or Sorghum, + *Cajanus cajan* or *Crotalaria spectabilis*), Soya + (Corn or Sorghum + *Stylosanthes guianensis*), Soya + (Corn or Sorghum + *Eleusine coracana* + *Cajanus cajan* or *Crotalaria spectabilis*), Soya + (Sunflower + *Crotalaria spectabilis ou Stylosanthes guianensis*) (Séguy 2003; Séguy et al. 2008; Husson et al. 2010).

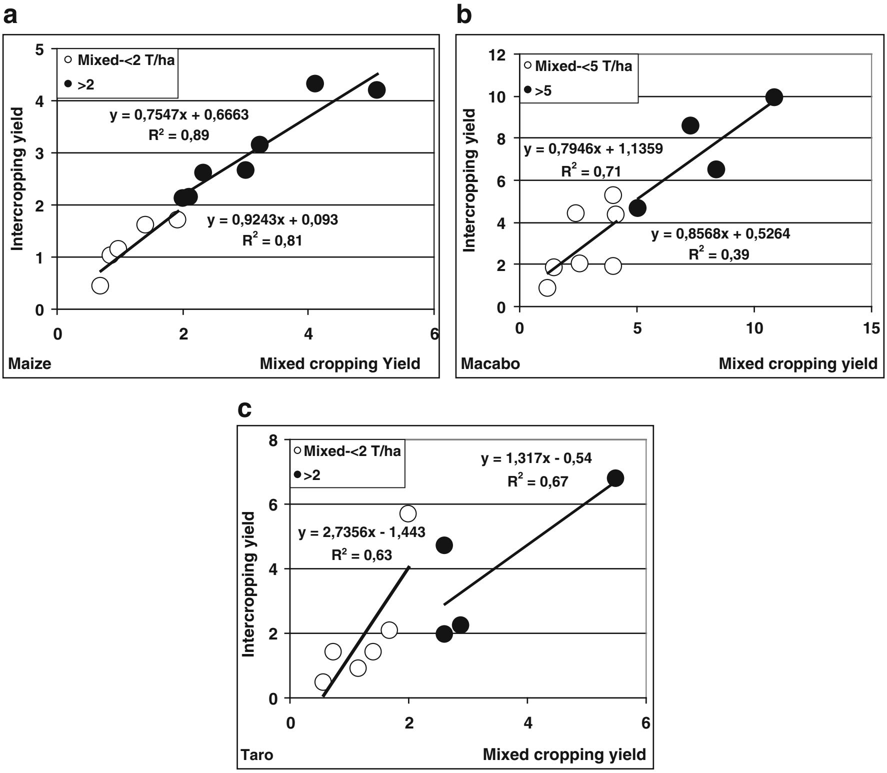


Fig. 6 Mixed cropping vs intercropping yields (T ha^{-1}) for two yield levels of (**a**) maize; (**b**) Xanthosoma and (**c**) Colocasia (West Cameroon 1968–1971)

Criteria for Differentiating the Farming Systems at the Watershade Scale

The permanence of a species or group of species or a particular system depending on the position on the slope in the watershade shall be adopted.

In the most rainy and hot tropical zones, a system as crops with or without coffee, cocoa, palm tree, grassland, forest, agro-forest, cultivated park has been made possible (Lamanda 2005). In the forest-savannah transition zone, cocoa-palm tree and fruit trees are commonly combined in center Cameroon and coffee – cocoa in Guinea with varying densities (Jagoret et al. 2012).

In the Sudanian zone, still complex combinations (two to about six species), either mixed or in row or in relay can be found on the slope (Valet 1984; Reij 2006) (Plate 7a and b). This variability is conditioned by the variability of the water supply. Indeed, along the slope, a water runon can be seen (Valet 1995). It plays the role

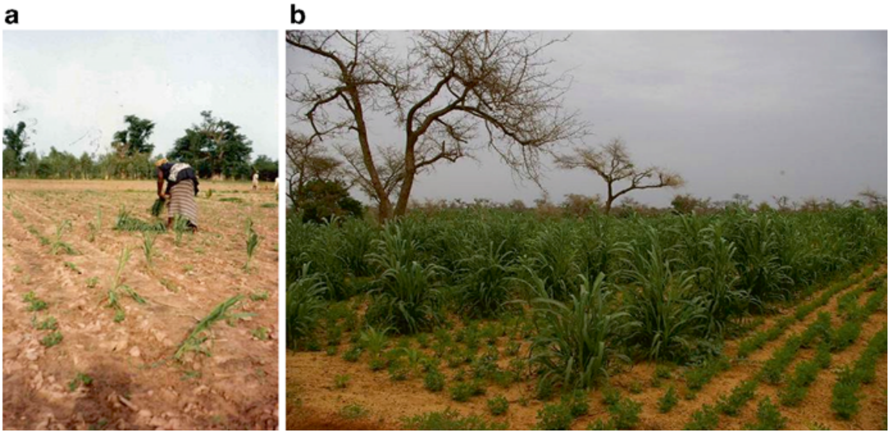


Plate 7 (**a**) Pricked out millet in groundnut field on footslope (Senegal). (Cliché S. Valet 1984); (**b**) groundnut and millet in 'park with Fhaiderbia' (Niger) (Cliché Chris Reij 2006)

of an additional irrigation to the rain which generated it depending on the surface and slope condition. Bouzinac et al. (2009), in the context of the doubly green revolution, have tested upland rain-fed sebotas rice combined and in rotation with other crops which not only help expand their geographical area to very irregular rainfall regions (Far N-Cameroon), but also conquer huge soil units considered infertile (*'Hardé'* soil of N-Cameroon) or underused [*Vertisolic 'Karal' soils of North Cameroon; iron baring, very acid, substantially desaturated high-altitude soils (1.000 m) of the Plain of Jars in the region of Xieng Khounag in Laos*].

Different cropping subsystems have been defined and arranged in terraces on the slope depending on soil fertility. Atop the hill, come first the meadow and the fallow, then the mixed food crops, then the mixed food crops and coffee, around the huts comes the garden with banana trees, then in the thalweg comes the raphiaie receding in front of the dry season gardening especially near markets (Fig. 7). Each side is remodeled physically and micro-climatically, specially by the type of crops imposed by climatic and soil characteristics. The small fields and quickhedges structure practiced by farmers with a rational distribution on the slope of living and dead quickhedges reflects bio-technical, agricultural, social and economic concerns. These systems ensure a saving of land, due to a maximum use of the land surface, and of time (Hecq 1958). It contributes to a significant overall increase in biomass production per unit of area.

Criteria for Differentiating the Farming Systems at the Territory Scale

These species distributions on the slope are also developed on the granitic hills of Central Africa especially among the Bashis in the DRC (Democratic Republic of Congo) where the banana plantation forms the ecological and economic backbone

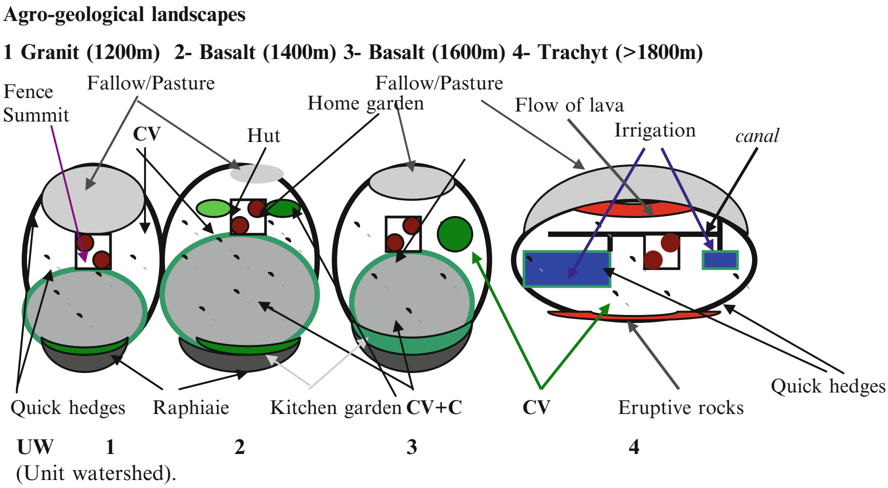
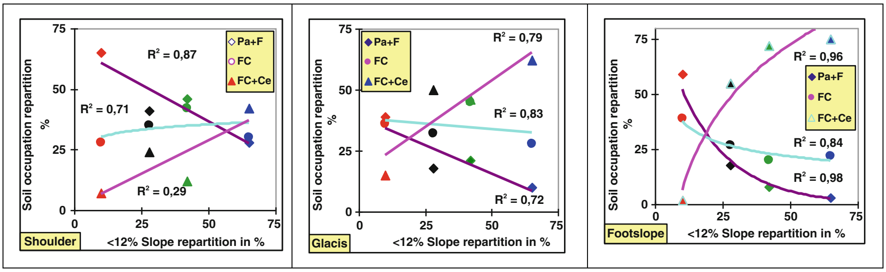


Fig. 7 Scheme of type distribution of innovative traditional and agricultural subsystems on the slope according to agro-geological landscapes and microclimates (West Cameroon) (Valet 1980, 2007)

of agro-systems (Dupriez 1980a, b; Hecq 1958; Ravignan 1969). The combination of coconut alone with food crops and other perennial crops is practiced in many countries and has led to the rise of agroforestry systems of varied nature in Asia (Das 1999) and the Pacific (Manu and Halavatau 1995). In Vanuatu, agro-forestry is based on coconut alone or with cocoa combined in different farming systems with fruit trees dominating food gardens (Lamanda 2005). In Burundi, farmers have, for 50 years, greatly complicated their systems implanted in rings on the hillsides around the *"rugo"* (enclosure) by the introduction of cash crops with a touch of finely reasoned intensification (Cochet 2001).

For the Bafu chiefdom, near Dschang, West Cameroon, the physiographic analysis of the unit watersheds explains the spatial distribution of cultivation sub-systems described in the previous paragraph for each agrogeological landscape. On the slopes, the hillsides of the agro-geological landscapes can be divided into three series (Slope ≤12 %, 12–25 % and ≥25 %). Indeed, Valet (1999) showed that soil fertility, characterized by the land gradient at different levels of the slope (top, mid-slope, down slope) for each unit watershed of different agrogeological nature, explains the extreme variability of mixed cropping systems observed on 486 fields but not explained by Autfray (1985).

The variability of the three major mixed cropping systems [mixed food crops without coffee (FC), with coffee (FC+Ce) and Pasture and fallow (Pa+F)] is due to the geomorphology and distribution of fertility on the slopes and between geofacies and climate (Valet 1974b, 1999). There is an excellent correlation between the percentage of these systems and the percentage of the lowest slope (≤12 %) on the three positions of the slope depending on altitude (Fig. 8a–c shoulder to foot-slope). At the top of the slope, the Pasture-Fallow system decreases whereas the mixed Food Crops and Coffee system increases, the mixed Food Crops system



Red : >2000m: trachyt and acid rocks; **Black**: 1600-2000m: Basalt; **Green**: 1200-14000m: Granit; **Blue**: 1400-1600m, Basalt.

Fig. 8 Percentage of ≤12 % slope vs percentage of agrarian systems occupation according to the agrogeologic landscapes fertility and the altitude for three hill slope positions (a-Shoulder; b-Glacis; c-Footslope) at the region scale. Pa + F = Pasture + Fallow; FC = mixed food crops; FC + Ce = mixed food crops + coffee

remains almost constant (Fig. 8a shoulder); in the middle of the slope, both mixed Food Crops and mixed Food Crops and Coffee systems increase whereas the Pasture-Fallow decreases proportionally (Fig. 8b glacis); and down the slope, only the mixed Food Crops and Coffee system increases sharply although not proportionally whereas the other two systems decrease (Fig. 8c footslope). The part occupied by Pasture, compared to Fallow, decreases from 38 % to 10 % down to 0 % at the top and from 40 % to 0 % down the slope, as the mixed Food Crops and Coffee systems increase. The presence of coffee is generally an indicator of the good fertility of the down slope geo-facies, and more specifically on basalt than on granite at 1,400 m.

The spatial distribution of agricultural systems is an empirical knowledge of the quality of agricultural land spread over agro-geological landscapes and covering a very broad spectrum of fertility, but also of the effects of climate.

In Chinese agriculture, intercropping has a 1000-year old history (Dong Zhou and Qin dynasties -770–206 BC) and is still widespread in modern Chinese agriculture (Knörzer et al. 2008; Li 2001). The monocropping systems have to be revised and may not be the best performing systems any more, considering sustainability, income security and nutritional diversity in rural areas. Therefore, intercropping systems about 28 million ha (Li et al. 2007) offer alternatives for a more sustainable agriculture with reduced input and stabilized yield. Intercropping (strip and relay intercropping) may be a suitable strategy to do so as multiple crops can be grown simultaneously over space and time offering the chance for a better use of solar radiation, nutrients and water over the growing period. Intercropping bears more advantages and is more than maximized field exploitation (Vandermeer 1989). Intercropping a cereal–cereal association such as wheat and maize become increasingly popular in irrigated areas and in the North China

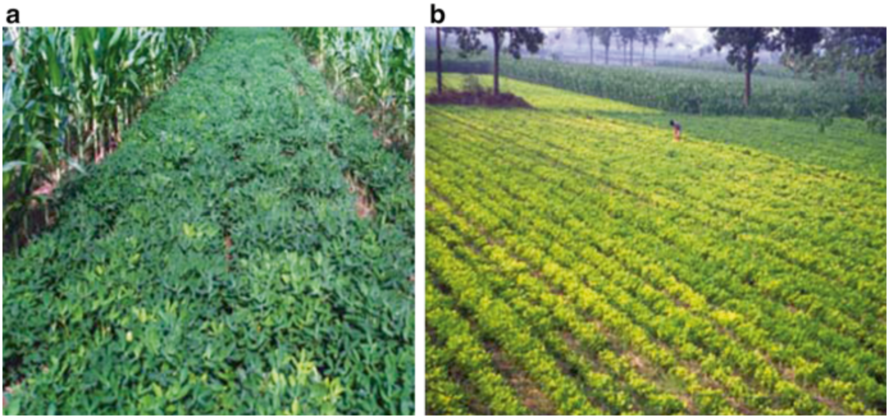


Plate 8 Intercropping of maize and peanut reduces iron chlorosis in peanuts on calcareous soils (**a**, **b**): differences between (strip) intercropped (l.) and monocropped (r.) peanut in the field (Pictures: Zhang, F. in Knörzer et al. 2008)

Plain. Both species grow together for about 70–80 days and yield more than 12,000 kg ha^{-1} (Zhang and Li 2003). Hence, a traditional cropping system could turn out to be a modern one (Lu et al. 2003; Zhen et al. 2005; Knörzer et al. 2008) (Plate 8a, b).

The knowledge of the heterogeneity and the spatial and temporal structure of the "*unit cell*" or micro-landscape at the field scale (Burel and Baudry 1999), of the agro eco-geological landscapes at the slope scale, and of the mix of these landscapes at the territory scale, is a prerequisite for predicting the ecological dynamics of a region. The levels of a natural organization, or resulting from agricultural practices, are stable only if the geo-morphological and climatic context of the place is respected (Burel and Baudry 1999). In these systems multi-terraced intercropping systems, each field is governed by a particular agricultural, economic, soil, social, use, transmission, gender (male-female), collective/individual status. At the field scale, the tree or several trees of variable density according to the soil and climatic conditions, is a typological feature (Valet 2011a). This feature has been noted by other researchers (Autfray 1985; Kelty 2006; Kleitz 1988; Torquebiau et al. 2002). For an efficient simulation, it would be interesting to check whether agroforestry, as practiced in tropical forest areas, retains the trees distribution of the primary forest corresponding to the distribution of the branches of a single tree per area of a given size, that is to say a fractal structure described by Enquist and Niklas (2001).

As described above, the temporal and spatial diversity of multispecies systems is broad, because of its adaptation to the environmental constraints, economic pressures and the strategy of farms. These systems are often more productive while ensuring the sustainability of ecosystems. This is due to multiple free EcoSystemic Services (ESS), shared by the plants themselves and with the biotic microorganisms components that grow there.

Multi-species Systems and Ecosystemic Services

General Context for the Analysis of the Ecosystemic Services Provided by Multi-species Cropping Systems

An increase in cultivated biodiversity (whether species or allelic) created through multi-species cropping systems (MCS) is generally associated with increased biological efficiency (Reddy and Willey 1981) while the provision of a variety of services – water, changes to the microclimate, protection against water and wind erosion, protection against disease and predators – also contributes to increased yields (Jolliffe 1997). Furthermore, multispecies cropping systems can contribute to a reduction in agricultural and economic risk and improve working conditions (Dupriez 1980a, b; Dupriez and de Leener 2003; Gomez Delgado et al. 2009; Malézieux et al. 2009).

The concept of ecosystemic services – a process whereby agricultural ecosystems produce benefits for society – introduced by the Millennium Ecosystems Assessment (MEA 2005), offers a more comprehensive analytic framework for classifying services, as well as disservices, liable to result from multispecies cropping systems. The services provided by ecosystems and the stock of natural capital that produces them are critical to the functioning of the Earth's life-support system. They contribute to human welfare, both directly and indirectly, and therefore represent part of the total economic value of the planet (Costanza et al. 1997). These **EcoSystemic Services** can be divided into four major categories:

- Provisioning services include production of food, water, fiber, fuel, and genetic resources.
- Supporting services include primary biomass production, nutrient cycling, nitrogen fixation, and soil formation.
- Regulating services include regulation of climate, water quality, disease and arthropod pests, natural hazards, and pollination.
- Cultural services include inspiration for art and spirituality, as well as opportunities for recreation, ecotourism, and education.

Malézieux et al. (2009) propose an initial redistribution of processes and properties induced by multi-species systems, without however arranging them on the basis of Millennium Ecosystems Assessment's proposal.

Table 1 is a proposal for an organization grid of the **ecosystemic services** produced by the multispecies cropping systems. On this basis, it should be possible to provide a more complete illustration, with a bibliography, of the experiences and results obtained from the ecosystemic services provided by the multispecies cropping systems while stipulating that a service can be provided by means of a combination of several processes.

Table 1 Generic conceptual framework for the classification of ecosystemic services provided by multi-species cropping systems

Major types of SES	Agricultural and no-agricultural services	Resource or process	Scale P: Parcel C: Catchment
Provisioning	Productivity	Differentiation between niches (space, time, functionality): use of the existing resources in the environment (light, water, minerals)	P
	Food, wood, fiber, and energy	Organoleptic improvement	
Supporting	Sequestration of C	Soil covering	P and C
		Leguminous species	
		Organic matter accumulation	
	Nutrient cycle	Addition of nutrients	P
	Soil formation	N fixation	
		Recycling nutrients	
		Trapping nutrients	
		Stopping leaching of nutrients	
		Conservation/transfer of fertility	
Regulating	Protection/ conservation of water and soil	Protection against water and wind erosion: soil covering/limiting runoff, improving the catchment area, modeling, planting in contours	P and C
		Inhibition of the formation of crusts and reducing soil	
		Evaporation by covering the ground and using wind-breaker hedges	
		Biological plowing (sol engineering: earthworms, roots, termites, etc.)	
	Regulation of plant pests and diseases	Dilution effect	P and C
		Repulsion effect	
		Physical barrier	
		Habitat effect (niche for harmful predatory insects)	
		Pest control effect	
		Orientation of trophic networks (macro and micro biodiversity)	
		Allelopathy	
		Coil covering vs. weeds	
		Predators on pests	
	Climate regulation	Sequestration of C and GES limitation	P and C
Socio-economic and cultural	Economic function	Risk-spreading	P and C
		Production for sale/own consumption	
		Weighting of variations in local, national and international prices	
		Social peace	
		Financial and food self-sufficiency	
	Social and cultural function	Ritual/cultural customs	P and C
		Curbing the exodus from the country	
		Ecotourism – wellbeing – education	

Provisioning Services

Effect on Plant Productivity

Productivity per area unit can increase when crops are associated, if compared with single crops (Willey 1979), or not if conducted in wrong conditions. Yield advantage occurs because growth resources such as light, water, and nutrients are more completely absorbed and converted to crop biomass by the intercrop over time and space as a result of differences in competitive ability for growth resources between the component crops, which exploit the variation of the mixed crops in characteristics such as rates of canopy development, final canopy size (width and height), photosynthetic adaptation of canopies to irradiance conditions, and rooting depth (Midmore 1993; Morris and Garrity 1993; Tsubo et al. 2001). We must also report that biotic factors as supported by mycorrhizae, bacteria, fungi, termites, collembles, insects etc., play an equally important role (Derelle 2012).

In normal rainfall conditions as well as in low rainfall, at the same input level, numerous researchers have demonstrated the supremacy of combined crops under all types of geo-morpho-pedological conditions.

Bispecies Associations

The main associations between cereals and legumes provide variable LERs dependent on the distribution of populations of:

- 0.97–2.6 for maize and legumes (French beans, soyabeans, pigeon peas, coriander, cowbeans or cowpeas) in India, Cameroon, Senegal and Nigeria (Ahmed and Rao 1982; Dancette 1984; Djangar et al. 2004; Hugar and Palled 2008; Marer et al. 2007; N'tare et al. 1987; Odhiambo and Ariga 2001; Salez 1990; Shetty 1987; Ullah et al. 2007).
- 1.04–1.24 for Barley intercrops with Austrian winter pea (*Pisum sativum* sp. *arvense* (Chen et al. 2004).
- LERs of 2.12 (1998) and 2.01 (1999) of Sorghum-Peanut intercropping (Langat et al. 2006).

For the Association of Tubercles with Legumes/Maize

- LERs of the sweet potato + bean variant of 1.69–1.79 depending on density of beans.
- LER varies from 0.98 to 1.6 for the yam with maize or peanut, mixed cropping favours yield per unit of area and, in intercropping, the size of the tubercles (Cornet 2005; Lyonga 1980; Odurukwe 1986).
- tomato-cowpea produces LERs of 1.08–1.31 depending on their respective densities (Obedoni et al. 2005).

Table 2 Ratio of equivalence of N and P_2O_5 efficacy in maize – bean/soybean intercropped

Mineral fertilization	Doses Kg/ha	EER Maize/soybeans	EER Maize/beans
N	40	3.53[a] (6)	2.36 (5)
P_2O_5	50	1.45 (2)	1.93 (1)

FEER = [kgU-1 of intercrop 1/kgU-1 of monocrop 1] + [kg/U-1 of intercrop 2 kg/U-1 of monocrop 2 + [kgU-1 of intercrop 3/kgU1 of monocrop 3]
[a](6) Number of trials

Trispecies Associations

The maize-taro-Xanthosoma association produces LERs of 1–2 (Valet 1968, 1972, 2007) and maize-soybean-bean and maize-xanthosoma-bean in Cameroon (Salez 1990).

This LER variability can be explained by the density and even the geometry of the seedling plantings and how much mineral or organic fertilizer they are given.

Multispecies Associations

In West Cameroon, food plots have an LER of 2.35 with coffee and 1.44 without coffee, the latter plantings being on low-fertility soil (Ducret and Grangeret 1986).

Effect of Mineral Fertilization Approvisionning

Impact of Practices

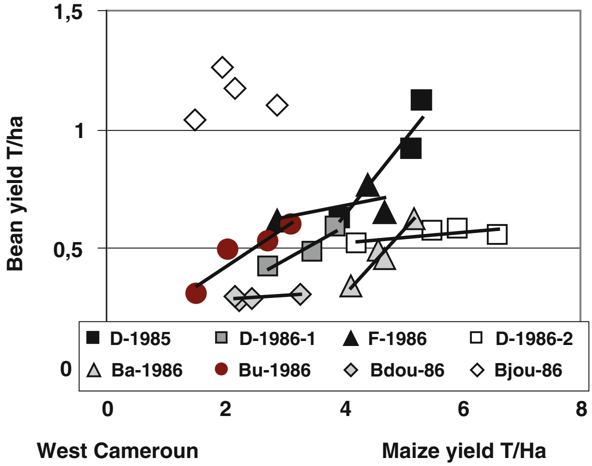
Bispecies Associations

In Cameroon, the Fertility Efficiency Equivalent Ratio (FEER) of bispecies (Maize-Bean/Soybean) association in tests using increasing doses of N and P_2O_5 shows that low doses of fertilizer have an efficacy of between 2.3 and 3.5 greater when in association than in monoculture in the case of N and 1.5–1.9 in the case of P_2O_5 (Table 2).

In Senegal, the yield from a millet-cowpea intercropping produced a LER of 1.44 with fertilizer (100 NPK) and 1.73 without fertilizer and 1.48 and 1.70 respectively for the grain and straw. Bispecies (Maize-Bean) association in Cameroon maximized maize as well as bean yields under any pedoclimatic conditions (Fig. 9) (Salez 1990).

Ofori and Stern (1987) obtained LERs of 0.96 through 1.82 with the application of fertilization consisting of more than 100 units per ha of N. But for lower doses of up to 100 units, the LER decreases. Yet Hugar and Palled (2008), using intercropping with doses of only 75 N, 75 P_2O_5 and 37 K_2O on maize and 25 N, P_2O_5 and 60 K_2O on cowpea, obtained LERs of 1.18 through 1.35. This could result, however, from the respecting density of plantings and roots that play an effective role in

Fig. 9 Positive correlation of maize yields and bean yields grown in association. (Sites = *D* Dschang, *Ba* Bansoa, *Bu* Bamendjou, *Bdou* Bamendou, *Bjou* Bandjou)



photosynthesis and Biological Nitrogen Fixation (Hardy and Havelka 1976; Peoples and Craswell 1992; Ofori and Stern 1987).

The direct and indirect transfer of atmospheric N from legumes to non-legumes, in this case cereals, may also be affected by physical, pedological, and climatic factors (Hulet 1986) proved in Mali that a delay in the planting of cowpeas for 1 week in relation to millet increased the effect of the contribution of 15 units of N by 75 % on the millet grain yield (Control planting 734 and 1,000 kg ha^{-1}). As a consequency, a 50 % dose of the recommended level of fertilizer for monocultures was the optimum dose for intercrops (Ahmed and Rao 1982; Dupriez 2006), sometimes less with leguminouses (Huley 1986; Natarajan and Willey 1986; N'tare et al. 1987; Shetty 1987; Zougmoré et al. 1998).

Optimal doses of P varied from 30 through 50 U ha^{-1}, as against 100 U ha^{-1} in monoculture, as confirmed by Harmsen et al. (2001) who found 40 Units per ha^{-1} in a wheat-lentil association in Syria, with rainfall of 250–650 mm. In Mali, the millet-vigna association increased the millet yield by 15–103 % (Hulet and Gosseye 1986). In normal years, the average LER (16 fields) was 2 (Millet = 1537 kg ha^{-1} and cowpea = 1112) (IAEA 2002). In average and good years, the LER for millet and cowpea varied from 0.96 through 1.96 with optimum doses of P of about 50 – a more efficacious environment than for millet.

During absence of nitrogen fertilizer, intercropped legumes will fix nitrogen from the atmosphere and not compete with maize for nitrogen resources (Adu-Gyamfi et al. 2007). This 50 % saving in additives (fertilizer and pesticides) was noted by Séguy et al. (2008) in a permanent '*Direct Seeding Mulch-based cropping system*' and multifunctional association in Brazil. With respect to the maize-bean association, a parallel increase of the two crops can be observed. The reduction in the effectiveness of nitrogenous fertilizers is due to the fact that in these associations, the legumes increase the number and weight of their nodules ensuring the transfer of nitrogen to non-leguminous plants (Thompson 1970).

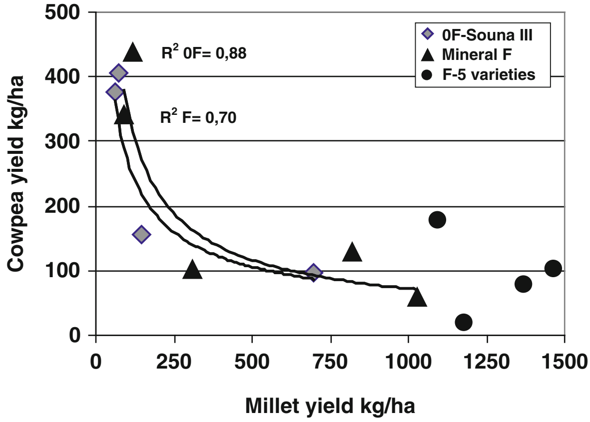


Fig. 10 Cowpea yield vs. millet yield with (F) or without (0 F) urea with increased water satisfaction in the Sudan – Sahel region

In a bispecies association (Maize-Soyabean), both mixed and in intercropping, a strong antagonism was observed, comparable to that observed with the peanut due to the shade produced by the maize (Valet 2004). This antagonism increases with density, one crop suffering as the other thrives (Soybean density of 243,000–303,000 ft ha^{-1} and maize density of 36,000–41,000 ft ha^{-1}). Yet this antagonism does not seem to have an adverse effect on overall yield. The LERs are fairly constant regardless of how the DERs are distributed between the two plants (LER = 1.39 on average).

Furthermore, high levels of soil nitrate can be a potent inhibitor of N_2 fixation because then the legumes thrive without fixing atmospheric N. Competition for N in a cereal/legume mixture acts as a stimulator for N_2 fixation. Intercropping reduces nitrate accumulation and the risk of loss through soil leaching, pollution, and water in comparison with monocropping.

In Senegal, the millet-cowpea association, in conditions of high water stress, with or without urea, showed a negative correlation of yields (Valet and Ozier-Lafontaine 2013). Most of the cowpea yield in comparison with that of millet reduces with the increase in water satisfaction (Fig. 10).

This shows that when water satisfaction is low, the cowpea is more resistant than millet whereas, when satisfaction is better, because the crop is sown later, it needs less feeding. The same asymmetric competition, where one species dominates another, e.g. wheat intercropped with maize, results from the greater root proliferation of high-yielding species underneath each other Li et al. (2007) showed that intercropped wheat had a greater root length density compared to sole-cropped wheat, occupied a larger soil volume and extended under maize roots. Roots of intercropped maize were limited laterally to about 20 cm, whereas roots of sole-cropped maize spread laterally about 40 cm. The failure of maize to extend into the soil immediately under wheat may help to explain why maize does not respond positively to intercropping until after the wheat harvest (Li et al. 2007).

Table 3 Efficacy Equivalence Ratio (EER) of N and P_2O_5 in tri species crop associations

	Doses	EER	Doses	EER	EER
Mineral fertilization	Kg/ha	Maize-colocasia-xanthosoma	Kg/ha	Maize-soybean-bean	Maize- xanthosoma -bean
N	75–90	3.06 (9)[a]	80	1.73 (1)	1.43 (2)
P_2O_5	75–100	1.42 (3)	–	–	–

[a](9) Number of trials

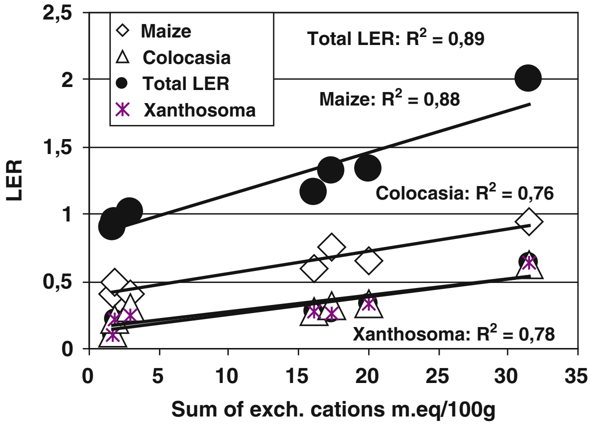


Fig. 11 Relationship between total LER, the LER of maize, Colocasia and Xanthomona and current soil fertility (sum of the exchangeable cations in m. eq./100 g) in West Cameroon (1968–1972) (Valet 1999)

Valet (1968) obtained a positive response between maize-colocasia-xanthosoma. LER, from 1 to 2, and soil fertility on Bamiléké and Bamoon regions (Fig. 11).

Association of Tree Plants

For increasing doses of N and P2O5, the N*P Efficacy Equivalence Ratio (EER) of three types of trispecies association, show that low doses of fertilizer have an efficacy 1.4–3 times greater in association for N and 1.4 times for P_2O_5 than in monocultures (Table 3).

These results were confirmed for two and tree plants by Ahmed and Rao (1982); Hulet and Gosseye (1986); Mhandawire (1989); Traoré et al. (2004); Valet and Motelica-Heino (2010); Valet (1968) (Fig. 11).

Association of Five Plants

On the pioneering fronts of central-north Mato Grosso, upland rice which until 1985, was merely a crop used to break in new land and was quickly replaced either by extensive grazing land or by soybeans, has now become the main association crop (Table 4) (Séguy and Bouzinac 1994).

With only four plants out of five the LERs in reasoned associations vary from 3.3 to 9 in comparison with traditional associations.

In the Republic of Congo, the LER is 1.52 with a 50 % saving in inputs. The 50 % of inputs (fertilizers and pesticides) were noted by Séguy et al. (2008) in a

Table 4 Average agronomic performance of cropping systems based on upland rice, in two village communities in the Cocais and Maranhão regions, 1981 (Séguy et al. 1982)

Systems	Area	Fertilizer	Herbicide	Rice	Maize	Cowpea	Manihot	Partial LER
0.5- CAT-Va	2 ha	Yes	Yes	3,940	512	143	11,270	4.9
0.5- CAS-Va		No	No	(1.70)[a]	(1.40)	(1.83)		
1- (R-Ma-R)-Vt		No	Yes					
1- (R-Ma-R)-Vt	1.5 ha	–	Yes	3,157	249	91	10,304	3.3
0.25-CAS-Va		Yes	Yes	(1.37)	(0.68)	(1.17)		
0.25-CAS-Va cm		Yes	Yes					
0.5 CAT – V	1.5 ha	Yes	No	5,535	450	173	2,321	5.8
0.5 (R-R-R) V		Yes	Yes	(2.40)	(1.22)	(2.22)		
0.25 CAS – V		Yes	Yes					
0.25 CAS –V cm, cc		Yes	Yes					
0.75 CAT – F	1.75 ha	Yes	Yes	6,194	881	305	3,309	9
0.50 CAS – F		Yes	Yes	(2.70)	(2.39)	(3.91)		
0.50 CAS – V cm, cc		Yes	Yes					
CAT itinerant control – T	1.5 ha	–	–	2,310	368	78	–	–

Note: CAT: traditionally associated crops; CAS: associated systematized crops; R: rice; Ma: manihot; V: improved varieties; T: traditional varieties; cm: average cycle; cc: short cycle
[a](1.70) LER

technique using multispecies and multifunctional permanent '*Direct Seeding Mulch-based cropping system*' in Brazil.

Organic Matter Sequestration

The soil organic matter content can be increased by conventional inputs as manure, compost, green manure, straw, etc., but also preserved by cultural techniques, such as fallow lands, rameal chipped wood, quickhedgerows, wooded parklands.

Fallow land: The mixture of cereals and forage and food legumes nourishes the soil, thanks to its high biomass content, with a high sequestration of organic C in Brazil even in very depleted soil (Séguy et al. 2008). This was verified by Salako and Tian (2001) in Nigeria and Autfray (2005) in Ivory Coast using a single cover plant that was rich in organic matter.

Wooded parkland: In Senegal, the presence of *Faidherbia albida* in the fields, an '*ancestral tradition*', makes it possible to establish production differences of around 150 % between plants in the immediate vicinity of the trees, in comparison with those that are further away (Charreau and Vidal 1965). The production due to the presence of this species has been estimated at 25 % (Depommier 1996).

Quickhedgerows: The quickhedges allow and increase in fertility and yield, especially by the uptake of nutrients and the biomass produced, 102–124 kg ha^{-1} year^{-1} of N, 6–9 kg ha year^{-1} of P_2O_5 and 18 kg ha^{-1} year^{-1} of K_2O (Köning 1992). In Burundi,

Plate 9 (**a**) Quickset hedge at Bafu in field and (**b**) bamboo traditional fence around case at Dschang with very dense mixed cropping during drought season (West-Cameroon) (Pictures Valet 1999)

on the other hand, they eliminate runoff and prevent water retention (Duchaufour et al. 1996). as well as through trapping CO_2 (Roose 1994). It improves the structure of the andosoils that are sensitive to erosion (Casenave and Valentin 1989) and it ensures land reclamation (Barral and Sagnier 1889). On Reunion Isle, on steep slopes and in a tropical climate, a quickhedge of *Calliandra calothyrsus* improves the structure of erosion-sensitive andosols (Casenave and Valentin 1989).

Wooden fences are also effective in stopping sediments and trapping nutrients while protecting poultry, pigs, sheep and goats (Plate 9).

Rameal Chipped Wood (RCW): it is based on the use of twigs (with a diameter of less than 7 cm) that are fragmented and would normally be considered as waste products of no use (Barral and Sagnier 1889). Rameal Chipped Wood can be provided by pruning/trimming quickhedges and trees in the associations (Dodelin and Valet 2007). They represent a source of energy through the slow breakdown of the lignin which produces stable carbon (Lemieux et al. 1999). The effect of boxwood wood chip is six times greater than that of manure and three times greater than that of compost (Barral and Sagnier 1889; Djediou 2006, oral communication; Noël 2005). They play a specific role in:

- reducing runoff and erosion (Wakindiki and Ben-Hur (2001);
- the soil's microclimate;
- improvement of depleted soils through contributing nutrients;
- protection against attack and disease (Chervonyl 1999);
- stifling weeds;
- increase in production (Ayuk-Takem and Cheda 1985; Kalemba and Ndoki 1995; Furlan and Lemieux 1996; Lemieux 1994; Mungaï 1995; Thé et al. 2001).

Table 5 Comparison in yields (T ha^{-1} and LER) of several maize varieties and a local yam variety in monoculture and intercropping (Ayuk-Takem and Cheda 1985)

	Pure cultures (T ha^{-1})		Intercrops (T ha^{-1})		
Varieties	Maize	Yam	Maize	Yam	LER
COCOA maize	6.5	–	4.7	17.8	1.60
SAW maize	5.7	–	5.7	12.5	1.33
COCOA control maize	6.6	–	5.6	11.6	1.21
Local yam	–	21.7	–	–	1

Table 6 Comparative effects of Maala burn-beating, slash and burn and pure cultures of slash and burn, burning and mineral fertilization on intercropping associations, in relays, and in monocultures

Cultural systems	Traditional mixed cropping		Pure cultures	Plant LER	
Practices	Maala burn-beating	Slash and Burn	Mechanized tillage	Burn-beating	Slash – burn
Maize	2,880[a]	720[b]	3,300	0.87	0.22
Groundnuts	1,700[b]	1,200[b]	2,010	0.85	0.60
Pigeon peas	800[a]				
Yams	5,600[a]				
Cassava	22,000[b]	11,100[b]	19,000	0.58	
Partial LER				2.30	0.82

[a]1 year mixed cropping
[b]Relay cropping during 2 years

Kalemba and Ndoki (1998) showed that the application of prunings from *Cassia stipulata, siamea and spectabilis* provided cowpea yields of the same value as 50 units ha^{-1} of NPK (Table 5).

The development of mycorrhizas that decompose lignin could favour the colonization of several grassland species (Derelle et al. 2010). Traditional practices such as burn-beating Maala or Slash and burn, comparated to mechanized tillage practices applied to a five crops, provide LERs of 2.3 and 0.82, respectively (Table 6).

Innovation Through the Introduction of Commercial Plants with DER Modification

An analysis of the development of cultivation systems in the cotton-growing region of Northern Cameroon over the past 10 years, illustrates the local farmers' ability to innovate. The innovation processes described concern techniques for introducing crops and controlling the weeds (Muskuwaari sorghum, rainfed sorghum, peanut) and the introduction of new crops into crop rotations (Onions, cotton-soybean, local forage crops), and the use of pest controls (Dugué 2006). The production of mulch using cover crops (*Brachiaria ruziziensis, Crotalaria retusa, Dolichos lablab, Mucuna pruriens, Vigna unguiculata*) intercropped within the cereal (maize-sorghum in rotation with cotton) ensures a 50 % increase for cereals and 12–24 %

for cotton (Naudin et al. 2009). In Vanuatu, the sudden fall in the price of copra and heavy demographic pressure on the land has forced a rethink in improving traditional system based on the coconut palm and replacing the coconut monoculture with the introduction of fruit trees (Labouisse 2004; Lamanda 2005). In south-western Cote d'Ivoire, the comparison of the standard rubber tree monocrop with rubber intercropped with coffee, cacao, lemon or cola (planted in a double quickhedge with wide inter-rows of 16 m) in a field trial showed that the yield of individual rubber trees was not affected by the intercropped trees until the twelfth year, after which the difference was no longer significant (Snoeck et al. 2013).

In the forest-savannah interface area in Cameroon, on soils unsuitable for cocoa cultivation, plantations established in gallery forests with fruit tree species and oil palm provide a Shannon Weaver Ratio of from 1.97 through 2.26 in comparison with plantation in grassland (*Imperata cylindrica*) (Jagoret et al. 2012).

Improving Organoleptic Qualities

A better protein yield has been recorded (Caballero et al. 1995; Dupriez 1980a; Salez 1990). The protein values, depending on the crops, are from 30 % (Maize) to 48 % (Sweet potato) better in association than in a monoculture (Dupriez 2006). Six néré (*Parkia biglobosa*) trees in a field of millet contributes 1.4 cal, 1.1 carbohydrates, 4.3 fats and 2 proteins and with 60 *Acacia albida* the protein quantity multiplies by 3.4 (Dupriez 2006). Dupriez and de Leener (2003) calculated that a néré produces annually in grains the same nutritional value of breeding 50 chickens. In Europe in the 2002/03, 2003/04 and 2004/05 growing seasons, intercropping wheat with fava bean (Denmark, Germany, Italy and UK) and wheat with peas (France) regularly increased the nitrogen and sulfur concentration in cereal grains, hence increasing the wheat quality for bread-making. Also, barley intercrops with the winter pea strain (*Pisum sativum* ssp. *arvense*) resulted in values from 1.05 to 1.26 on a protein basis showing the production benefit of intercropping (Chen et al. 2004). Also, intercropping common bean with maize in two-row replacements improved silage yield and the protein content of forage compared with single crops (Lithourgidis et al. 2008). Furthermore, protein and vitamin extracts from the leaves of numerous edible species and others can be used as nutritional supplements for children, the sick and pregnant women since they are almost as rich as Spirulina (blue micro-algae) (Soynica - Nicaragua– Appendix 5).

Regulating Services

Protection/Soil Conservation Services

Cropping associations and the quickhedges or trees associated with them, due to high crop density, play a significant role in reducing all soil erosion from water in the topsoil and subsoil and from wind erosion. This contributes to the conservation or resilience of soils.

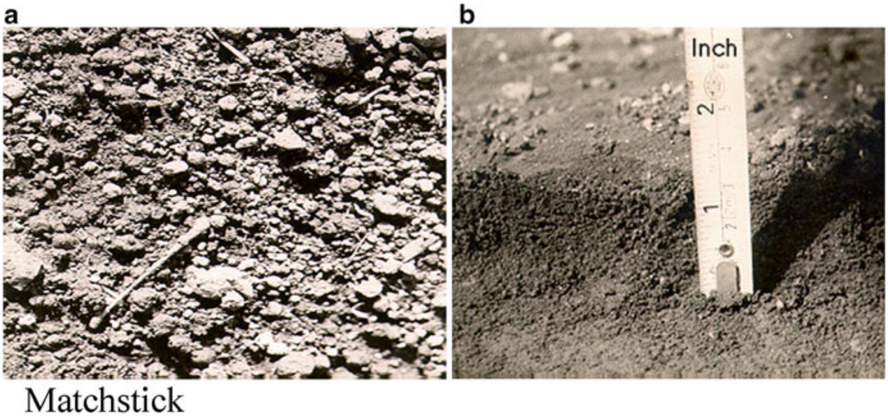


Plate 10 (**a**) Structural crust. (**b**) Stacking effect of runoff crusts shown against a stick on a vegetable plot at Dschang, gradient <1 % during 1967 (Valet 1968, 1999)

Protection Against Surface Deterioration

In West-Cameroon intensified monoculture is infinitely less protective of the soil against the '*splash*' effect of raindrops that have high kinetic energy than are associated crops (Plate 10, Valet 1999). For andosol cultivated with monocrops of maize on 25 % slope, this erosion can reach 122 T $ha^{-1}an^{-1}$. This phenomenon was previously observed in the soudanian climate by Rishirumuhirwa (1996), and so in the Sudano-Sahelian by Casenave and Valentin (1989).

Erosion, however, affects the distribution of organic matter to an even greater extent with exchangeable cations and available phosphorus which are very labile and are exported to outside the plot. The pH varies depending on the types of crusts. This annual loss of nutrients through runoff soon affects soil fertility. Valentin et al. (1990), found the same tendencies in traditional peasant farming systems in northern Ivory Coast. The plant cover developed through annual and perennial multistratified associations thus dissipates the kinetic energy of rainfall and reduces its destructive effect on aggregates, preventing the formation of crusts and the removal nutrients (Aussanac and Boulangeat 1980; Tétio 1994; Valet 2004).

Protection Against Water Erosion

In Western Cameroon, at Bambui Station, at an altitude of more than 1,800 m, the monocultural intensification of maize caused serious chiselling erosion after only 2 years of cultivation in humus-rich ferralitic soil (Plate 11).

Köning (2004) showed in trials conducted over a 2-year period that associated crops reinforced by bispecies quickhedges, especially in alley-cropping, considerably reduced erosion. The efficacy of association over monoculture and even on direct plantings is significant.

Plate 11 Cutting a channel about 30 cm wide after 2 months of maize monoculture on a ridge at right angles to the slope (Bambui Station –1,800 m) (Pictures Valet 1968)

Table 7 Effect of managed water runon whether or not managed by a quickhedge on the median grain yield for millet (kg ha^{-1}) at Thyssé (Senegal)

Rainfall quantity		Excessive	Normal		Deficient	
Quick hedge					Chiselling	Plowing
Effect of chiselling	*Above site*	800	1,150	900	*Below site*	*Below site*
	Below site	1,120	850	600		
Natural	*With run-off*				300	–
Effect of run-on	*Without run-off*				750	1,150
	Test				145	155

Quickhedges reduce the water runoff coefficient in the same way that they regulate the hydraulic system (Guillerme et al. 2009; Köning 2004; Mérot 1976). The increase in pore size from 1 to 3 mm crossing the parts above, below and at 1.50 m from the quickhedge explain the increase in hydraulic conductivity to a saturation point of 46, 176 and 191 mm h^{-1} respectively at 1.5 m above and below the quickhedge. They may, however, compete for water and light (Bizimana and Duchaufour 1997; Duchaufour et al. 1996). In Sudano Sahelian zone, the quickhedge facilitates the management of the water run on (Table 7).

Protection Against Wind Erosion

By causing the topsoil to become uneven, agro-forestry systems and quickhedges that are sensibly distributed (Long 1989; Valet 1999; Zougmoré et al. 2000) reduce wind speed and wind movement (Hauggard-Nielsen et al. 2001). Rows of cereals (maize, millet) in a field with a shorter crop will reduce the wind speed above the shorter crops until 35–70 % after 35 days after sowing. and thus reduce desiccation. It mentioned taller crops acting as a wind barrier for short crops. This physical restriction on erosion translates into a sustainable productivity gain and benefits for the peasant-farmer. In Niger at Sadoré, Andropogon planted around the edge of a field of millet- reduced wind speed by 34–40 % over 40 days with an accumulation of about 225 t ha^{-1} of sand in 3 years (Renard and Vandenbeldt 1990).

Water Conservation Service

Increase in water efficiency is the result of different combinations of limitation of water losses (Grema and Hess 1994; Nouri and Reddy 1990; N'tare et al. 1987; Ozier-Lafontaine et al. 1997, 1998).

Increase in Water Efficiency and Reducing the Risk of Water Deficit

The drop in soil and air temperature reduces water demand (Gomez Delgado et al. 2009; Midmore 1993; Morris and Garrity 1993). In eggplant-groundnut intercropping, pod weight of eggplant in monocropping was low due to absence of intercrops, which leads to high water evaporation in soil area It has been shown that the millet-cowpea association in intercropping or is relay is important having been shown to be effective in the Sahel area to use the water reserves in the soil as economically as possible (Dancette 1984; Diagne 1987; Reddy and Willey 1981; Reddy and Ramanatha 1984; Van Duivenbooden et al. 2000) and in France (Guillerme et al. 2009), the intercrops have been identified to conserve water more largely because of early high leaf area Ratio and higher leaf area (Ogindo and Walker 2005). Morris and Garrity (1993) mentioned that water capture by intercrops is higher by about 7 % compared to mono crop. Willey (1979) and Tsubo et al. (2003) stated cereal-legume use water more efficiently than monocropping. Barhom (2001) reported that water use efficiency was the highest under soybean-maize intercropping compared with monocropping maize and monocropping soybean. Singh and Joshi (1994) confirmed that mixed, row, and strip cropping systems (millet-clusterbean/greengram) under severe drought conditions during reproductive phases in both seasons have a LER = 1.26. It has been shown that the water use (W_UE) in semi-arid areas is higher for mixed crops than for monocrops. Arslan and Kurdali (1996) agreed with the results of Hulugalle and Lal (1986). The two crops explore a larger volume of soil and do so more thoroughly and efficiently (Willey 1979; Thobatsi 2009). Improvement of water use efficiency (kg mm^{-1}) in intercropping

Table 8 Partial and total Water use Efficiency Equivalent Ratio (WuEER)[a] of millet-cowpea intercropping in water stress in Senegal[b]

	Pure cropping			Partial WuEER				Total WuEER	
	Yields grains (Kg ha^{-1})			Millet		Cowpea		Millet + Cowpea	
Treatment		Millet	Cowpea	Grains	Fallow	Grains	Fodder	Grain	Fallow
F0[c]	Average	359	600	1.15	1.07	0.93	1.11	2.08	2.18
F1[c]	Average	552	724	1.19	0.70	0.70	0.75	1.89	1.45

[a]WuE: varieties in kg mm^{-1}
[b]4 trials
[c]6. Millet F1: 150 kg ha^{-1} N10-P21-K21 + 100 kg of urea; cowpea F1: 150 kg ha^{-1} of N8-P18-K27

leads to increased use of other resources (Hook and Gascho 1988). So, two trials (millet-cowpea intercropping) demonstrated that the Water use Efficiency Equivalent Ratio (WuEER) in semi-arid areas, is higher in different mixed crops than for monocrops, for heavy water stress conditions (Valet and Ozier-Lafontaine 2013) (Table 8).

$$\text{WuEER} = \begin{bmatrix} (\text{Wu millet intercrop / Wu millet monocrop}) \\ +(\text{Wu cowpea intercrop / Wu cowpea monocrop}) \end{bmatrix}.$$

These two Senegalese trials mainly confirm the results found by different researchers (Azam-Ali et al. 1984; Hulet and Gosseye 1986), corroborated by Morris and Garrity (1993) that stated that water capture by intercropping is about 7 % greater than for monocrops.

Under normal condition cereal-legume intercropping uses water equally (Ofori and Stern 1987). Conversely, it has been shown that two or four associated species consume respectively 7–10 % (Morris and Garrity 1993; Reddy and Willey 1981) and 28 % (Sinha et al. 1985) more per unit per hectare than each monoculture.

In an area of water scarcity, intercropping is a suitable method (Lynam et al. 1986). The importance of association crops, intercropping or relay was shown in the Sahel for economising on water reserves in the soil (Diagne 1985; Van Duivenbooden et al. 2000) and in France (Guillerme et al. 2009). Furthermore, the rainfall interception by vegetation is an important factor in the water balance (de Jong and Jetten 2007). In eggplant-groundnut intercropping, pod weight of eggplant in monocropping was low due to absence of an intercrop causing high water evaporation from the soil Yet under certain combinations of conditions such as under drought and soil compaction, water competition restricts the use of water by intercropped pearl millet, forcing pearl millet to shift to the recently supplied water. In contrast, cowpea did not show any significant changes under these stressful conditions (Zegada-Lizarazu et al. 2006).

The coffee agroforestry system compared to coffee monoculture, monitored over a 3-year period in Costa Rica, showed an advantage in rainfall interception, with a water runoff of less than 56 %, and best infiltration and water content in the soil.

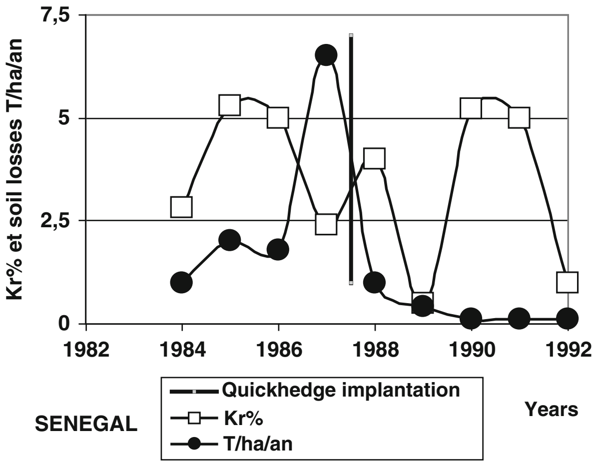


Fig. 12 Effect of quick hedges and rows of stones in reducing erosion and maintaining water runoff in a 1.5 ha watershed

This suggests complementarity for water content in the soil between coffee and the shade impact produced by *Inga densiflora* on water use and drainage (Cannavo et al. 2011).

Quickhedges in the Sudan-Sahel region (Thyssé in Central Senegal), combined with rows of stones in a watershed of 1.5 ha, reduce topsoil erosion by 90 % with a 20 % reduction in runoff from the first year (Fig. 12). Maintaining this level of run-off favours a field upstream with water runon ensuring a water surplus as well as nutrients (Ca^{++}, K^{+}, Mg^{+++}, Na^{+}, P_2O_5 and C) thus improving crop demand for water and feed (Valet 2000, 2004). Maximum millet yields increased by 250 kg ha^{-1}–1,150 kg ha^{-1} and mean yields by 145–900 (Valet 1995).

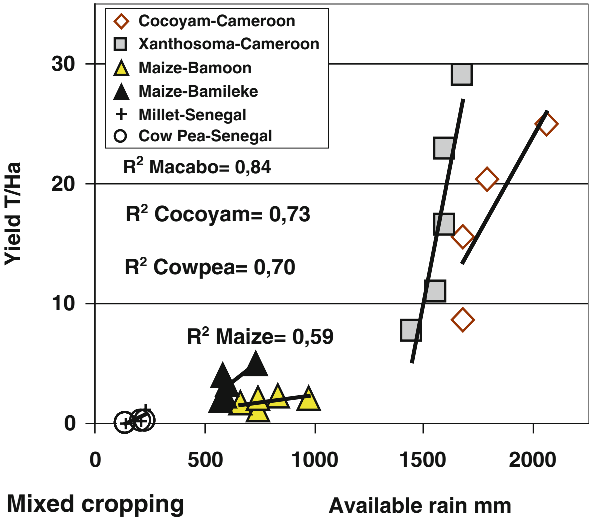
Improving Water Properties

In mixed crops especially when reinforced by quickhedges with high density during critical erosion periods:

- Favours the rate of infiltration which can reach 41 cm h^{-1} on fallow land and 81 cm h^{-1} under mulch (Rishirumuhirwa and Nyabuhwanya 1993) due to very uneven ground (Boli 1996),
- In Burkina-Faso, the Sorghum-Cowpea association reduces water runoff by 20–30 % and by 5–10 % respectively in comparison with pure sorghum and pure cowpea (Zougmoré et al. 2000).

Furthermore, a cereal-legume association acted as the best cover crop and reduced soil erosion which can attain 80–90 % (Reddy and Ramanatha 1984). In Burkina Faso, Zougmoré et al. (2000) showed an erosion rate of 80 % and 45 at 55 % respectively in comparison with pure sorghum and pure cowpea. The improvement in water quality is due to a reduction in erosion and leaching of agronomic inputs (N, C, etc.). The reduction is also the result of the interception factor of the canopy (Cannavo et al. 2011).

Fig. 13 Correlation between yield and available rain for millet grains and cowpea in monoculture and on association with tubercles (the Sahel (shown in *black*) and Sudan-Sahel to tropical zone (shown in *white*)



The reduction in water runoff also reduces the risk of pollution in lakes and rivers (Caldwell and Richards 1986; Dupraz and Liagre 2008; Innis 1997; Ofori and Stern 1987; Zhu 1991; de Willingen and Van Noordwijk 1987). Furthermore, planting seedlings in stages with their different lengths of cycle reduces nutritional and water needs since they are not the same at all times (Baldy and Stigter 1997). Competition between plants, a theory advanced by Donald (1958), is reduced accordingly.

Adapting to Climate Change by Increasing Droughtness

Contrary to certain received ideas whereby low densities reduce the risks of crop failure during drought years, an increase in the density of bispecies plantings increases yield by increasing the efficiency of transpiration over evaporation even under low fertility conditions (Hulet and Gosseye 1986; Payne 1997). In every latitude, the amount of rainfall appears to be decisive in explaining the variability of yields (Fig. 13).

Trees, with their screening and coverage effect, reduce the importance of direct evaporation on soil and wind (Gomez Delgado et al. 2009). A study of a pearl millet/groundnut intercrop (1:3 row arrangement) showed a wind speed reduction of 35 % at 35 days after planting in 1985 and 70 % in 1987. It increased the radiation use efficiency of groundnut by 21–35 % (Ong et al. 2001).

Regulating the Microclimate

Solar radiation provides energy for photosynthesis, which ultimately provides the potential for crop productivity and also determines water use by the process involved in evaporation and transpiration (Baldy and Durand 1970; Thobatsi 2009).

Intercrops have been identified to conserve water largely because of early high leaf area Ratio and higher leaf area (Ogindo and Walker 2005). There is an attenuation of solar radiation and extreme temperature variations through the reduction in albedo (Dancette and Poulain 1968; Salau et al. 1992; Valet 1974, 1976) with the maintenance of a species ambient microclimate that is more humid, having an effect on the reduction in evapo-transpiration (Othieno et al. 1985; Stigter 1984, 1994).

Ozier-Lafontaine et al. (1998) showed through a model that there was greater water efficiency in the case of bispecies associations vs. pure cultures, thanks to niche differentiations produced by colonization contrasts of the aerial and subterranean sensors, and differentials in flow resulting from the regulation of supply and demand.

"*The Iroquois also grow crops on low hills ensuring a warmer substrate for the grainlings, as well as better drainage, and preventing compaction…*" (Tremblay 2008). These methods also contribute to resistance to climate change (Valet et al. 2008). The modification of the microclimate within the canopy of the intercrop reduce moderate-to-severe disease due to a reduction in leaf wetness duration during and after flowering (Schoeny et al. 2010). Atiama-Nurbel et al. (2012) showed that the mean LER (2 years) grow up 1.31.

Root Colonization and Niche Differentiation

The root system coverage depends on the type of soil, the species, their planting density and age (Lamanda 2005). A denser root system, as well as greater complementarity resulting from better layering could be seen in mixed crops whose RER (Root Equivalent Ratio) varied from 1.2 to 1.5 (Moreau 1982), or even more (Balde 2011).

Root higher length and dry weights in a vetch/barley and barley/pea mixture were higher than those under sole cropping (Arslan and Kurdali 1996; Izaurralde et al. 1992). This ensures better soil structure, better root penetration in depth, better anchorage as well as better complementarity in the use of nutrients and water in the deeper layers in comparison with monocultures (Autfray 2005; Hulugalle and Willatt 1987; Nouri and Reddy 1990; Osseni and N'Guessam 1990; Rao et al. 1998). In a maize-peanut association the plants excrete phytosiderophores into the rhizosphere, thus becoming more efficient in Fe deficiency surroundings and benefitting from the iron nutrition of maize and of peanut (Zhang and Li 2003).

Increased root system density can facilitate the interconnection of mycorrhiza (Hauggaard and Jensen 2006). The growth of mycorrhizal fungi on and in plant roots dramatically increases the area of roots available for soil exploration of nutrients, particularly P, but also N. This complementarity of root systems via niche differentiation facilitates the use of nutrient resources and water at various depths and over time, minimizing competition, and these are high productivity factors in tree-crop associations (Caldwell and Richards 1986; Dupraz and Liagre 2008; Zhu 1991; de Willingen and Van Noordwijk 1987).

Pest and Disease Control

One of the major roles of crop associations is their ability to resist attacks by multiple pests and diseases. An analysis performed on two plots published by Risch (1983) – respectively, 150 and 209 published studies – concerning an assessment of pests and natural enemies in polyculture vs. monoculture, showed that in 53 % of cases, crop associations suffered from less serious attacks than did pure crops. on particular t the percentage of natural enemies of mixed crops is greater than in monocultures (59 % vs. 9 %), yet in only 32 % of the situations studies was it shown that there was no difference between monocultures and associations. The beneficial effect of crop associations in controlling disease and parasites was confirmed by other researchers (Rämert et al. 2002; Root 1973; Szumigalski and Rene 2005; Vandermeer 1989). But this aspect is not easy to demonstrate, since it is complex and unpredictable (Trenbath 1999). A mixture of species with very different usage/purpose is the essential condition for confusing the issue for insect pests (Lefrançois and Thorez 2012).

Six hypotheses are generally advanced to explain the ability of crop associations to regulate plant pests:

The disruption hypothesis (push): one of the associated species disrupts the ability of the pathogen to attack the host plant through confusing it: emission of volatile substances, visual effects, barrier effect, etc. (Khan et al. 1998).

– The hypothesis of the trap plant (pull): one of the associated species attracts pathogens, keeping them out of reach of the more vulnerable crop or the species attracts predators on the pests.
– The natural enemies hypothesis, based on the ability of mixed systems to favour greater diversity of predators and parasites.
– The hypothesis of micro-environment modification, involving mixed crops that can create more favourable conditions for the plant under attach or less favourable conditions for the development of the parasite, or those more favourable for the development of its natural enemies.
– Vertical and horizontal barrier effect.

The *push–pull* system (see Ratnadass and Bartzman, Chap. 3), has been tested on over 450 farms in two districts of Kenya and has now been released for uptake by the national extension systems in East Africa. Participating farmers in the breadbasket of Trans-Nzoia are reporting a 15–20 % increase in maize yield.

In Réunion Island, Deguine et al. (2012), by planting lines of maize around truck farm and horticultural plots, protected zucchini, chayotes or christophines, cucumbers, pumpkins, melons and other cucurbitaceae from predatory flies (*Bactrocera cucurbitae, Dacus ciliatus* and *D. demmerezi)* who were thus trapped.

Furthermore the association of certain species offers a protective effect (against disease) or a repellent effect (against pests) such as absinth against aphids, marigolds (*Tagetes* sp.) or rattlepods (*Crotalaria*) against nematodes (Agrisud 2010), maize and sweet potatoes (Afessa 1997) and numerous plants associated with legumes (Berry et al. 2009; Chikte et al. 2008; Epidi et al. 2008; Fernandez-Aparicio et al. 2007; Kinane and Lyngkjær 2002; Sekamatte et al. 2003).

Mixtures of winter rye with winter wheat and spring barley with oats reduced the incidence of leaf fungal diseases (Vilich-Meller 1992). This reduction of bacterial effect was about 20–80 % (Hauggaard-Nielsen et al. 2008; Sikirou and Wydra 2008).

In other cases, there is recourse to so-called ‘satellite’ plants that cover a field to serve as a trap for predators, i.e. the association of eggplants in a potato field to fight Colorado beetle (Agrisud 2010). When they meet, chayote or christophine flies are destroyed by a micro-wasp that hides in the weeds (Gamour Program: Agro-ecological management of vegetable flies at the CIRAD meeting). This technique economizes on insecticides and herbicides and improves the harvest by 60 % (page 14–15, A-F Roger). Atiama-Nurbel et al. (2012) showed that the LER in association and without spraying was 1.31 (2 years mean) in comparison with spray control.

Crop associations offer weed suppression possibilities, pest and disease control, and use of soil resources under organic farming systems (Bulson et al. 1997; Jensen et al. 2005; Theunissen 1997). Their efficiency varies with the environmental conditions. However at present, organic farmers still depend mainly on modern varieties developed from conventional breeding programs (Murphy et al. 2007; Vlachostergios and Roupakias 2008; Vlachostergios et al. 2010), but the majority of these varieties cannot face up efficiently problems as pest and fungus pathogens, weed competitiveness, or resource exploitation under organic farming systems (Wolfe et al. 2008; Lammerts van Bueren et al. 2003).

These performances can largely be explained by the barrier effect (horizontal and vertical), enabling plants to be concealed from insects, diluting the vector, modifying temperatures and the exposure that favours insects climbing up a stem (Altieri et al. 1978; Baldy 1986; Deen et al. 2003; Egunjobi 1984; Hauggaard-Nielsen et al. 2001; Kinane and Lyngkjær 2002; Rajvanshi et al. 2002; Singh et al. 1990; Steiner 1985; Tétio 1994).

Weed Control

Weed control is a major constraint in tropical wet areas. This effect produced by the action of associated crops is known (Banik et al. 2006; Bulson et al. 1997; Hauggaard-Nielsen et al. 2006; Liebman and Dick 1993; Welsh et al. 1999). It brings various actions into play that can act concurrently:

(i) increase in DER (Saucke and Ackermann 2005);
(ii) increase in leaf area index with increased light interception.

Sans and Altieri (www.ub.es/agroecologia/pdf) found that intercropping with cover crops significantly reduced the structure of the weed community but no fertilization effect was observed.

The suppression of weeds was also confirmed by Steiner (1985) when maize was intercropped with groundnuts, vigna and sweet potato leading in all cases to the reduction of weed growth, yield losses and the amount of time required for weeding. Depending on the years, the effect of weed control can be between 52 and 63 %, in pea-false flax (Saucke and Ackermann 2005) and 70–96 % in inhibiting purple nutsedge density (Iqbal et al. 2007). In the first year of cultivation the Bamilekes (West Cameroon) sow a large quantity of taro and eddoes whose large leaves smother the weeds (Valet 2011a). Intercropping leek and celery in a row-by-row replacement design considerably shortened the critical period for weed control in the intercrop compared with the leek pure stand. Furthermore, the relative soil cover of weeds that emerged at the end of the critical period in the intercrop was reduced by 41 % (Baumann et al. 2000). The high fertility levels and weed stress conditions favoured the intercropping advantage (Ayieni et al. 1984; Thobatsi 2009; Weil and McFadden 1991).

An additional benefit was the reduced Striga infestation in millet/groundnut systems (N'tare et al. 1987). There are conflicting reports on the effect of intercropping cereals (hosts) with legumes (non-hosts of cereal Striga). Three techniques were used:

(i) Similarly, a push-pull strategy for integrated Striga management has shown that fodder legumes (Khan et al. 1998).
(ii) decrease available light.
(iii) should be used for rotation instead of continuous culture

Studies in Kenya indicate that intercropping with cowpeas between the rows of maize significantly reduced Striga numbers when compared to those within the maize rows (Odhiambo and Ransom 1993). On-farm trials show that intercropping of maize and Cowpea with *Desmodium* spp. planted in the same hole in Striga-infested farmers' fields increased maize yields by 78.6 % in western Kenya (Odhiambo and Ariga 2001). Here again, *Desmodium uncinatum and D. intortum* intercropped with maize reduced Striga infestation (Khan et al. 1998). This is attributed to allelopathic mechanisms of *Desmodium* spp. that involved a germination stimulant for *S. hermonthica* as well as an inhibitor for haustorial development (Khan et al. 2002).

Thus crop associations offer effective weed suppression, pest and disease control, and better use of soil resources in organic farming systems (Bulson et al. 1997; Jensen et al. 2005; Theunissen 1997).

Supporting Services

Fertilization Transfer Services

Nitrate Fertilization

An increase in the supply of nitrogen is the result of two principal mechanisms:

– Nitrogen-fixing: the legumes associated with maize, thanks to the number and weight of their nodules, enable continuous transfer of atmospheric nitrogen into maize without reducing the efficacy of N in the soil (Dala 1974; Hiebsch and McCollum 1987; Masson et al. 1986; Mhandawire 1989; Schmidtke et al. 2004; Trenbath 1976; Haugaard et al. 2001). This additional use of the environment by most of the species has been called the "*annidation phenomenon*" (Ludwig 1950). It has been reported that the Cowpea can fix N at rates varying from 8 kg ha^{-1} $year^{-1}$ (IRRI 1974), to 84 kg ha^{-1} $year^{-1}$ (Johnson 1970, quoted by Skerman 1982), to as much as 240 kg ha^{-1} $year^{-1}$ (Nutman 1971, quoted by Rachie and Roberts 1974). *Desmodium*'s N-fixing ability increases soil fertility and is an excellent forage crop.

– Reduction in leaching N and its nutrients (Njoku et al. 1984): the coffee-*Erythrina* association reduces N leaching from 14 to 2 NO_3-N (mg NL^{-1}) in relation to conventional monoculture – trees enable nutrient return, and other factors related to high productivity (Dupraz and Liagre 2008). In Quebec, Allen et al. (2004) reported an 80 % reduction in the quantity of nitrates recovered by plants thanks to the power of interception in the roots (safety net).

In France, 1 km of quickhedges can recycle 60 kg of nitrogen and reduce the nitrate content of the water by 85 % (Guillerme et al. 2009; Macary and Bordenave 2008). Harmand et al. (2007) demonstrated that the coffee-Erythrina association reduces N leaching from 14 to 2 NO_3-N (mg NL^{-1}) in comparison with conventional monoculture.

In West Cameroon, a test performed by Salez (1990) confirmed that in a maize-bean association, using the same dosage of mineral fertilizer, the maize yield increased from 1.8 to 5.2 T ha^{-1} and that of the beans increased from 0.37 to 1.1 T ha^{-1}.

This reduction in the leaching of nitrogen and nutrients (in the order of 20–30 U ha^{-1} of NPK), due to greater efficiency of use was demonstrated by Njoku et al. (1984) in a manioc and maize crop association.

However a surplus of nitrogen can cause competition between the maize and the legume. In such a case, it is preferable to cultivate them in relays to double the yield obtained in monocultures as recommended by Balde (2011) in the pedoclimatic conditions of the Brazilian Cerrados.

Phosphate Fertilization

Phosphate fertilization, after nitrate fertilization, is used much more effectively by plants grown in association than in monocultures. This is the result of several mechanisms that may act separately or simultaneously:

– A pH reduction linked to high-density root systems enables an association (a cereal –durum wheat- and two legumes – pea and fava bean – in an intercropping system) to access various forms of P, especially organic P (Betencourt et al. 2010).
– The effect can be transmitted from root to root thanks to radicular connections and more efficient use connected to the great density of the root system on the same subject of intercropping (LER = 1.5) observe that a share of a slight contribution of P is stored by bacteria which are then recovered after their predation.

Thus, in a millet-cowpea rotation, ridging and P fertilizer input increased biomass production by 10 % for millet grain, 21 % for millet straw, and 27 % for cowpea fodder, but reduced cowpea grain yields by 8 % (Klaij et al. 1994). In another experiment, tillage resulted in a 76–167 % millet yield increase (Klaij and Hoogmoed 1993).

The Organo-Mineral "*Turnover*"

The biogeochemical cycles and storage of organo-minerals have tremendous contemporary significance due to their critical roles in determining the structure and function of ecosystems, and their influence on atmospheric chemistry and the climate system. The recycling of nutrients is a critical function that is essential to life on earth. These cycles involve carbon, nitrogen, sulfur, and phosphorus but operate on different space and time scales (Ecosystem-level processes are studied in forest, grassland, and agricultural ecosystems. They are dependent on biotic and abiotic factors such as parent material (acidic and basic rocks), soils (texture and structure soil, bulk density, oxides and hydroxides, waterlogging), climate (cool, wet, desert), topography, time, micro- and macro-fauna and their activity (Bacteria, fungi, termites, earthworms, millipedes, arthropods), cultivation (forest, pasture, crops), cation bridges, fertility (total biomass above and below the soil). Heterogeneity is a prominent feature in most ecosystems. As a result of environmental heterogeneity the distribution of many soil organisms shows a temporal as well as horizontal and vertical spatial patterning Soil represents a major pool in the recycling of C from the biosphere and constitutes the habitat for terrestrial photosynthetic organisms which fix them in roots, shoots, leaves, branches and all parts of plants and animals.

Currently, human impacts on these nutrient cycles are responsible for a multitude of global changes that threaten the sustainability of ecosystems essential to mankind. In the forest-savannah interface area of Cameroon, the level of organic matter in the soil is 3.13 % in old cocoa plantations (along with oil palm, fruit trees, and coffee), as compared to 1.7 % for cocoa in grasslands (*Imperata cylindrica*) (Jagoret et al. 2012). Organic compost (Compost, loam and dung heaps varying from 1 to 5 tha^{-1}) provide the best yields in association with mineral fertilizer regardless of the level of water satisfaction (Because many of our current environmental problems are manifestations of disturbed biogeochemical cycles, the study is fundamental to an understanding of environmental issues such as global climate change, changes in atmospheric composition, land cover/land use changes, carbon sequestration, nitrogen saturation, acid precipitation, nonpoint-source pollution, and water quality. The soil biota benefits soil productivity and contributes to the sustainable function of all ecosystems. The abundance of plant waste from associations and trees/fences; trapping organo-mineral sediments using quickhedges, wooden fencing and wood chip favours the sequestration of carbon and N, effectively combats the greenhouse effect and regenerates soil (Scopel et al. 2005; Peichl et al. 2006). Peichl et al. (2006) measured the net flow of organic carbon for the agroforestry Inter Cropping Systems, in a poplar-barley combination, of 13 T ha^{-1} a against -3 T ha^{-1} for barley on its own.

Agroforestry maintains the fertility of the environment and high productivity from cocoa bushes that is greater than in conventional monoculture (Jagoret et al. 2012). In agro-forestry systems a stabilization (Sanchez et al. 1985) and even an increase in the SOM is observable (Kowal and Tinker 1959) except for cacao bushes in the sandy soils of the Ivory Coast coastline which remain deficient in organic matter.

These results confirm that the ecological techniques that increase the sequestration of OC with an improvement in the aggregation of soils efficiently combat erosion (Barthès and Roose 1983; Mutuo 2004). The overall result is a more effective fight than in monocultures against the greenhouse effect and soil regeneration through simple or complex stable organo-minerals (Peichl et al. 2006; Tiessen et al. 1984). In New Zealand mixed cropping short term rotations (pasture and arable) increase the aggregate stability of a group of soils mainly due to the production of binding organic carbon by virtue of the microbial biomass present in the pasture rhizosphere, and they do this more rapidly than the increase in clod porosity (Haynes et al. 1990).

Proliferation of Biodiversity and the Gene Pool

The vast range of agroforestry practices most strongly favour the potential for the conservation/rehabilitation of biodiversity (Lamanda 2005; Michon and de Foresta 1995; Schroth et al. 2004). The variety of biochemical and biophysical mechanisms variety – thanks mainly to the action of fungi – improves the formation of the soil structure (structural genesis), both directly and indirectly (Kihara et al. 2012; Ritz and Young 2004). Biological efficiency and the creation of habitats and nutritional niches promote greater stability and conservation of this biodiversity (Francis 1989). The biological efficiency of intercropping is due to exploration of a larger soil mass than in monocropping (Francis 1989). *Faidherbia* trees reinforce the microbiome (Jung 1966). Crop associations increase the quantity and number of mycorrhizal fungi and bacteria, or add them to plants that have a poor supply thereof (Derelle 2012). The increase in the microbiological mass (*bacteria and mycorrhiza*) linked to the expansion of the root system and of their exudates in associations ensure better cultivation and use of a larger volume of soil (Derelle 2012). The authors concluded that these bacteria could play a key role in N availability to plants and could be important for the interactions between plant species in intercropping. During anthesis the nitrate concentrations in the rhizosphere of wheat intercropped with fava bean were nearly twice as high as in monocropped wheat. The N released from fava bean roots was rapidly mineralized into ammonia and then converted into nitrate. This was accompanied by better stability and conservation through the contribution of organic and mineral waste from crops and trees, promoting the creation of habitats and nutritional niches (Hobbs and Morton 1999). Fungi affect the formation of soil structure (structural genesis) directly and indirectly, via a variety of biochemical and biophysical mechanisms (Ritz and Young 2004).

Economical Services

The debate about the relationship between the economy and ecology, a source of confrontation, is over (Vallée 2011). An economic assessment of the gratuitous Eco-Systemic Services is based on very different yet complementary approaches which sometimes offer each other mutual support. One can thus speak of '*natural capital*' over and above which the long-term survival of the biosphere would be compromised (Vallée 2011). In view of the difficulty of assigning a price to Eco-Systemic Services provided by associated, multi-level crops – i.e. the difficulty of assessing the economic value of (micro)biodiversity (Costanza 1991). The following paragraphs will provide examples of their cost/advantage.

A provisional context for the physical accounts of ecosystemic natural capital was published in the journal Ecological Economics (Weber 2007). It can be summarized as follows (Fig. 14):

– Accounts created by type of ecosystem (stock, flows, resilience, services, pressures) on the one hand, and by industry sectors on the other (materials and energy flows, ecosystem services by origin, resources and usage, natural capital).
– Ecosystem services measured directly in cash terms (when incorporated into products) or physical units and in cash (free services for end-use).
– Costs of maintenance and restoration of ecosystems (with respect to the objectives indicated by society) in physical units and in cash.

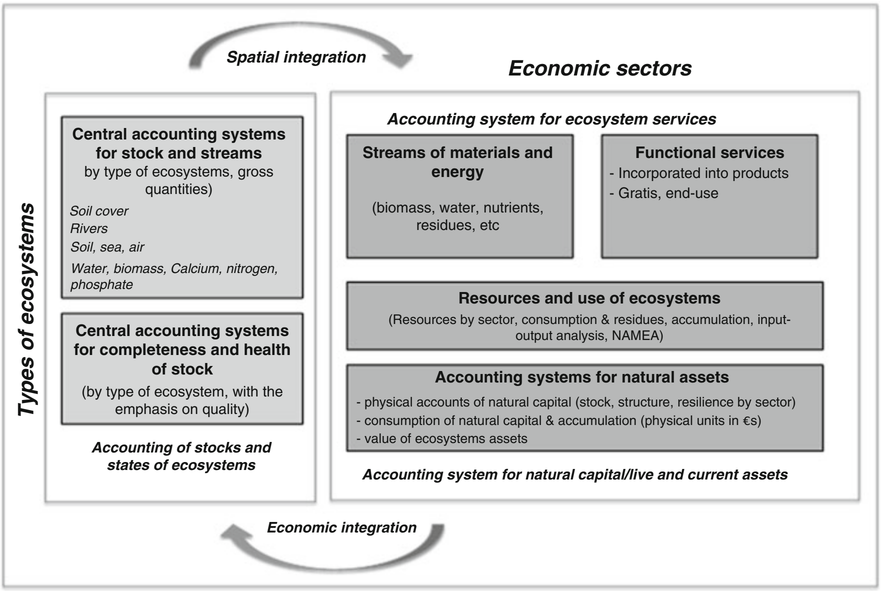


Fig. 14 Context of ecosystem accounts (Weber 2007)

– Natural ecosystemic capital in physical units only.
– Incorporation of geographical information (soil cover, rivers, topical information, zoning) and socio-economic statistics.

However, the interdependencies between the various accounts should be made explicit, especially their implications for cross-classifications and levels of details (Millennium Ecosystem Assessment 2005).

Long before there was awareness of climate change, the backlash from economic liberalism and limits of the conventional model prioritized monocrop intensification, but peasant farmers of both sexes were able to develop traditional farming systems that were nevertheless able to develop and were capable of managing the complexity of local environments while dealing with the uncertainty of local changes and national and world food prices. It is these agricultural systems that have inspired the natural ecosystems, of which farmers had sufficient empiric knowledge to convert into multi-species and multi-level associations that varied enormously in number and species on the basis of the morpho-pedoclimatic conditions and those of the societies in which they lived. They also invented new space-time arrangements in order to introduce into their traditional crops, species that were commercial and industrial, as well as truck farms and fruit trees (coffee, cacao, coca, oil-palms, cotton, bananas, coconut palms, vegetables, tomatoes, cabbages, …) on the recommendations of agronomists.

These multispecies, innovative associations produce and benefit, in the same way as traditional farming, from ecosystemic services that can contribute to sustained intensification.

Economic Services Relate to Several Main Functions

– The combination of conditions that are propitious for maintaining profitable and long-term production are based on the minimum use of synthetic inputs and fossil fuels. Production must be capable of being understood in both the short and the long term, especially with respect to reinforcing the resilience of production systems in view of the risks and uncertainties of all kinds (erosion, soil, food and water pollution, and so on).
– Risk reduction. Alongside the anti-risk logic (between zero risk and maximization of minimum income), diversification in farming can be interpreted as a response to the difficulties of accessing credit and using short cycle crops to finance crops with a longer cycle depending on climatic, topographical and pedological circumstances (Dury and Zoa 2001; Ellis 1998; Valet et al. 2008). In the case of a disease problem or one of climate impact (such as a cyclone), diversification of speculation in farming could attenuate the risk.
– The contribution of economic services to social functions. In multiple crop farming and animal husbandry, for example, the arrangement of various plant and animal training workshops, can support a more complex organization but one that is more varied and thus offers more resilience in case of the unexpected.
– Better use of time.

Beyond this, the agro-ecological advantages of these systems can contribute to restricting ultra-mechanization that leads to a reduction of the degree of use of human energy, and thus to an increase in rural unemployment (Dumont 1975). Curbing the exodus from the countryside and a reduction in the demographic pressure in cities will ensure the maintenance of social cohesion, as shown by Lamanda (2005), in the case of the peoples of Vanuatu.

Units of Analysis and Units of Synthesis, Context of the Accounts

The assessment of economic services requires a contextual analysis to be defined for the relevant indicators (Weber 2008). Alongside the classic concept of an ecosystem described as "*a dynamic complex of plants, animals, and communities of micro-organisms and the non-living environment acting in relation to each other as a functional unit*", there is a tendency to use a more comprehensive concept of socio-ecological systems that are spatial entities in which the production functions of the ecosystems satisfy social demand:

– through their conversion into saleable goods,
– or directly through the individual or collective end-use of recreational, cultural or regulatory services.

Ecosystemic accounts contribute, when incorporated into an ecosystem, a macro-ecological loop without which the assessment contributed by economic and environmental accounts is incomplete. Part of the development work in producing economic and environmental accounts has already been done, in the form of "*non-standard accounts*" for the future SEEA-2003 (Integrated Environmental and Economic Accounting System) revised and constituting an extension and update for the "*Assessment of Ecosystems for the New Millennium*" (MEA 2005). Yet the interdependency between the various accounting systems must be rendered explicit, especially their consequences in terms of cross-classification and level of detail (MEA 2005). Figure 15 shows the general articulation of the system.

Clearly, in this review, the ESSs cannot be treated fully due to lack of scientific, technical and investigative data. Only the main services have been subject to calculation or only of an estimate.

Benefits of Socio-economic Services Rendered by Multi-species Cropping Systems

Figures 14 and 15 which determine the organizational framework for national and international accounts and the main services incorporated into them, clearly show all the difficulties that need to be taken into account with respect to the effects, stocks and positive or antagonistic flows that these services may product and/or preserve. This is all the truer when reasoned on different scales of human and natural activity as well as on variable time scales. The ecological imprint of human

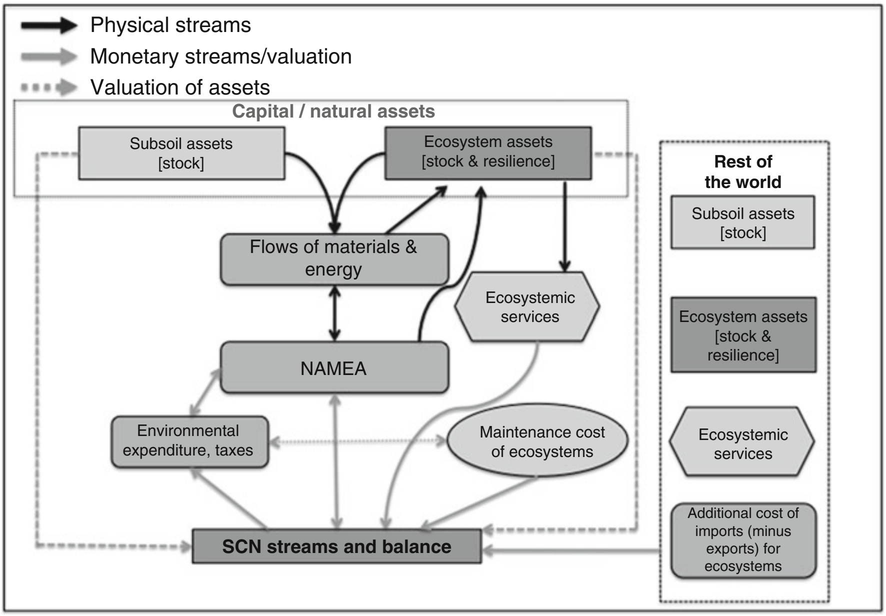


Fig. 15 SEEA incorporating ecosystems (Weber 2007) (SCN = NAS = national accounting system)

activity and inaction in relation to climate change have a cost that needs to be determined. Currently, discussions are focusing on composite or disconnected indicators and an assessment of their cost in the present and long-term future (Weber 2007). Our own assessments and those in the literature presented here are restricted to farming results and biodiversity that is restricted geographically and over time (10 years maximum). These results are thus difficult to aggregate and extrapolate beyond the regions in which they were calculated. The most frequently mentioned limitations in assessing ecosystem services are the ignorance of important benefits (regulation in particular), for the present and even more so for the future, the impossibility of adding up the values of exchanges and usage, and the impossibility of aggregating individual preferences (Weber 2007).

Regulating

They remain no less interesting since they represent a hope for other regions. An assessment of ecosystemic services will be translated into monetary terms.

Use of Biophysical Techniques Against Erosion

Biophysical control techniques against erosion provide several benefits, some of which are computable. To estimate the ecosystemic services that reduce wind and

Table 9 Assessment of wind and water erosion and climate change (flooding and drought) for different countries and by different authors (Brahic and Terreaux 2009)[a]

Country	Purpose of the study	Assessment method	Price in Euros[a]	Authors (in Brahic and Terreaux 2009)
New Mexico	Wind erosion	Replacement cost	600.98 an^{-1}	Huszar (1989)
Australia-Manilla	Rainfall	Hedonic pricing	3.07 ha^{-1}	King and Sinden (1988)
Turkey	Rainfall	Replacement cost	44.99 ha^{-1}	Bann (1998)
US- Palouse	Rainfall	As a function of production	5.82–8.73 $acre^{-1}$	Walker and Young (1986)
Indonesia	Drought	As a function of production	2.7–31.53/household	Pattanayac and Kramer (2001)
Cameroon	Flooding	Prevention cost	0–21.62/household	Yaron (2001)

[a]2008 value

water erosion, and involved the adaptation to climate change has been made by area per household and per capita (Brahic and Terreaux 2009). They point some regional variability (Table 9).

Valuation of the *Push-Pull* Effect: Savings in Pesticides

In Nigeria, the *push–pull* system was tested on over 450 farms in two districts. These systems are used to deter borers and striga that attack maize crops by associating the crop with push–pull plants (*Cotesia sesamiae, Pennisetum purpureum, Desmodium and S. vulgare sudanese*). This system assures a net return of US$ 2.30 for every dollar invested (Khan et al. 1998).

The services supplied by these natural predators on aphids in ten plots in Sweden were assessed at €45.39 per ha^{-1} for the barley production function (Brahic and Terreaux 2009).

In Western Kenya, with 1,400 mm rainfall, in terms of financial returns, GS4 (two rows of groundnuts alternated with two rows of sorghum, with sorghum sown at a row spacing of 105 × 17.5 cm and groundnuts at a row spacing of 105 × 9 cm, giving a final plant population of 60 % sorghum and 40 % groundnuts) made a significant contribution. The equivalent profit ratio (IER) was 3.95 (1998) and 4.11 (1999) (Langat et al. 2006).

Provisioning

Erosion Economy

Assessment of wind and water erosion and climate change (flooding and drought) for different countries and by different authors (Brahic and Terreaux 2009).

Table 10 Assessment by different authors (Brahic and Terreaux 2009), of the costs of preservation/resilience of water quality in different countries

Country	Purpose of the study	Assessment method	Price in Euros[a]	Authors (in Brahic and Terreaux 2009)
US-Pittsburg	Diverse	Contingency/ transport cost	50.90–163.43	Smith and Desvousges (1986)
US-Millesburg	Contaminants	Cost of avoiding	14.23–36.59/ household	Laughland et al. (1996)
US-Pittsburg	Water table	Cost of avoiding	23.4 $year^{-1}$	Abdalla et al. (1992)
US-Ogallala	Aquifer[b]	As a function of production	16.79 $acre^{-1}$	Torell et al. (1990)
US-10 regions	Stopping pollutants	Cost of avoidance	5.66 billion	Ribaudo (1989)
Malaysia	Ditto	As a function of production	15.25 ha^{-1}	Kumari (1996)
US-countries	Forest and runoff	Value transfer	26.41billion $year^{-1}$	Dunkiel and Sugarman (1998)

[a]2008 value
[b]Differential between the price of un-irrigated and irrigated land

Water Quality

An estimate of the preservation or resilience of water quality is very variable due to the diversity of the causes of pollution, by erosion, metals, and by the methods used, that are either technical or natural such as those that include the role of the forest (Brahic and Terreaux 2009). This variability is clearly shown in Table 10.

Spatio-temporal Valuation of Agro-forestry Production

For Multispecies Crop Associations

In West Cameroon, the calculation of the net benefits of the various associated cropping systems, both traditional and innovative, was performed through trials at agricultural stations and in the field (Valet 1968, 1976; Valet and Motelica 2008). For associations consisting of 12 food plants, the traditional manual system was worth 125,000 CFA as against 40,000–55,000 CFA in intensified monoculture of the tubercles and of – 12,000 to +12,000 CFA for maize and legumes in pure cultivation. Income from the trees, shrubs and keeping pigs and goats were not taken into account in this calculation, but they ought to be added since they occupy an important place. So the trees, if equal in age, produce three times the biomass if in an intercropping association than if grown in isolation.

The significant increase in profits is proportional to the number of plants per unit of area or DER as shown in Fig. 16.

In associated cropping, the benefits increase with the number of associated plants:

In the case of intensified monoculture (calculation performed solely with the cost of fertilizer thus, for these mechanized monocultures, the costs of depreciation and

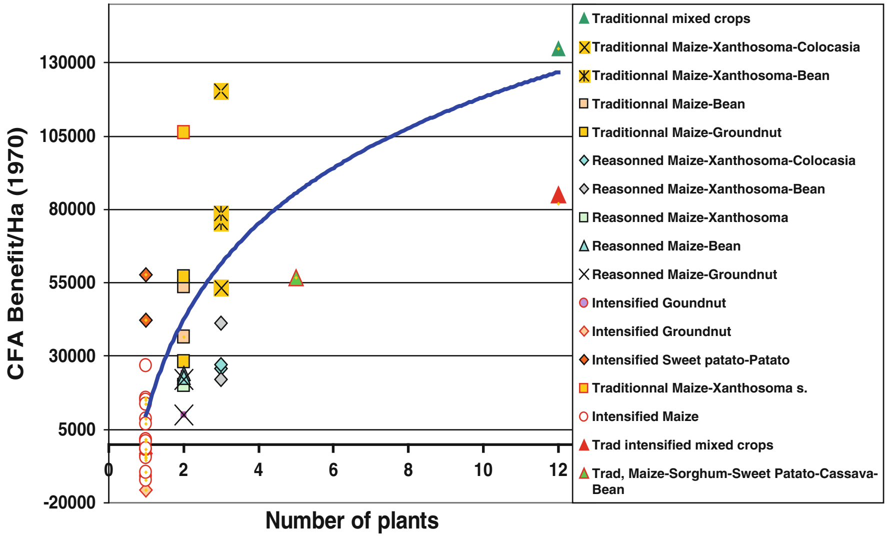


Fig. 16 Losses and benefits (CFA in 1970 value) evolution of systems vs. crop number (mono-, bi-tri-, quinqua, multi-cropping system) in West-Cameroon (Valet 2007)

machinery maintenance – grain-drill, tractor, etc. – were not taken into account, nor were fuel, the barn, grains and pest controls).

What recorded was:

– losses for soybean, peanut and maize in half the trials, and profits capped at 30,000 CFA ha^{-1} for the last two crops;
– for sweet potatoes and potatoes, there were profits of around 40,000–57,000 CFA ha^{-1}.

For Associations of Two Species

In the traditional systems, the Control planting proceeds were 55,000–105,000CFA (Maize–Xanthosoma) whereas the rational system only brought in less than 30,000 CFA.

For Associations of Three Species

There is the same cutoff point at 55,000CFA, entre le rational system and the traditional system, with maximum profits of about 12,0000CFA. Whitmore (2000) noted that in south-east Asia, the profit from associations (cassava-cover plants, rice-cassava-maize followed by legumes), was two to three times greater than from monoculture. The profits are very much greater where two tubercles are associated with maize rather than with one legume and one tubercle.

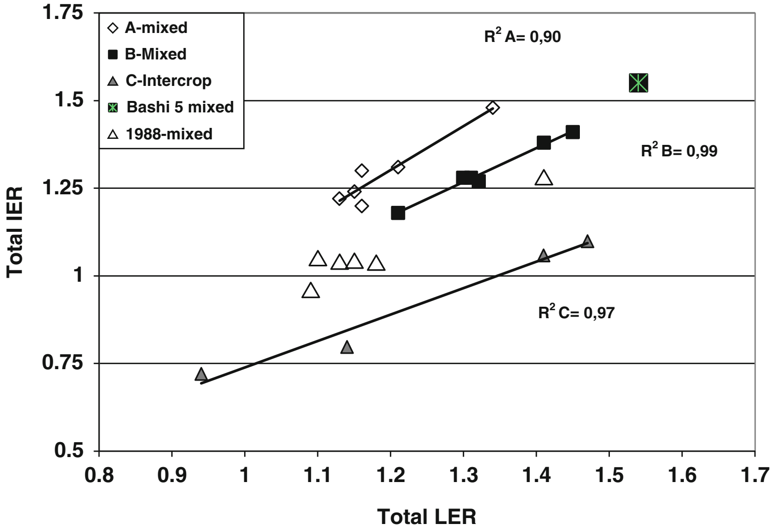


Fig. 17 Total MER vs. total LER for maize-soybean association cropping in Cameroon and the mixed maize-sorghum-manihot-potato-beans among the Bashis (Dem. Rep. of Congo)

For Associations of Five Species

With few tubercles profits do not exceed 55,000 CFA ha^{-1}.

For the bispecies maize-soybean association studied by Salez (1990) in the same regions, the profits are capped due to the antagonism of these two crops. The profits from soybean reduce with the increase of those for maize, and are greater in mixed plots than in those cultivated by intercropping, but nevertheless remain attractive (mean LER = 1.30). Shetty (1987) states that in the sorghum-groundnut association yields are inversely proportionate, in the same way as for the sorghum-millet association except at the Sikasso research station in southern Mali where the yields grew through canning.

In East Cameroon, among the Béti and Baka peoples, the seven main crops, in course of two seasonal cycles, along with gathering, fishing and hunting brought in about 100,000 CFA $ha^{-1}$to the peasant-farmers who relied on '*the assurance of a minimum coverage of the family's food in the worst weather year*' and income of up to more than 190,000 CFA for those who wanted to earn more by cultivating cash crops (cocoa, coffee, wood) (Webert 1977; Sieffert and Truong 1992).

Among the Bashi people, in the Republic of Congo, the LER and the IER are positively correlated (Fig. 17) (Hecq 1958).

Mixed cropping ensures IERs that are always higher than 1, while intercropping only provides 50 % of results greater than 1. For different associations, in Kenya, it was obtained higher profits in monocultures of 56–148 % (Table 11). It is interesting to note that the IER increases from 1 to 2.48 when the plants increase from 1 to 4. These results accord with for eggplant-groundnut intercropping systems those of Valet (2007) in West Cameroon.

Table 11 IER (dollar) at Zaria Upland in Kenya (Baker and Norman 1973)

No	Crops: Types	Crops: Plants	No. of hours Year acre^{-1}	Income acre^{-1} Brut	Income acre^{-1} Net	Manual labor taken into account	Total IER
a	Pure	Millet, peanut, cotton	146.5	21.5	20.8	10.4	1
b	Mixed	Millet/sorghum Sorghum/peanut Cotton/cowpea	235.6	33.7	33	16.2	1.56
c		Millet/sorghum/peanut Millet/sorghum/cowpea Cotton/cowpea/sweet potato	225.3	32.2	30.8	14.7	1.41
d		Millet/sorghum/peanut/cowpea	272.1	47.7	45.2	25.8	2.48

Table 12 Comparison of the benefits of several varieties of maize and a local species of yam in percentage of the monoculture and intercropping cultivation (1970) (After Ayuk-Takem and Cheda 1985)

Varieties	Gross income in CFA: Pure culture	Gross income in CFA: Intercrop	Profit in %
COCOA maize	249,500	403,000	62
Maize SAW	245,500	307,000	25
COCOA maize (control)	250,000	288,000	15
Price kg^{-1}	Maize =10 CFA	Yam = 20 CFA	

The peanut-cassava system of south-east Asia provides a net profit of 495 dollars (Whitmore et al. 2000). In Kenya, Wakindiki and Ben-Hur (2001) showed an increase of 60–92 % of the financial yield of wheat-vigna in comparison with the Control. In India, the net income from the bean-sesame combination was 2.57 times greater than when they were grown in monocultures (Control = 31,560). Ayuk-Takem and Cheda (1985) show that the two-species association (maize-yam) ensured a profit, depending on the variety of maize, of 15–62 % greater than in monocultures (Table 12) and Obedoni et al. (2005) for tomato-cowpea).

Other researchers, some whose work dates back 30 years, confirm an improvement in profits from intercropping in comparison with monocultures, in the USA and in India, as confirmed in 2009 (Ahmed and Rao 1982; Grimes et al. 1983; Kalra and Ganger 1980; Kurata 1986; Seran and Jeyakumaran 2009). Francis and Sanders (1978), showed with 20 trials in Colombia, the economic superiority of the improved maize-bean association with an average IER of 1.84. Furthermore, these authors showed that family manual cultivation with few inputs produced a higher IER of 1.78 as against 0.98 with mechanization and inputs and of 0.90 under heavy intensification. Family farming maximizes the area and manpower much better than under low intensification and especially with the high intensification recommended by Tourte (1971). Similar results were also reported on maize-cowpea (Pandita et al. 2000) and on maize-pigeon pea intercrops (Marer et al. 2007) (Fig. 18).

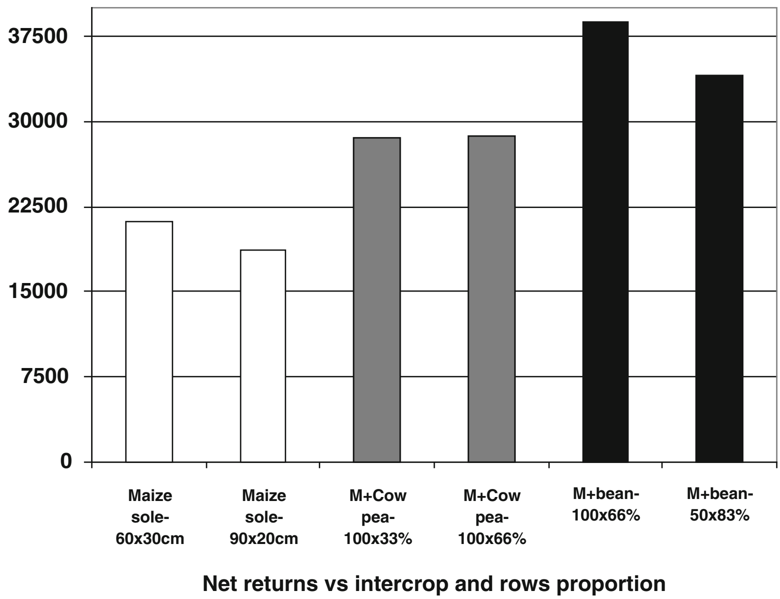


Fig. 18 Net returns vs. intercropping and row proportion for maize-cowpea-bean (Panditaet al. 2000)

The benefits are closely dependent on the proportion of respective species present. In this regard, vegetables are considered to be a profitable proposition because of additional yield and higher net returns (Prabhakar and Srinivas 1989; Pandita et al. 2000). The association with maize (DER = 1) was dominant and beans (DER = 0.6) offered the best net income.

The net margins produced by associations are significantly and very much greater than those of pure crops but with a much higher number of working days and provide high quality in all continents (Langat et al. 2006; Séguy and Bouzinac 1994; Seran and Jeyakumaran 2009; Seran and Brintha 2009).

Yet in heavily populated regions, these associated cultures would appear to represent a solution to endemic unemployment.

In Ivory Coast in the associations of rubber trees with other tree crops (fruit trees, oil palms, coffee, cocoa), rubber tree revenues accounted for 88 % of total revenues and intercrops for 4 % (cola) to 25 % (coffee). By contrast, the rubber tree-lemon tree association was not profitable due to the low price of lemons, and the rubber tree-cola association was not profitable because the cola-trees only started yielding from the seventh year (Snoeck et al. 2013).

Intercropping often provides higher cash return than growing one crop alone (Grimes et al. 1983; Kurata 1986). Intercropping occupies greater land use and thereby provides higher net returns (Seran and Brintha 2009), capsicum and cowpeas production and Langat et al. (2006), with Sorghum and peanut, radish and amaranth intercropping and capsicum and cowpeas.

Kalra and Ganger (1980) reported that intercropping helped increase farm income on sustained basis. Intercropping commonly gave greater combined yields and monetary returns than those obtained from either crop grown on its own (Ahmed and Rao 1982). Net return of radish and vegetables intercropped with amaranth intercropping correlated with amaranth (intercrop) plant density (Seran and Brintha 2009). Francis and Sanders (1978) and Brown et al. (1985) showed that illiterate peasant men and women farmers are able to manage their very complex farming systems very well financially. The 50 % devaluation of the CFA franc in 1994 increased losses of revenue in intensified monocultural systems (Valet 1999).

Examples in Europe

In Europe, intercropping agro-forestry systems compare advantageously with each other in comparison with pure crops and forestry (Graves et al. 2007). Piraux et al. (1997) confirm that revenue (excluding the cost of manpower) is only positive in extensive cultivation but are negative in intensified animal husbandry and are even more so in mechanized cultivation, corresponding to Tourte's (1971) light and heavy intensified systems.

Supporting

Add to this the various crops of wood for woodworking, forage, fruit, cosmetics, pharmacopeia, firewood and others (binding, ropes, tool handles, combs, sap, latex, rubber, leaves, wood chip, saponaceous grains, thorns, roots used as toothpicks, musical instruments,…). Quickhedges thus provide populations with the services previously offered by the forest.

Socio-environmental Services

Valuation of Work

A second method of valuing crop associations is linked to the efficiency of the work. In the case of slash-and-burn systems, the valuation of work not only involves the initial clearing work but also the quantity of work per unit of the area cultivated (Ravignan 1969). Crop systems based on upland rice, in the two rural communities in Brazil in 1981, provided a mean valuation of a day's work that was clearly of greater benefit for associated crops than for monocultures (Fig. 19). (Séguy et al. 1982). Short cycle varieties appear to make better use of manpower and significantly so with dual treatments (herbicide and fertilization). Furthermore, they

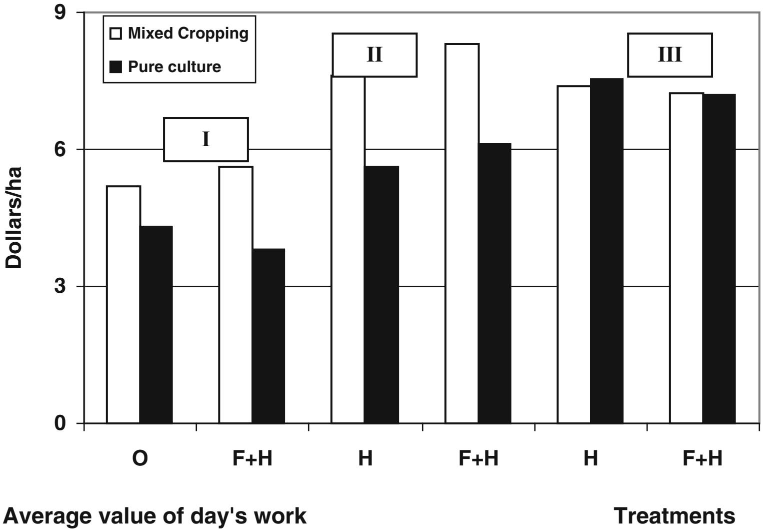


Fig. 19 Average value of a day's work in associated crop systems based on upland rice in two rural communities, Brazil, 1981 (Séguy et al. 1982)
0 = Control = without fertilizer nor herbicides
F = + Fertilization
H = + herbicides
Group I = traditional variety
Group II = IRAT 10 variety (short cycle)
Group III = IRAT100 variety (long cycle)

occupy the soil and labour for less time. This is comparable with the Melanesian or "*creole*" kitchen garden, in which there is great efficiency of labour (Baker and Norman 1975).

Upland rice, depending on the various successions and associations, presented as a marriage of convenience for setting up sustainable agriculture on pioneering fronts to replace deteriorated pasture, makes it possible to achieve significant and sustained profits (Table 13). The farming systems associated with inputs make better use of the working day than the traditional itinerant farming without inputs. Treatment A with few inputs has the same value for a working day as does C with inputs that support the effect of ecosystemic services. It would have been interesting, however, to compare these treatments with an itinerant fertilized Control and for comparable areas.

In Benin, Beauval (1991) calculated that the succession of crops associating palm trees with vineyards generated a gross profit margin of close to 120,000 F FCAha^{-1}year^{-1} (2,400 euros) taking into account the selling prices of cotton, maize, peanut and oil-palm. This proves to be regularly greater than the profit for cotton cultivated as a pure crop in the region.

Table 13 Average agronomic performances in farming systems based on upland rice in two rural communities, Cocais and Maranhão regions, 1981 (Séguy et al. 1982)

Crops	Varieties	Cycle	Treatments	Net profit in Dollars ha^{-1}	%/Control (0)	Days valuation in Dollars ha^{-1}	No. of working days (kg ha^{-1})
Mixed	Trad.	Long	Control 0	406	100	5.27	77
			F+H	399	99	5.54	72
	IRAT10	Short	H	610	150	7.53	81
			F+H	773	190	8.5	91
	IRAT101	Average	H	615	151	7.41	83
			F+H	700	172	7.14	98
Pure	Trad	Long	H	258	64	4.37	59
			F+H	232	57	3.74	62
	IRAT10	Short	H	360	89	5.62	64
			F+H	493	121	6.16	80
	IRAT101	Average	H	491	121	7.44	66
			F+H	555	137	7.02	79

Rice dominant+maize+manihot; cowpea in annual succession after rice. 2: 0=no fertilizer or herbicide; H=herbicide only; F+H=fertilizer (60 N+60 P_2O_5+30 K_2O/ha)+herbicide (Oxadiazon=1,000 g m.a./ha). < BR > 3 Economic performance in relation to crop system+in the case of associated crops rice+maize+manihot+cowpea, not included in income from perennial crops

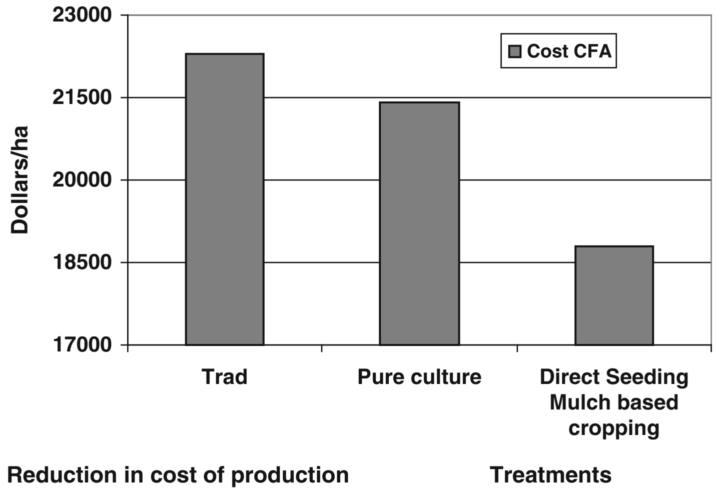


Fig. 20 Reduction in cost of production between a Direct Seeding Mulch-based cropping, associated with intensified monoculture and traditional cultivation (CIRAD et al. 2005)

In Northern Cameroon, a peasant-farmer compared the costs using different treatments. A crop planted under a vegetation cover (Direct Seeding Mulch-based cropping systems) was 16 % less costly in comparison with the traditional manual treatment in association but without fertilization and 13 % less than for an intensified monoculture (Fig. 20) (CIRAD et al. 2005).

Certainly, here again traditional manual farming is unbalanced because it does not receive the same inputs. Furthermore, in the case of Direct Seeding Mulch-based cropping systems, the depreciation of machinery and the cost of soil pollution, water and feeds and a reduction in biodiversity due to synthetic inputs have not been taken into account.

Mixed Cropping as a Strategy for Minimizing Socio-economic Risk

Taking various levels of socio-economic risk into account through a peasant strategy reduces variations in income, depending on the land and manpower involved (Dury and Zoa 2001). The choice of crops, connected with food habits, provides the answer to the difference in demographic pressure. Thus, Camara et al. (2010) showed that an association based on upland rice in the Guinean forest took up far more space (0.91 ha per inhabitant) than that observed in Cameroon (0.15 ha inhabitant^{-1}) which was based on tubercles and banana plants which have a much better yield. The choice of plants for local consumption or international export (coffee, cacao, tea, cotton, rubber, avocado, truck farms, sugar-cane, palm-oil,…) tended to increase the pressure. In addition to anti-risk logic (between seeking zero risk and the maximization of minimum revenue), diversification of farming can be interpreted as a response to the difficulties of access to credit; short cycle crops make it possible to finance longer-cycle crops depending on the climatic, topographical and pedological circumstances (Dury and Zoa 2001; Ellis 1998; Valet 1999). The logic behind the decision taken by a peasant farmer in what crops to grow involves these agricultural and agro-forestry associations combined with the imperatives to grow food (self-sufficiency, organoleptic qualities, food preservation and spreading out the harvests), as well as economic imperatives (local values, national and international prices, revenue and capitalization) and environmental constraints (rocks, soil, climate and geomorphology). This system makes it possible to keep young graduates and non-graduates in the country and to reduce demographic pressure in the cities (Lamanda 2005).

Direct and indirect economic performances which include, during bad years, minimizing losses, making savings in water, land and inputs, improving the cost of labour, and a socio-economic role explain the maintenance of associated crops on the different continents (Dupriez 1980a, b; Dupriez and de Leener 2003; Li 1990; Li et al. 2007; Malézieux et al. 2009) and this, above all, until subsidies and having, moreover, to deal with climate change (Valet et al. 2008). Socioeconomic role because of human welfare explain the maintenance of associated crops on the different continents. So in China, crop associations have drastically reduced wind erosion and pollution produced by the inputs used in intensified monocultures and have played a major economic role though one that is difficult to quantify. But Costanza et al. (1997) estimated the current economic value of 17 ecosystem services for 16 biomes, based on published studies and a few original calculations. For the entire biosphere, the value (most of which is outside the market) is estimated to be in the range of US$ 16–54 trillion (1,012) year^{-1}, with an average of US$ 33 trillion per year.

The impossibility of totally or partially mechanizing associated crops either due to their large number, their different heights, the different times at which they ripen or the fact that they ripen at the same time, or due to the steep gradients of cultivated slopes has kept a large number of young people in the countryside. Continuity or introduction of these mixed crops to replace intensified, mechanized monocultures thus requires much more manpower from among family labour at a time when "*globalization*" is creating unemployment.

Contribution of Mixed Cropping to the Social Aspect: Curbing the Exodus from the Countryside

This could slow down and even stop the exodus from the countryside to the cities and to other countries in the South and North. A return to the fields from the shantytowns is to be hoped for, as long as the investments in industry capable of giving work to the unemployed have not materialized. Lamanda (2005) showed in the case of Vanuatu, that the agro-ecological advantages made it possible to curb the rural exodus and reduce demographic pressure in the cities, ensuring the maintenance of social cohesion.

Health and (Eco)Tourism

Ecosystemic services for safeguarding or reintroducing biodiversity play very varied roles. They can ensure the manufacture of new medicines, preserve hunting and develop (eco)tourism (Brahic and Terreaux 2009).

Towards an Agroecological Engineering Approach: Designing a Multispecies Framework Linking Modern and Traditional Features

Mixing Agronomical and Ecological Understanding

The link between functional ecology and agronomy was initiated 30 years ago (Hart 1986), but was not formalized until very recently (Lefroy et al. 1999). This cooperation is based upon the paradigm according to which natural ecosystems are sustainable and adapted to local constraints. Species diversity is one of the major features of natural ecosystems. Thus, contrary to conventional intensive systems which are open to strong exports, ecologically intensive agrosystems should seek to reduce the entropy bill via a networking activation of different biological functions. By incorporating some characteristics of natural ecosystems into the cultivated agrosystems, we can hopefully give them some interesting properties such as stability (Aerts 1999), resilience, in particular with regards to pests (Trenbath 1999), energy efficiency in the context of depletion of fossil fuels, productivity (Fukai and Trenbath 1993), and ultimately sustainability. The challenge is to find compromise between these different properties. In addition to the difficulty in understanding how interactions and their synergies/antagonisms are organized on the process scale, should be added the difficulty of their management, within a broader systemic framework, integrating spatial dimensions exceeding that of the plot, but also socio-economic dimensions, and this in a global changing and unpredictable environment. In keeping with this approach, agroecology and/or ecological intensification raise new questions about the concepts and tools to mobilize or create, in order to understand, act and adapt with flexibility (Jackson et al. 2010). Necessary changes should be brought both in the field of the concepts involved, and in the attitudes, for conducting research. One of the priorities to promote agroecological engineering is to intensify research on the concepts of ecology at the crossroads of other concepts provided by other disciplinary fields, to allow the analysis, the design and the assessment of agrosystems with an enhanced biodiversity.

A Prospective Study on the Concepts, Tools and Methodologies Towards an Agroecological Engineering

Engineering here refers to '*a thinking making activity that uses knowledge and technology to design and make products and systems for social benefit*'. It is one of the high stakes of ecological intensification in a broad sense, in the current trend under development around ecological engineering as an academic discipline. Mitsch and Jorgensen (2003) define ecological engineering as '*the design of sustainable systems, consistent with ecological principles, which integrate human society with its natural environment for the benefit of both*', with particular reference to the integration of natural processes contributing to self-organization and negentropy. In its attempt to redefine ecological engineering, Gosselin (2008) introduces a distinction between practical ecological engineering on the one hand, as a scope of practical application of engineering projects and scientific ecological engineering on the other hand, as a scope of application of ecological sciences, while advocating for a strengthening of the second component in terms of theories and concepts. The prospective study we are developing prioritizes the strengthening of the concepts and tools of ecology to be mobilized in order to improve our ability to analyze, model, predict and assess ecologically intensive and innovative agricultural systems.

Concepts and Tools of Ecology for Analysis and Modelling of Ecologically Intensive Cropping Systems

Specifications for ecologically intensive cropping systems and challenges for modelling

In the '*mimetic*' approach of ecologically intensive cropping systems to natural systems, notions of maximizing solar energy and microbiodiversity, structural hierarchy, structural and functional complexity and nesting, self-organization, negentropy and multifunctionality come into play. The application of these characteristics to ecologically intensive cropping systems is contingent on the strengthening of a cultivated and mixed biodiversity through the networking of bioregulations allowing to maintain the components of fertility (biological, physical and chemical) in balances that are compatible with cropping performances and the supply of ecosystem services. Reasoning these balances will require the use of concepts and methods of integration, defining a key challenge around the emergence of a new generation of models. The differentiation of ecological niches, the integration by functional traits and the thermodynamic intake can be their structuring elements. The generalization of the experimental results obtained on multispecies systems thus requires the design and use of relevant models that take into account the maximum processes and their sequential aggregation.

Niche Differentiation and Functional Traits as Structuring Concepts

Enhancing biodiversity in farming and production systems is considered as a crucial challenge for their sustainability (Jackson et al. 2010). On the scale of the cropping system, this biodiversity can be controlled in time, by crop rotations and sequences, and space, via mixed cropping, cover crops and agroforestry (Malézieux et al. 2009). Compared to pure cultures, the search for a better efficiency in the use of the environment resources by optimizing the spatial or temporal occupation of resource niches is a central issue, the purpose of which is to control the interactions allowing the selection and conduct of associations of the most complementary species according to environmental contexts.

The traditional and innovative management exercised by many farmers in the field of spatial and sequential combinations of species and varieties is an essential prerequisite to the design of ecologically intensive cropping systems (Valet 1999, 2007). It is however not really taken into account in conventional models, which, for the most part, are inherited approaches on monospecies cover, keeping to a number of species, spatial conditions for crop establishment and limited bioregulation processes (Malézieux et al. 2009). Although they provide many useful concepts and supports to the development of the next generation of models for the simulation of multi-species systems, progress is expected in the design of plot scenes (Plate 12) allowing to simulate the diversity of spatio-temporal combinations of mixtures of species and varieties and their coupling with simulation models of multispecies systems operation (to be designed in 1D, 2D or 3D depending on configuration).

A new generation of models based on these principles would allow searching of the most complementary spatio-temporal combinations by optimization of niche differentiation between species on a multi-criteria basis integrating agronomic, environmental and technical characteristics just as well.

As an example, for multilayered plant communities, the Hi-sAFe model (Dupraz et al. 2004) allows an integration of competition relationships for water, light and nitrogen between individuals belonging to different species and layers. It is spatialized

Plate 12 Samples of multi-species systems establishment simulated with the MIX-Sim platform developed under Open-Alea) (**a**), structure in alternate rows, (**b**) alternating between and on rows, (**c**) mixed structure creole-type garden and Bamileke and Bamum fields (Ozier-Lafontaine et al. 1998; Valet 1968)

in 3D for both the aerial and underground parts. It allows reporting on the following major functional traits:

– Phenological discrepancies between species.
– Architectural plasticities of aerial and underground parts.
– Species skills of mixed species in the competition for water and nitrogen.

Hi-sAFe thus allows, through a parallel simulation of the mixed system and the pure systems, to calculate the studied mixed cropping LER. The number of simulated mixed species depends on the ability to set up the species. Nevertheless, Hi-sAFe is currently limited to temperate crops and trees, and its tropicalization will help it evolve into a reference tool for multilayered multi-species cropping systems. With such a tool, it becomes possible to investigate the optimization of ecological niches in relation to production (yield), simultaneously taking into account of technical constraints such as the possibility of spending between the rows with a tractor, or the return of a stock of water, nitrogen and organic matter necessary for the resumption of the following crop. In future versions, Hi-sAFe could therefore constitute a reference model to approach resource sharing. The challenge is to predict and understand the effectiveness of mixed cropping, and to explore innovative technical arrangements to operate these systems. This could lead to optimize the choices and combinations of species in relation to objectives of crop protection. One of the advantages of such a modelling platform will be to highlight emerging species properties of mixed systems, properties that are not readily accessible for observation. Without prejudging the outcome of this work, we propose a list of emerging properties whose highlighting and quantifying would result in real scientific advances:

– Importance of rare events (such as drought) on the functioning of mixed species, and the resilience of these systems.
– Terms and conditions of the expression of facilitative relationships between species.
– Importance of night-time redistributions of water by the root system of trees on the functioning of mixed systems (hydraulic lift).

- Reactivation of biogeochemical cycles by deep colonization of the soil with plant roots induced by interspecies competitions.
- Impact on the carbon balance by deep burial of carbon from the root turn-over of trees.

The mobilization of concepts allowing the integration of the functional groups involved at different levels of regulation, including that of the food webs is another important issue worth developing in future models (see the chapter by Clermont-Dauphin et al., this volume).

The concept of functional traits derived from ecology-trait-based ecology (Brussaard et al. 2010; Lavorel and Garnier 2002), yet little used in agronomy, could be a useful medium for this reflection. One of the important issues associated with the possible uses of functional traits for crop species is that of the transition from the individual to population. In ecology, functional traits are considered at the level of the individual and its interactions with other components. In agronomy, the notion of population is the one that dominates through its responses to changes in the environment and practices. The issue of the robustness of a functional trait and its ability to become more widespread will thus be crucial to assist the design of innovative cropping systems via a selection of species based on expected services and via the terms and conditions of their integration in the agroecosystem. Benchmarks will have to be produced around the calibration of functional traits from ad hoc devices and research protocols in order to facilitate their widespread use.

Finally, this new generation of models must match a renewed experimental approach, allowing to experiment with network interactions. For example, when we will focus on the regulation of a bio-aggressor where regulations of various kinds, direct (trophic, chemical i.e. allelopathic) or indirect (enhanced plant vigour through nutrition) are involved, it will be necessary to consider mechanisms for tackling with the synergies involved. Conducting trials allowing dealing with integrated issues of agro-ecosystem functioning is required. The example of "*Biodiversity experiment*" or Jena experiment (http://www.ufz.de/Ratio.php?en=7000), which studies the interactions between the diversity of meadow species and ecosystem processes by focusing on biogeochemical cycles and trophic interactions, is therefore highly instructive.

Contribution of Concepts from Thermodynamics to the Modeling and the Development of Indicators

The flow of energy in environmentally intensive systems and the way in which technical choices affect its conservation/degradation will be a central issue for the design of innovative environmentally intensive systems. Besides the concepts of ecology of populations and communities drawn from the evolutionary biology, another more recent theoretical approach has taken place around thermodynamic ecology (Odum 1975, 1988, 1995; Odum and Odum 2003), which provides structuring bases for the energetic analysis of the systems. A major interest is the use of universal variables such as the *eMergy* for coupling and analysing processes and compartments of different nature. This approach based on thermodynamic analysis could be decisive, both in the comparative assessment of the energy efficiency of environmentally intensive systems in different technical scenarios, as in the approach to the scaling change between compartments or spheres of different nature (scale independent concept). On the output, indicators for the design of environmentally intensive systems could also be provided to supplement usefully more conventional indicators of diversity, productivity and efficiency, required for the assessment of these ecologically intensive systems (Monzote et al. 2009).

Development of Traditional Ecological and Innovative Modern Knowledge

In recent years, numerous studies have fuelled the debate on the design of new farming systems and agronomic engineering sensu *lato* (Meynard and Sébillotte 1989). This directive is therefore based on a disciplinary field where agronomy, as a discipline for action, has managed to structure its foundations and develop its concepts in agreement with the new specifications of agriculture for the design of innovative cropping systems (Doré et al. 2006). However, compared to conventional systems, the higher complexity of multispecies systems (number of species, stand structure, biological interactions and regulations,…) creates additional difficulties in the integration process. Thus, apart from the development of the culture of monitoring, testing and co-designing of cropping systems, the richness of the expert farmers' empirical knowledge will have to be properly mobilized to develop solutions (Valet 2007). Environmental practices thus make an invaluable benchmark for promoting the principles of an ecological intensification (Gliesmann 2001; Griffon 2006).

The multi-species systems designed to support productivity in the long term have been widely used in traditional agricultures, particularly in the tropics. The bottom-up approach with *feedback "farmers' Knowledge-Ecosystems-multidisciplinary research-Ecosystems-farmers' Knowledge"* offers a practical framework for the integration of farming practices, too often ignored, in a perspective of sustainable improvement (Fig. 21).

Many agronomic trials conducted in tropical areas, at a time when they were given less interest, should be revisited in order to capitalize and develop the lessons learned from the diversity of traditional cultural combinations and the terms and conditions of their implementation into innovative crop systems. This should take into account all the aspects covered by these combinations and not stop at the only available techniques which are often added together, and assessed for yield only, rather than combined in an integrated approach (Lançon et al. 2007). One of the priorities is to bring together dispersed knowledge (often in the form of grey literature) based on meta-analysis to provide quantitative references and guidelines and the development of expert systems. These approaches will be structured around a typology of agrosystems and geographical and socio-economic contexts; they will also have to consider the modern variants of ecologically intensive systems such as Direct Seeding Mulch-based cropping systems, like SAMBAs which decrease the nutrients leaching and more recently permaculture (Gliessman 1997).

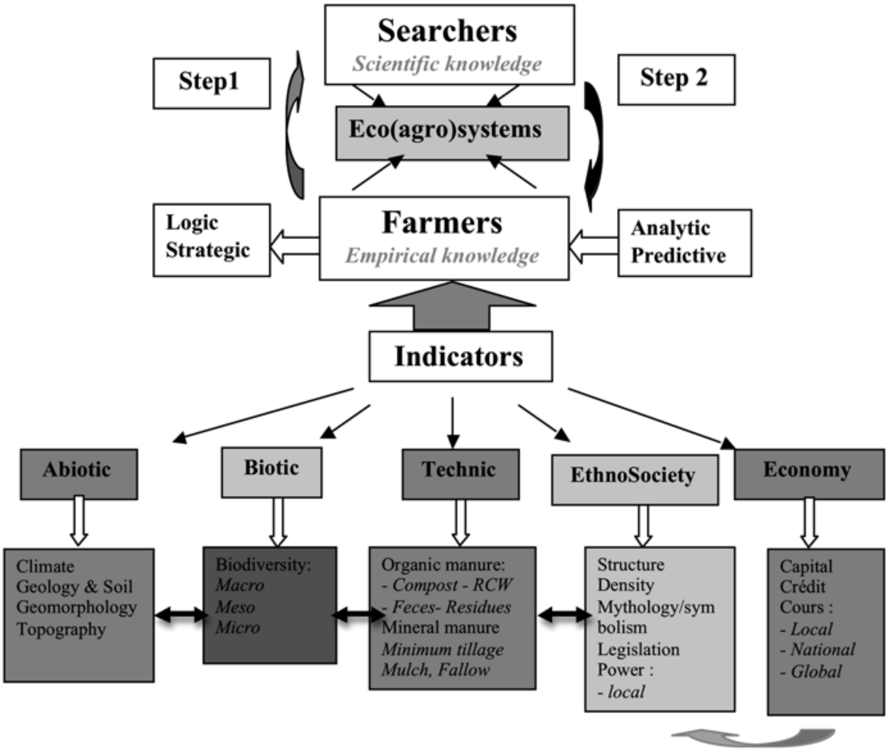


Fig. 21 Illustration of an integrative approach combining in an interactive loop 'farmers' know-how- knowledge of ecosystems – multidisciplinary research- innovation'

Conclusion

Traditional mixed cropping, mostly practiced in the tropical zone, and long marginalized compared to the conventional model of intensification, is now experiencing a strong revival. The environmental, productivity and resilience limits imposed by the intensified monoculture and denounced in 1975 by Trenbath *'Diversify or be damned',* are now reaching a critical threshold requiring a new and genuine technological revolution in systems engineering and modes of production. The FAO calls for an agricultural paradigm shift *'The present paradigm of intensive crop production cannot meet the challenges of the new millennium. In order to grow, agriculture must learn to save'* Shivaji Pandey, Head of FAO's Plant Production and Protection Division, explained that *'The Green Revolution brought agriculture to the level where crop productivity growth rates are declining everywhere … the soil, the water, the friendly pests, have to be saved for us to produce that extra food by 2050'*. The assessment of agricultural systems will no longer rely exclusively on the basis of the food they provide, but also on their ability to limit the impact on the environment as well as their contribution to the mitigation and adaptation to the climate change. To support this paradigm shift, adequate agricultural policies must be developed (Griffon 2007; Malézieux 2012).

In this chapter, the results obtained on the diversity of multi-species systems, from the plot to the territory scale, covering a long period from the 1960s up to now, are a significant credit to the knowledge of traditional practices and performances permitted by these very adaptative systems in peasant tropical or Sudan-Sahelian farms. The work presented shows the comparative advantages permitted by the ecosystem services provided by mixed cropping, resulting in (i) yields, often significantly higher than in monocultures, (ii) a decrease by 2 of the use of mineral and organic fertilizers, (iii) effective alternative to biocidal products, (iv) very significant water saving opportunities and also a significant saving of energy, (v) a better use of mountain soils and (vi) a more pragmatic use of time.

From a general point of view, the scarcity of results on the assessment of the cost/benefit of ecosystem services, demonstrates the difficulty of establishing the global accounts of ecosystems including resources, flows, services, stocks, integrated in the SEEA. The development of original indicators, such as the IER and the SEEA provides an initial assessment of the free functions of ecosystem services, performed with less investment and annual expenditure, and leading to a significant reduction in the risks of soil degradation, water and food pollution, due to the reduction of inputs.

The relevance of the economic assessment of the environment is emphasized by many economists (Brahic and Terreaux 2009; Rotillon 2005). The calculations carried out were limited to the monetization of the most accessible ecosystem services. No predictive calculations were considered in terms of individual well-being and societal benefits. However, the financial statements provided by ecosystem services demonstrate the need to change behaviour to protect the environment, to imagine other modes of growth, and therefore, to choose an ecodevelopment protecting the agro(eco) systems. The estimate of the profits generated by all of the services is not easy to realize. It does not enter into the subject of this review, but it would deserve a species development.

The development of an agro-ecological engineering, and specially the expected progress in the integration of ecological concepts for analysis, assessment and conduct of multispecies systems, has highlighted the need for a close cooperation between "*exper*t" and "*empirica*l" knowledge. In their analysis of the new '*paradigm of ecological intensification*' Doré et al. (2006) recommend some changes in attitudes breaking with the conventional view of agronomic research in order to produce knowledge and new learning for the benefit of the design of innovative agroecosystems. The emergence of these '*new avenues*' poses the challenge of building an 'actionable' knowledge to the benefit of an engineering of ecologically intensive agrosystems. This encourages us to set a new perspective of our reasoning to develop innovative concepts, it also goes through a renewal of academic approaches at different levels of physical (m^2, plot, watershed, small area: Pavé 1997; Van Duivenbooden et al. 2000; Valet 1999, 2008) and cognitive perception. This necessarily implies:

(i) The construction of a frame breaking with the classic conventional agronomic thought, backed by new cognitive requirements, including the ability to cope with technological and eco-sociological breakthroughs: adapting collective knowledge, sharing with unusual partners, tackling cloudy even contradictory logics, enriching the logic by the intuitive and the sensitive, facing the unimaginable.

(ii) The promotion of '*amazing*' tactics as those consisting, for example, in engaging in multidisciplinary teams (peasant, cook, healer, sorcerer, nutritionists, researchers, etc.), sharing unusual converging values, abandoning learned beliefs and certainties, revisiting the traditional unknown, detecting the unsuspected '*sleeper variants*', having a critical follow-up of methods/results in a group.

(iii) While developing innovative methods based on both the empirical discovery of traditional farming *empirical knowledge*, as close as possible to the actors, while applying academic knowledge to their understanding, identifying new contingencies, which requires a renewed perspective of rational analysis grids, facing a '*chaotic breakup*' along with the creation of new scientific trainings.

This can be established by encouraging constant *feedback* between the farmers' innovative, logical, strategic, traditional ***'empirical knowledge***', and the scientists' analytical and predictive '***expert knowledge***' (Valet 1976; Valet and Motelica-Heino 2010) (Fig. 21).

Thus, faced with new and old challenges that agriculture, livestock and forest must meet, two schools of thought are emerging. The first, a reasoned conservative farming is to explore new ways of conceptual agroecosystems proposing to mimic the structure of natural ecosystems, forest and meadow, through the Direct Seedling Mulch-based cropping systems, or the Agroforestry Intercropping Systems (AIS) with a very limited number of species even under excellent soil and climatic conditions (Jackson 2002; Malézieux and Moustier 2005; Séguy et al. 2008). The second, an agriculture of maximization, aimed at strengthening traditional mixed cropping (at least 47 species) and innovative practices with new biophysical techniques to achieve a more efficient and sustainable resilience to climate change, demographic increase and liberalism, decline in water and nutritional resource and with the role played by the ecological processes of these combinations (Autfray 2005; Baldy 1963; Baldy and Stigter 1997; Baker and Norman 1975; Charreau 1972; Dugué 1998; Dupriez and de Leener 2003; Dupriez 1980a, b, 2006; Jagoret et al. 2012; Le 2002; Salez 1990; Trenbath 1975; Valet 1968, 1976, 2007; Wilken 1972).

The recurrence of food crises in the world has contributed to a shift in thinking about emergency and development. The model that separates development – to prevent crises – from humanitarian – to solve them – now seems outdated. For several decades, food security policies have focused on increasing agricultural productivity, but in front of the relative failure of these policies, demonstrated by repeated food crises, the need for a broader approach has emerged so as to deal with all aspects of vulnerability i.e. economic, but also social, climatic, … (Oxfam 2011). We are going to enter a new stage: not only that of the 'major risk' but rather that of the 'mega-shocks', likely to operate global destruction. Therefore, the very concept of temporary crisis and shock needs to be readjusted, by addressing the root and chronic causes of vulnerability. Since 2005, the Hyogo Framework For Action, a strategic 10-year plan, developed by UNISDR (United Nations International Strategy for Disaster Reduction), has proposed to '*build the resilience of nations and communities facing disasters*' (Inter réseaux 2013).

Resilience was introduced in thinking on development and adaptation to climate change through Disaster Risk Reduction. The aim is to invent new *'amazing and miraculous'* solutions to address the fundamental changes that lead to the new paradigms presented, and offer open and creative concepts shared among the farmers and the scientists to manage these crises, and prevent any collapse. The global conversion to an agro-ecological agriculture is neither a utopia nor a return to the past, but rather the best road to meet future food challenges. This type of agriculture would allow small producers (more than 500 million family farms in the World: Planète 2012) to break the vicious cycle of poverty and dependence on large petrochemical companies, and live from their work without having to go into exile.

Although the idea that '*intercropping was only for peasant farming and has no place in modern agriculture*', (Tardieu 1970) has persisted for a long time among researchers and developers, it appears more than ever that 'in many areas of the world, traditional farmers developed or inherited complex farming systems in the form of poly-cultures that were well adapted to the local conditions and helped them to sustainably manage harsh environments and to meet their subsistence needs, without depending on mechanization, chemical fertilizers, pesticides or other technologies of modern agricultural science (Denevan 1995). These practices, thus generally more efficient than the high-intensity agricultural systems, highlight the '*agricultural engineering*' developed over centuries by the so-called 'primitive' peoples. Hence, traditional and innovative multispecies cropping systems could turn out to be a modern one.

Glossary

ANR	Assisted Natural Regeneration
CA	Conservation Agriculture
CFA	Franc des Colonies Françaises d'Afrique
CIRAD	Centre International de Recherche Agronomique et de Développement
DER	Density Equivalent Ratio
DMC	Direct Seeding Mulch-Based Cropping System
FAO	Food and Agriculture Organization
FEER	Fertility Efficiency Equivalent Ratio
ESS	EcoSystemic Services
ICS	Inter Cropping Systems
ICS	Inter Cultural System
IER	Income Equivalent Ratio
IRRI	International Rice Research Institute
Kram	Run off Coefficient
LAI	Leaf Area Index
LAR	Leaf Area Ratio

LER	Land Equivalent Ratio
MCS	Multi-species Cropping Systems
MEA	Millennium Ecosystem Assessment
MOS	Matter Organic Sum
N	Nitrogen
OC	Organic Carbon
OM	Organic Matter
P	Phosphorus
RCW	Rameal Chipped Wood
RER	Root Equivalent Ratio
TE	Transpiration over Evaporation
UNISDR	United Nations International Strategy for Disaster Reduction
USAID	United States Agency for International Development
WuEER	Water use Efficiency Equivalent Ratio

References

Adu-Gyamfi JJ, Myaka FA, Sakala WD, Odgaard R, Vesterager JM, Hogh-Jensen H (2007) Biological nitrogen fixation and nitrogen and phosphorus budgets in farmer-managed intercrops of maize-pigeonpea in semi-arid Southern and *Eastern Africa*. Plant Soil 295:127–136

Aerts R (1999) Interspecies competition in natural plant communities: mechanism, trade-offs and plant-soil feedbacks. J Exp Bot 50:29–37

Afessa T (1997) Management of two major diseases of maize in Ethiopia. Afr Crop Sci Conf Proc 3:910–920

AGRISUD (2010) L'agro écologie en pratiques -20 ans d'apprentissage en Angola – Brésil – Cambodge Gabon – Inde – Laos – Madagascar. GUIDE édition 2010

Ahmed S, Rao MR (1982) Performance of maize-soybean intercrop combination in the tropics: results of a multilocation study. Field Crop Res 5:147–161

Ahmed S, Alam MJ, Ma MS, Zaman S (2007) Etude sur le Mungo bean. Exploitation de polycultures avec Sésame à différent taux de semis. Int J Sustain J Sust Crop Prod 2(5):74–77

Allen SC, Nair PKR, Brecke BJ, Nkedi-Kizza P, Ramsey CL (2004) Safety-net role of tree roots: evidence from a pecan (*Carya illinoensis* K. Koch) – cotton (*Gossypium hirsutum*) alley cropping system in the southern United States. For Ecol Manage 192:395–407

Altieri MA (1999) The ecological role of biodiversity in agroecosystems. Agr Ecosyst Environ 74:19–31

Altieri MA, Francis CA, van Schoonhoven A, Doll JD (1978) A review of insect prevalence in maize (*Zea maize* L.) and bean (*Phaseolus vulgaris*) polycultural systems. Field Crop Res 1:33–49

Anil L, Park J, Phipps RH, Miller FA (1998) Temperate intercropping of cereals for forage: a review of the potential for growth and utilization with particular reference to the UK. Grass Forage Sci 53:301–317

Arslan A, Kurdali E (1996) Rainfed vetch-barley mixed cropping in the Syrian semi-arid conditions. II. Water use efficiency and root distribution. Plant Soil 183:149–160

Atiama-Nurbel T, Deguine JP, Quilici S (2012) Maize more attractive than Napier grass as non-host plants for *Bactrocera cucurbitae* and *Dacus demmerezi*. Arthropod-Plant Interact. doi:10.1007/s11829-012-9185-4

Augusseau X, Nikiéma P, Torquebiau E (2006) Tree biodiversity, land dynamics and farmers strategies on the agricultural frontier of south western Burkina Faso. Biodivers Conserv 15:613–630

Aussanac G, Boulangeat C (1980) Interception of precipitations and actual evapo transpiration in planting of leafy and coniferous trees. Ann Sci Forest 37:91–107

Autfray P (1985) Cultures associées et systèmes de culture en pays bamiléké (Ouest Cameroun). Centre Universitaire de Dschang-CNEARC, mémoire 1ère année ESAT. 82 p + annexe

Autfray P (2005) Effets de litières sur l'offre en azote d'origine organique dans des systèmes de culture de maïs à couvertures végétales Etude de cas dans la zone à forêt semi-décidue de Ivory Coast. Thèse de Doctorat en Sciences du Sol. Ecole Nationale Supérieure Agronomique de Montpellier, France

Ayieni AO, Duke WB, Akobandu IO (1984) Weed interference in maize cowpea and maize/cowpea intercrop in a sub-humid tropical environment. I. Influence of cropping season. II. Early growth and nutrient content. III. Influence of land preparation. Weed Res 24:269–279

Ayuk-Takem JA, Cheda HR (1985) Grain yield potential of some diverse maize (Zea maize L.) morphotypes intercropped with cocoyam (Xanthosoma sagittifolium). Exp Agr 21:145–152

Azam-Ali SN, Gregory PJ, Monteith JL (1984) Effects of plant population on water use and productivity of pearl millet (Pennisetum typhoides) grown on stored water. I. Growth of roots and shoots. Exp Agr 20:203–214

Baker EFI, Norman EW (1975) Cropping system in northern Nigeria. In: Proceedings of the cropping system workshop, IRRI, Los Branos, 18–20 Mar 1975, pp 334–361

Balde AB (2011) Analyse intégrée du partage des ressources (eau, azote et rayonnement) et des performances dans les systèmes de culture en relais sous semis direct en zone Tropicales subhumides. Thèse. Centre International d'Etudes Supérieures en Sciences Agronomiques, Montpellier, 160 p

Baldy C (1963) Cultures associées et productivité de l'eau. Ann Agro 14(4):484–534

Baldy C (1986) Agrométéorologie et développement des régimes arides et semi arides. INRA, 115 p

Baldy C, Durand R (1970) Evapotranspirations potentielles calculées et humidités relatives sous forêt et en clairière a Zernizea (Tunisie) Ann. INRF-Tunisie, 4, 17 p

Baldy C, Stigter CJ (1997) Agrometeorology of multiple cropping in warm climate. Translation of Agrométéorologie des cultures multiples en région chaudes. INRA, Paris, 1993. INRA, Paris, p 236

Banik P, Midya A, Sarkar BK, Ghose SS (2006) Wheat and chickpea intercropping systems in an additive series experiment: advantages and weed smothering. Eur J Agron 24:325–332

Barhom TIH (2001) Studies on water requirements for some crops under different cropping systems. M.Sc. thesis, Facility of Agriculture Cairo University

Barral JA, Sagnier H (1889) Dictionnaire d'Agriculture: Encyclopédie agricole complète. Librairie Hachette & Cie.70 Bd St Germain, 4 vols, 3900 p

Barthès B, Roose E (1983) Aggregate stability as an indicator for soil susceptibility to runoff and erosion; validation at several levels. Catena 47:133–149

Battesti (1997) Les oasis du Jérid :des révolutions permanentes ?Projet "Recherche pour le développement de l'agriculture d'oasis". INRAT/Centre de Recherches Phoenicicoles Degache – Tunisie. GRIDAO/CIRAD – SAR, Montpellier. Financement Ministère de l'Agriculture Tunisien et Ministère des Affaires Etrangères Français

Baudron F (2011) Agricultural intensification – saving space for wildlife? Wageningen University, IX. Thesis Ph.D., University of Wageningen, 244 p

Baumann DT, Kropff MJ, Bastiaans L (2000) Intercropping leeks to suppress weeds. Weed Res 40:359–374

Beauval V (1991) Association de cultures comprenant des cultures annuelles et des palmiers vignobles dans le MONO (sud-ouest du Bénin): Etude coton AFD – MDR, 20 p

Bernardès M, De Pury P, Eltz F, Vedy J-C (1999) Bilan comparé de pratiques culturales (Maïs, engrais vert sur semis direct) dans la lutte contre l'érosion hydrique au Brésil. Bull. EROSION No 19, IRD BP 5045, 34032 Montpellier Cedex 1, pp 353–363

Berry SD, Dana P, Spaull VW, Cadet P (2009) Effect of intercropping on nematodes in two small-scale sugarcane farming systems in South Africa. Nematropica 39:11–33

Betencourt E, Colomb B, Cordier F, Guilleré C, Juste E, Souche G, Hinsinger P (2010) Soil phosphorus pool differ when *durum wheat* is grown alone or intercropped with *pea* or *fababean* in

low versus high-input conditions. AGRO2010. XI[th] Congress, Montpellier, 29 Aug–3 Sept 2010, pp 169–170
Bilalis D, Papastylianou P, Konstantas A, Patsiali S, Karkanis A, Efthimiadou A (2010) Weed-suppressive effects of maize-legume intercropping in organic farming. Int J Pest Manag 56:173–181
Bizimana R, Duchauffour PH (1997) Projet de recherche pour la protection de l'Environnement. Institut des Sciences Agronomiques du Burundi. BP 795. Bujumbura, pp 166–168
Bogale T, Debele T, Gebeyehu S, Tana T, Getela N, Workayehu T (2001) Development of appropriate cropping systems for various maize producing regions of Ethiopia. Second international maize workshop of Ethiopia, 12–16 Nov 2001, pp 59–70
Boli B (1996) Fonctionnement des sols sableux et optimisation des pratiques culturales en zone soudanienne humide du Nord-Cameroun (Expérimentation au champ en parcelles d'érosion à Mbissiri). Thèse de Dr. Etat, Université de Bourgogne, France, 344 p
Bouzinac S, Taillebois J, Séguy L (2009) La SAGA SEBOTA – Les riz poly-aptitudes (SBT) créés pour et dans les DMC au service de rizicultures alternatives performantes diversifiées "propres" et à faible coût. Chapitres I, II, III. In: Le Réseau du Semis Direct sur Couverture Végétale Permanente (SCV). Doc CIRAD (site agroécologie), Bp 5045, 34032 Montpellier, France
Brahic E, Terreaux J-P (2009) Evaluation économique de La biodiversité. Méthodes et exemples pour les forêts tempérées. Quae éditions. Savoir Faire, 196 p
Brokensha D, Warren DM, Werner O (1980) Indigenous knowledge systems and development. University Press of America, Lantham, 460 p
Brown JE, Splittstoesser WE, Gerber JM (1985) Production and economic returns of vegetable intercropping systems. J Am Soc Hort Sci 110(3):350–353
Brussaard L, Caron P, Campbell B, Lipper L, Mainka S, Rabbinge R, Babin D, Pulleman M (2010) Reconciling biodiversity conservation and food security: scientific challenges for a new agriculture. Sci Direct 2:34–42
Bulson HAJ, Snaydon RW, Stopes CE (1997) Effects of plant density on intercropped wheat and field beans in an organic farming system. J Agr Sci 128:59–71
Caballero A, Goicoechea Oicoechea RE, Ernaiz PJ (1995) Forage yields and quality of common vetch and at sown at varying graining ratios and graining rates of vetch. Field Crop Res 41:135–140
Caldwell RM (1995) Simulation model for intercropping systems. In: Sinoquet H, Cruz P (eds) Ecophysiology of tropical Intercropping. INRA, Versailles, pp 353–368
Caldwell MM, Richards JH (1986) Competing root systems: morphology and models of absorption. In: Givnish T (ed) On the economy of plant form and function. Cambridge University Press, Cambridge, England, pp 251–260
Camara A (2007) Dynamiques régionales et systèmes ruraux en Guinée Forestière. Vers la conception d'un observatoire pour le développement. Ph.D. thesis, Université d'Avignon et des Pays de Vaucluse, Avignon, France, 250 p
Camara AA, Dugué P, Cheylan JP, Kalms JM (2009) De la forêt naturelle aux agroforêts en Guinée forestière. "From natural forests to agroforests in the Guinea forest region". Cahiers Agric 18(5):425–431
Camara A, Dugué P, Kalms J-M, Soulard CT (2010) Systèmes de culture, habitudes alimentaires et durabilité des agro-systèmes forestiers en Afrique (Guinée, Cameroun): une approche géo-agronomique. ISDA 2010, 28–30 juin 2010, 12 p
Cannavo P, Sansoulet J, Harmand JM, Siles Gutierrez P, Dreyer E, Vaast P (2011) Agroforestry associating coffee and Inga densiflora results in complementarity for water uptake and decreases deep drainage in Costa Rica. Agr Ecosyst Environ 140(1–2):1–13
Casenave A, Valentin C (1989) Les états de surface de la zone sahélienne. Influence sur l'infiltration. Editions de l'ORSTOM (Institut français de Recherche Scientifique pour le Développement en Coopération). Collection Didactique.70, rue d'Aulnay 93143 Bondy, France, 229p
Chabanne A, Husson O, Tuan AD, Lhienard P (2009) Technical set- soil smouldering for a low cost restoration of fertility. Site sur le réseau du CIRAD, Agroécologie, 20 p

Charreau C (1972) Problèmes posés par l'utilisation agricole des sols tropicaux par des cultures annuelles. Agron Trop XXVII(9):905–929

Charreau C (1974) Soils of tropical dry and dry-wet climatic areas of West Africa and their use and management. A series of lectures. Agronomy Mimeo 74–26. Cornell University, Department of Agronomy, Ithaca, USA, 434 p

Charreau C, Vidal P (1965) Influence de l'*Alcacia Albida* del. sur le sol. Nutrition minérale et rendements des mils pennisetum au Sénégal. *Agronomie Tropicale* (4):600–636

Chen C, Westcott M, Neill K, Wichman D, Knox M (2004) Row configuration and nitrogen application for barleypea intercropping in Montana. Agron J 96:1730–1738

Chervonyl AY (1999) Rapport d'étape sur la technologie des BRF, utilisant le seigle comme référence pour les années 1997–98. No 107. Université de Laval. Département des Sciences des Bois et de la Forêt. Québec GIK 7P4 Québec, 61 p

Chikte P, Thakare SM, Bhalkare SK (2008) Influence of various cotton-based intercropping systems on population dynamics of thrips, *Scirtothrips dorsalis* Hood and whitefly, *Bemisia tabaci* Genn. Res Crop 9:683–687

CIRAD-AFD-FFEM-JLFIDA (2005) Ministère affaires étrangères- FAO. 2005 Regards sur l'agriculture de conservation en Afrique de l'ouest et du centre et ses perspectives. (Synthèse). 3ème congrès agri conservation, 3–7 Octobre 2005, Nairobi, 101 p

Clark EA, Francis CA (1985) Bean maize intercrops: a comparison of bush and climbing bean growth habits. Fields Crop Res 11:151–156

Cochet H (2001) Crises et révolutions agricoles au Burundi. INAPG, Karthala, Paris, 125 p

Cornet D (2005) Systèmes de cultures associées a base d'igname et gestion des plantes adventices. Année académique 2004–2005, Faculté des Sciences Agronomiques de Gembloux, 30 p

Corre-Hellou G, Brisson N, Launay M, Fustec J, Crozat Y (2007) Effect of root depth penetration on soil nitrogen competitive interactions and dry matter production in pea-barley intercrops given different soil nitrogen supplies. Field Crop Res 103:76–85

Costanza R (1991) Ecological economics: the science and management of sustainability. N-Y Colombia University Press, New York, USA

Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill R, Paruelo J, Raskin R, Sutton P, van den Belt M (1997) The value of the world's ecosystem services and natural capital. Nature 387:253–260, 15 May 1997

Dala RC (1974) Effects of intercropping maize with pigeon peas on grain yield and nutrient uptake. Exp Agric 10:219–224

Dancette C (1984) Principaux résultats obtenus en 1983 par la division de bioclimatologie sur les systèmes de cultures à base de mil et de Niébé. Collection: Etudes techniques du CNRA. CNRA, BP 53 Bambey

Dancette C, Poulain JF (1968) Influence de l'*Acacia albida* sur les facteurs pédo-climatiques et les rendements des cultures. IRAT/CNRA Nouvelle contribution. Institut de recherches agronomiques tropicales et des cultures vivrières. Centre national de recherches agronomiques, Paris

Das PK (1999) Coconut-based cropping systems in India and Sri Lanka. In: Ohler JG (ed) Modern coconut management. Palm cultivation and products. Food and Agriculture Organization of the United Nations (FAO), Rome, pp 277–287

Debar JC (2013) Journée mondiale de l'alimentation: un besoin de clarification. Fondation FARM. Blog de la Fondation pour l'agriculture et la ruralité dans le monde: www.fondation-farm.org, 4 p

Deen W, Cousens R, Warringa J, Bastiaans L, Carberry P, Rebel K, Riha S, Murphy C, Benjamin LR, Cloughley C (2003) An evaluation of four crops: weed competition models using a common data set. Weed Res 43:116–129

Deguine JP, Atiama-Nurbel T, Douraguia E, Chiroleu F, Quilici S (2012) Species diversity within a community of the Cucurbit fruit flies *Bactrocera cucurbitae, Dacus ciliatus* and *Dacus demmerezi* roosting in corn borders near cucurbit production areas of Reunion Island, Cirad, BP 5045,34032 Montpellier, France, 12p

Denevan WM (1980) World systems of traditional resource management. Winston & Son/Edward Amold, London, pp 217–244

Denevan WM (1995) Prehistoric agricultural methods as models for sustainability. Adv Plant Pathol 11:21–43

Depommier D (1996) Structure, dynamique et fonctionnement des parcs à *Faiherbia albida* (Del.) A. Chev. Caractérisation et incidence des facteurs biophysiques et anthropiques sur l'aménagement et le devenir des parcs de Dossi et Watinoma, Burkina Faso. Thèse. Université de Paris VI, Paris, vol 1, 541 p

Derelle D (2012) Effets des associations de plantes sur la symbiose mychorizienne et réponse spécifique des plantesà la mychorization. Alliances au pays des racines. 14ème Colloque scientifique et journées à thème. Société Nationale d'Horticulture de France. 25 mai 2012. Paris, pp 17–19

Derelle D, Declerck S, Genet P, Dajoz I, van Aarte IM (2010) La coexistence entre espèces végétales influe sur la colonisation racinaire d'une espèce cible par un champignon mycorhyzien. Colloque Ecologie 2010. Premier colloque National d'Ecologie Scientifique 2–4 septembre 2010

Diagne M (1985) Situation agro-pluviométrique au Sénégal à la mi-octobre 1986. Dot. Ronéo – ISRA, CNRA

Diagne M (1987) Agro-climatologie du niébé. Synthèse de résultats de 1980. Dot. Ronéo – ISRA-ICNRA, 5 p

Diouf J (2004) Ethique et intensification durable. Collection FAO: Questions d'éthique. FAO: Organisation Des Nations Unies Pour L'alimentation Et L'agriculture, Rome, 46 p

Djangar S, Fofana A, Diagne M, Yamoha CF, Dick RP (2004) Pearl millet-based intercropping systems in semiarid areas of Senegal. Afr Crop Sci J 12(2):13–139, Printed in Uganda

Dodelin B, Valet S (2007) Du bois Raméal fragmenté ?. Les rémanents en Foresterie et agriculture. Réseau Ecologique Refora. Forestier Rhône-Alpes, France. Colloque BRF de Lyon, France, 1–2 février 2007, 13p

Donald CM (1958) The interaction of competition for light and for nutrients. Aust J Agr Res 9:421–435

Doré T, Le Bail M, Martin P, Ney B, Roger-Estrade J (2006) L'agronomie aujourd'hui. Editions Quae, 365 p

Duchaufour PH (1997) Abrégé de Pédologie. Masson Edit, 361 p

Duchaufour H, Guizol PH, Bizimana M (1996) Avantage et inconvénients comparatifs de la haie mixte Calliandra/Setaria et du mulch comme dispositif anti-érosif en milieu rural burundais. Bull EROSION No 16, IRD BP 5045, 34032 Montpellier Cedex 1, pp 132–151

Ducret G, Grangeret J (1986) Quelques aspects des systèmes de culture en pays bamiléké (Dschang, Cameroun). CUDS, 33 p. CIRAD. BP 5035, 34032 Montpellier 16–19 Déc, pp 115–127

Dugué P (1998) Gestion de la fertilité et stratégies paysannes. Le cas des zones de savanes d'Afrique de l'Ouest et du Centre. Agriculture et Développement- Spécial sols tropicaux, 18:13–20

Dugué P, Mathieu B, Sibelet N, Seugé C, Vall E, Cathala M, Olina JP (2006) Smallholders are innovating, what about agronomists? Case study: cropping systems in a cotton production area in Cameroon. In: Jacques C (ed) Agronomes et innovations: 3ème édition des entretiens du Pradel. Actes du colloque des 8–10 septembre 2004. L'Harmattan, Paris, pp 103–122. Les Entretiens du Pradel, Journées Olivier de Serres. 3, 2004-09-08/2004-09-10, Mirabel

Dumont R (1975) La croissance de la famine. Une agriculture repensée. Seuil. Tecno-critique. 191 p

Dupraz C, Liagre F (2008) Agroforesterie– des arbres et des cultures. Editions France Agricole, Paris, 413 p

Dupraz C, Lecomte I, Mayus M, Mulia R, Vincent G, Jackson N, Van Noordwijk M (2004) Integrating tree-crop dynamics interactions in the Hi-sAFe model. In: Working together for sustainable land-use systems, 1st world congress of agroforestry, Orlando, 27 Jun–2 Jul 2004, p 177

Dupriez H (1980a) Cultures associées ou monocultures? Validité du savoir paysan. Cahier d'Etude du milieu et d'Aménagement du territoire. Environnement africain et Développement du Tiers-monde (ENDA). BP 3370 Dakar. Sénégal, 24 p

Dupriez H (1980b) Paysans d'Afrique noire. Terre et Vie. Bruxelles, 256 p

Dupriez H (2006) Agriculture tropicale et exploitations familiales d'Afrique. Terre & Vie. Belgique. CTA. Coopération belge.Diobass, Ecologie et Société, 480 p
Dupriez H, de Leener PH (2003) Arbres et agricultures multiétagées d'Afrique. CTA, Terres et Vie. L'Harmattan, 7, rue de l'école Polytechnique, 75005, Paris, 280 p
Dury S, Zoa JM (2001) Modélisation économique des associations de cultures pérennes. Test du modèle de portefeuille sur des données réelles (systèmes cacao-palmiers-agrumes) au Cameroun. Communication à la journée "*Diversification fruitière*". Réunion annuelle 2001 Centre de coopération internationale en recherche agronomique pour le développement-Productions fruitières et horticoles (Cirad-Flhor). Montpellier, 7 p
Eden MJ (1980) A traditional agrosystem in the Amazon region of Columbia. Trop Ecol Dev, pp 509–514
Egger K (1986) L'intensification écologique. Conservation (LAE) et amélioration des sols tropicaux par les systèmes agro-sylvo-pastoraux, pp 129–135. Docu Syst Agraires no 6: Aménagements hydro-agricoles et systèmes de production. Actes du III^{ème} Séminaire. Tome I
Egunjobi OA (1984) Effects of intercropping maize with grain legumes and fertilizer treatments on populations of Protylenchus penetrans Godfrey (Nematoda) and on the yield of maize (Zea mays L.). Prot Ecol 6:153–167
Ellis F (1998) Household strategies and rural livelihood diversification. J Dev Stud 35:1–38
El-Swaify SA, Lo AKF, Joy R, Shinshiro L, Yost RS (1988) Achieving conservation effectiveness in the tropics using legume-intercrops. Soil Technol 1:1–12
Enquist BJ, Niklas KJ (2001) Invariant scaling relations across tree-dominated communities. Nature 410:655–660
Epidi TT, Bassey AE, Zuofa K (2008) Influence of intercrops on pests' populations in upland rice (Oryza sativa L.). Afr J Environ Sci Technol 2:438–441
FAO (2010) L'état de l'insécurité alimentaire dans le monde. FAO, Différents rapports annuels. Organisation des Nations Unies pour l'alimentation et l'agriculture
FAO (2011) Promotion des Intrants Agricoles par les organisations de producteurs au Niger. Le Projet "Intrants" de la FAO. GCP/NER/041/BEL. Organisation des Nations Unies pour l'alimentation et l'agriculture
Fernandez-Aparicio M, Sillero JC, Rubiales D (2007) Intercropping with cereals reduces infection by *Orobanche crenata* in legumes. Crop Prot 26:1166–1172
Fleck NG, Machado CMN, de Souza RS (1984) Efficiencia da consorciao de culturas no controle de plantas danhinas. (Port.). Presq. Agrip. Brazil 19(5):591–598
Fortmann L, Rocheleau D (1985) Women and agroforestry: four myths and tree case studies. Agroforest Syst 2:253–272
Fotsing JM (1993) Erosion des terres cultivées et propositions de gestion conservatoire des sols en pays bamiléké (ouest-Cameroun). Cahiers ORSTOM *Série pédol* XXVIII(13):351–366
Francis CA (1986) Distribution and importance of multiple cropping systems. Macmillan, New York, pp 1–10
Francis CA (1989) Biological efficiency in multiple cropping systems. Adv Agro 42:1–42
Francis CA, Sanders JH (1978) Economic analysis of bean and maize systems: monoculture versus associated cropping. Field Crop Res 1:319–335
Fukai S, Trenbath BR (1993) Process determining intercrop productivity and yields of component crops. Field Crop Res 34:247–271
Furlan et Lemieux (1996) Méthode d'application et d'évaluation pour l'utilisation des bois raméaux fragmentés. No 67. Groupe de coordination sur les BRF. Université de Laval. Département des Sciences des Bois et de la Forêt. Québec GIK 7P4 Québec, 8 p
Giri J (1983) Le sahel demain: Catastrophe ou renaissance? Edition Karthala, 240 p
Gliessman SR (1997) Agroecology: ecological processes in sustainable agriculture. Ann Arbor press, Chelsea, 357 p
Gliesmann SR (2001) Agro ecosystem sustainability: developing practical strategies. CRC Press, Boca Raton
Gomez Delgado F, Moussa R, Rapidel B, Roupsard O (2009) Impacts des arbres d'ombrage sur les services hydrologiques et l'érosion dans un AFS de café du Costa Rica, la mise à l'échelle de

la parcelle au bassin versant. In: 2nd world congress of agro-forestry. Agro-forestry, the future of global land use: 23–28 Aug 2009, Nairobi (book of abstracts), p 101

Gooding MJ, Kasyanova E, Ruske R, Hauggaard-Nielsen H, Jensen ES, Dahlmann C, Von Fragsten P, Dibet A, Corre-Hellou G, Crozat Y, Pristeri A, Romeo M, Monti M, Launay M (2007) Intercropping with pulses to concentrate nitrogen and sulphur in wheat. J Agr Sci 145:469–479

Gosselin F (2008) Redefining ecological engineering to promote its integration with sustainable development and tighten its links with the whole of ecology. Ecol Eng 32(3):199–205

Grant RF (1992) Simulation of competition among plant populations under different managements and climates. Agron. Abstr. American Society of Agronomy, Madison

Graves AR, Burgess PJ, Palma JHN, Herzog F, Moreno G, Bertomeu M, Dupraz C, Liagre F, Keesman K, van der Werf W, de Nooy A k, van del Briel JP (2007) Development and application of bio-economic modelling to compare silvoarable, arable, and forestry system, three European countries. Ecol Eng 29:237–255

Grema AK, Hess TM (1994) Water balance and water use of pearl millet-cowpea intercrops in north east Nigeria. Agri Water Manag 26:169–185

GRET (1982) Cultures associées en milieu tropical. Eléments d'observation et d'analyse. Dossier Technologies et Développement. Coopération Française, 34, rue d'Umont d'Urville, 75116, Paris Cedex, 75 p

Griffon M (2006) Nourrir la planète. Odile Jacob Sciences ed, 455 p

Griffon J (2007) Lettre d'Information, No 22, octobre 2007. CIRAD, 1 p

Grimes A, Quasem AM, Uddin MS, Jahiruddin N, Mallik RN (1983) Performance of different cropping patterns in 1992–93 at the cropping system research site. RARS, Hathazari, Chittagong

Guillerme S, Alet B, Briane G, Coulon F, Maire E (2009) L'arbre hors forêt en France. Diversité, usages et perspectives. Rev. For. Fr. LXI – 5 p

Hallé F (2010) La condition tropicale: une histoire naturelle, économique et sociale. Actes Sud, Arles, France, 572 p

Harmand JM, Avila H, Dambrine E, Skiba U, De Miguel S, Renderos Duran RV, Oliver R, Jimenez F, Beer J (2007) Nitrogen dynamics and soil nitrate retention. Rica Biogeochem 85:125–139

Haugaard-Nielsen H, Jensen AB, Jensen ES (2001) Interspecies competition, N use an interference with weed in pea-barley intercropping. Field Crop Res 70:101–109

Haynes RJ, Swift RS, Stephen RC (1990) Influence of mixed cropping rotations (pasture arable) on organic matter content, water stable aggregation and clod porosity in a group of soils. Soil Till Res 19:77–87. Elsevier Science Publishers B.V., Amsterdam

Hecq H (1958) Le système des cultures Bashis et ses possibilités- Bull. Agric. du Congo belge. XLIX(4):969

Hiebsch CK, McCollum RE (1987) Area-x time equivalency ratio. A method for evaluating the productivity of Intercrops. Agron J 79:15–22

Hobbs RJ, Morton SR (1999) Moving from descriptive to predictive ecology. Agroforest Syst 45:43–55

Hook JE, Gascho GJ (1988) Multiple cropping for efficient use water and nitrogen. In: Hargrove WL (ed) Cropping strategies for efficient use of water and nitrogen. American Society of Agronomy, Crop Science Society of America and Soil Science Society of America, Madison, pp 7–20

Hugar HY, Palled YB (2008) Studies on maize-vegetable intercropping systems. Karnataka J Agric Sci 21:162–164

Hulet H (1986) Improving millet/cowpea intercropping in the semi-arid zone of Mali. The Sahel Programme ILCA, P.O. Box 60, Bamako. The Sahel Programme *in* Haque et al (1986)

Hulet H, Gosseye P (1986) Effects of intercropping cowpea on dry matter and grain yield of millet in the semi arid zone of Mali. In: Potentials of forage legumes in farming systems of sub-Saharan Africa. Actes du Séminaire tenu au CIPEA, Addis Abeba. Ethiopie 16–19 Sept 1985, 557 p

Hulugalle NR, Lal R (1986) Soil-water balance of intercropped maize and cowpea grown in a tropical hydromorphic soil in western Nigeria. Agron J 77:86–90

Hulugalle NR, Willatt ST (1987) Seasonal variation in the water uptake and leaf water potential of intercropped and monocropped chillies. Exp Agric 23:273–282

Husson O, Charpentier H, Razanamparany C, Moussa N, Michellon R, Naudin K, Razafintsalama H, Rakotoarinivo CH, Rakotondramanana JN, Enjalric F, Séguy L (2010) Maïs ou sorgho associé à une légumineuse alimentaire volubile (Dolique, Niébé ou *Vigna umbellata*). CIRAD-Gsdm-TAFA-AFC. Manuel pratique du semis direct à Madagascar, vol III. Chapitre 3. § 2.2, 19 p

Huxley PA (1983) Phenology of tropical woody perennials and seasonal crop plants with reference to their management in agroforestry systems. In: Huxley PA (ed) Plant research and agroforestry. ICRAF, Nairobi, pp 503–526

IAEA (2002) Réunion Technique sur "*l'utilisation des techniques nucléaires pour la gestion intégrée du sol, de l'eau et des éléments nutritifs en agriculture pluviale des zones arides et semi arides en Afrique*" AIEA CT projet régional RAF/5/048 Rapport: "Lutte contre la désertification dans le Sahel". 18–22 mars 2002. AIEA, Vienne et Seibersdorf

Idiety E, Bokonon-Ganta E (2002) Fondements climatiques endogènes de l'occupation agricole des sols chez les Bètammaribè de l'Atacora (nord-ouest du Bénin)

Innis WH (1997) Intercropping and the scientific basis of traditional agriculture, 1st edn. Intermediate Technology Publications Ltd, London

Inter –Réseaux (2013) La promotion de la résilience au Sahel: changement d'approche ou nouvelle mode? Développement rural. Bulletin de synthèse souveraineté alimentaire. No 8. janvier 2013

International Rice Research Institute (IRRI) (1974) Atmospheric nitrogen fixation. In: Annual Report 1973. Los Banos, Indonesia, pp 108–111

Iqbal J, Cheema ZA, An M (2007) Intercropping of field crops in cotton for the management of purple nutsedge (*Cyperus rotundus* L.). Plant Soil 300:163–171

Izaurralde RC, McGill WB, Juma NG (1992) Nitrogen fixation efficiency, interspecies N transfer, and root growth in barley-field pea intercrop on Black Chernozemic soil. Biol Fertil Soil 13:ll–16

Jackson W (2002) Natural systems agriculture: a truly radical alternative. Agr Ecosyst Environ 88:111–117

Jackson T (2010) Prospérité sans croissance. De Boeck, Bruxelles

Jackson L, van Noordwijk M, Bengtsson L, Foster W, Lipper L, Pulleman M, Said M, Snaddon J, Vodouhe R (2010) Biodiversity and agricultural sustainagility: from assessment to adaptive management. Sci Direct 2:80–87

Jagoret P, Bouambi E, Abolo D, Snoeck D (2006) Improvement of traditional coffee farming system in Cameroon by introducing three technical innovations. Biotechnologie, agronomie, société et environnement, 10(3):197–207. ISSN 1370-6233 [11 page(s) (article)] INIST-CNRS

Jagoret P, Michel-Dounias I, Snoeck D, Todem Ngnogue H, Malézieux E (2012) Afforestation of savannah with cocoa agroforestry systems: a small-farmer innovation in central Cameroon. Agroforest Syst 86(3):493–504

Jensen ES, Hauggaard-Nielsen H, Kinane J, Andersen MK, Jørnsgaard B (2005) Intercropping – the practical application of diversity, competition and facilitation in arable organic cropping systems. In: Köpke U, Niggli U, Neuhoff D, Lockeretz W, Willer H (eds) Researching sustainable systems 2005. Proceedings of the first scientific conference of the International Society of Organic Agricultural Research (ISOFAR). International Society of Organic Agriculture Research, Bonn, Allemagne, pp 22–25

Jolliffe PA (1997) Are mixed populations of plant species more productive than pure stands? Acta Oecol Scand (OIKOS) 80(3):595–602, issued by the Nordic Society

Jong de SM, Jetten VG (2007) Estimating spatial patterns of rainfall interception from remotely sensed vegetation indices and spectral mixture analysis. J Geogr Inform Sci Int Inst Geo-Inform Sci Earth Obs ITC, 7500 AA Enschede, 21(5) (Jan). Taylor & Francis, Inc. Bristol, pp 529–545

Jung G (1966) Etude de l'influence de l'acacia albida DEL. sur les processus microbiologiques dans le sol et sur leurs variations saisonnières. ORSTOM. Centre de Dakar, rapp. mimeo, 63 p

Kalemba L, Ndoki N (1995) Effets d'émondes arbustives et d'engrais minéraux sur le rendement du niébé en cultures en couloirs. Symposium régional sur la recherche et le Développement dans les zones tropicales humides d'Afrique Centrale et de l'Ouest, Yaoundé 1995. CIRAD, BP 5035, Montpellier, pp 231–237

Kalifa Traoré A, Madu Doumbia J, Ganry F, Oliver R (2004) Runoff control and Vitellaria paradoxa park land regeneration: effects on soil fertility and carbon storage. Arid Land Res Manag

1818(4), Jan 2004. http://www.informaworld.com/smpp/title~db=all~content=t713926000~tab=issueslist~branches=18
Kalra GS, Ganger B (1980) Economics of intercropping of different legumes with maize at different levels of N under rainfed conditions. Ind J Agron 25:181–185
Kelty MJ (2006) The role of species mixtures in plantation forestry. Forest Ecol Manag 233:195–204
Khan ZR, Overholt WA, Hassanali A, Chiliswa P, Wandera J, Muyekho F, Pickett JA, Smart LE, Wadhams LJ (1998) An integrated management of cereal stem borers and *Striga* weed in a maize based cropping system in Africa. In: Maize production technology for the future: challenges and opportunities,:Proceedings of the 6th Eastern and Southern Africa regional maize conference. CIMMYT (International Maize and Wheat Improvement Centre) and EARO (Ethiopian Agricultural Research
Khan ZR, Hassanali A, Overholt WA, Khamis TM, Hooper AM, Pickett JA, Wadhams LJ, Woodcock CM (2002) Control of witchweed *Striga hermonthica* by intercropping with *Desmodium* spp. and the *options for* Striga *management in Kenya* 12 mechanisms defined as allelopathic. J Chem Ecol 28:1871–1885
Kihara J, Martius C, Bationo A, Thuita M, Lesueur D, Herrmann L, Amelung W, Vlek PLG (2012) Soil aggregation and total diversity of bacteria and fungi in various tillage systems of sub-humid and semi-arid Kenya. Appl Soil Ecol 58(1):12–20
Kinane J, Lyngkjær M (2002) Effect of barley-legume intercrop on disease frequency in an organic farming system. Plant Prot Sci 38:227–231
Klaij MC, Hoogmoed WB (1993) Soil management for crop production in the West African Sahel. II. Emergence, establishment, and yield of pearl millet. Soil Till Res 25:301–315
Klaij MC, Renard C, Reddy KC (1994) Low input technology options for millet based cropping systems in the Sahel. Exp Agric 30:77–82
Klee GA (1980) World systems of traditional resource management. Winston & Son/Edward Amold, London, 290 p
Kleitz G (1988) Les systèmes de culture en pays Bamiléké (Ouest Cameroun): Exemple de la chefferie de Bafou. Centre Universitaire de Dschang. CIRAD-CNEARC-ASSAA, Montpellier
Knörzer Heike, Simone Graeff-Hönninger, Buqing Guo, Pu Wang, Wilhelm Claupein (2008) The rediscovery of intercropping in China: a traditional cropping system for future Chinese agriculture – rediscovery of intercropping in China. A review
Köning D (2004) Conservation et amélioration de la productivité des sols dans des systèmes agro forestiers au Rwanda. Bull. du Réseau Erosion, Gestion de la Biomasse: Erosion et séquestration du Carbone. No 23, IRD-CIRAD-AGER-Labo-MOST, BP 5045, 34032 Montpellier, 23–28 Sept 2002, pp 41–49
Kowal JML, Tinker PBH (1959) Soil changes under a plantation established from high secondary forest. J West Afr Inst Oil Palm Res 2:376–389
Kurata T (1986) A study on the farming system in USSA. Quart J Agro Eco 26:179–205
Labouisse JP (2004) Systèmes agraires et économie du cocotier au Vanuatu: historique et perspectives. J la Société des Océanistes 118:11–33
Lamanda N (2005) Caractérisation et évaluation agroécologique de systèmes de culture agroforestiers: une démarche appliquée aux systèmes de culture à base de cocotiers (*Cocos nucifera* L.) sur l'île de Malo, Vanuatu. Institut National Agronomique Paris-Grignon. Discipline: Science Agronomique, 230 p
Lammerts van Bueren ET, Struik PC, Tiemens-Hulscher M, Jacobsen E (2003) Concepts of intrinsic value and integrity of plants in organic plant breeding and propagation. Crop Sci 43:1922–1929
Lançon J, Wery J, Rapidel B, Angokaye M, Gérardeaux E, Gaborel C, Ballo D, Fadegnon B (2007) An improved methodology for integrated crop management systems. Agron Sust Dev 27:101–110
Langat MC, Okiror MA, Ouma JP, Gesimba RM (2006) The effect of intercropping groundnut (Arachis hypogea L.) with Sorghum (Sorghum bicolor L.) on yield and cash income. Agric Tropica Et Subtropica 39:87–91

Larwanou M, Abdoulaye M, Reij C (2006) Etude de la régénération naturelle assistée dans la région de zinder (Niger): Une première exploration d'un phénomène spectaculaire. USAID/EGAT. International Resources Group, Washington, DC, 48 p
Lavorel S, Garnier E (2002) Predicting changes in community composition and ecosystem functioning from plant traits: revisiting the Holy Grail. Funct Ecol 16:545–556
Le Buannec B (1979) Intensifications des cultures assolées en Ivory Coast. Milieu physique et stabilité des systèmes de cultures motorisées. Agron Trop 34I:54–73
Le Courrier (2002) Le système de production agricole de Machobane. Comment faire face à la crise alimentaire au Lesotho. Le Courrier, No 194, Sept–Oct 2002, 2 p
Lefrançois S, Thorez J-P (2012) Plantes compagnes au potager bio: Le guide des cultures associées. Terre vivante, 190 p
Lefroy EC, Hobbs RJ, Connor MHO, Pate JS (1999) What can agriculture learn from natural ecosystems? Agroforest Syst 53:269–281
Léger-Cresson N (1989) Introduction d'une légumineuse fourragère (*Mucuna aterrima*) dans la culture du maïs pluvial à Colima (Mexique). Thesis USTL. Montpellier, 144 p
Lemieux G (1994) Rapport de mission africaine au Sénégal- 2 au 13 décembre 1994. No 5. Groupe de coordination sur les BRF. Université de Laval. Département des Sciences des Bois et de la Forêt. Québec GIK 7P4 Québec, 20 p
Lemieux G, Lachance L, Stevanovic-Janezic T (1999) La structure des sols et le bilan du carbone: une fonction de l'effet de serre. Groupe de coordination sur les BRF. Université de Laval. Département des Sciences des Bois et de la Forêt. Québec GIK 7P4 Québec, 8 p
Leplaideur A (1978) Les travaux agricoles chez les paysans du Centre-Sud Cameroun. IRAT, BP 5035, 34032, Montpellier. Multigr
Li W (2001) Agro-ecological farming systems in China, man and the biosphere series, Jeffers JNR (ed), vol 26, Paris
Li L, Li SM, Sun JH, Zhou LL, Bao XG, Zhang HG, Zhang F (2007) Diversity enhances agricultural productivity via rhizosphere phosphorus facilitation on phosphorus deficient soils. Proc Natl Acad Sci U S A 104(27):11192–11196
Liebman M, Dick E (1993) Crop rotation and intercropping strategies for weed management. Ecol Appl 3:92–122
Lithourgidis AS, Dordas CA, Lazaridou TB, Papadopoulos II (2008) Silage yield and protein content of common bean intercropped with corn in two row-replacements. Proceedings of the 10th European Society of Agronomy (ESA) Congress, 15–19 Sept 2008, Bologna, pp 217–218
Lithourgidis AS, Dordas CA, Damalas CA, Vlachostergios DN (2011) Annual intercrops: an alternative pathway for sustainable agriculture. Aust J Crop Sci 5(4):396–410
Long SP (1989) Influence of neem windbreaks on yield, microclimate and water use of millet and sorghum in Niger, West Africa. Texas A & M University, M.S. thesis
Lu CH, Van Ittersum MK, Rabbinge R (2003) Quantitative assessment of resource-use efficient cropping systems: a case study for Ansai in the Loess Plateau of China. Eur J Agron 19:311–326
Ludwig W (1950) Zur theory der konkurrenz. Neue Ergeb. Prob Zool Klatt Ferstschrift 516–537
Lynam JK, Sanders JH, Mason SC (1986) Economics and risk in multiple cropping. In: Francis CA (ed) Multiple cropping systems. Macmillan, New York, pp 250–266
Lyonga SN (1980) Aspects économiques de la culture de l'igname au Cameroun. In: Terry ER, Oduro KA, Caveness F (eds) Plantes-racines tropicales: stratégies de recherches pour les années 1980, compte rendu du premier symposium triennal sur les plantes-racines de l'ISTRC-AB. Ibadan: 1980, IITA, pp 219–224
MA (Millennium Ecosystem Assessment) (2005) Ecosystems and human well-being: synthesis. Island Press, Washington, DC
Macary F, Bordenave P (2008) Estimation d'un risque environnemental: la contamination des eaux de surface par les intrants agricoles. Application sur les coteaux de Gascogne. Colloque "*Vulnérabilité sociétale, risques et environnement*". Toulouse, 14–16 mai 2008
Malézieux E (2012) Designing cropping systems from nature. Agron Sust Dev 32(1):15–29

Malézieux E, Moustier P (2005) La diversification dans les agricultures du Sud: à la croisée de logiques d'environnement et de marché. I: Un contexte nouveau. Cah Agr 14:2777–281
Malézieux E, Trébuil G, Jaeger M (2001) Modélisation des agro écosystèmes et aide à la décision. Collection Repères. Montpellier: Inra éditions. Cirad éditions, 447 p
Malézieux E, Crozat Y, Dupraz C, Laurans M, Makowski D, Ozier-Lafontaine H, Rapidel B, de Tourdonnet S, Valantin-Morison M (2009) Mixing plant species in cropping systems: concepts, tools and models. A review. Agron Sust Dev 29:43–62
Mandal BK, Dhara MC, Mandal BB, Das SK, Nandy R (1990) Rice, mungbean, soybean, peanut, ricebean and blackgram yields under different intercropping systems. Agron J 82:1063–1066
Manu VT, Halavatau S (1995) Agroforestry in food production systems in the South Pacific. In: Foale et al (eds) Soil organic matter management for sustainable agriculture. ACIAR proceedings, Canberra. 56, pp 63–68
Marer SB, Lingaraju BS, Shashidhara GB (2007) Productivity and economics of maize and pigeonpea intercropping under rainfed condition in northern transitional zone of Karnataka. Karnataka J Agric Sci 20:1–3
Masson SC, Leinher DE, Vorst JJ (1986) Cassava-cowpea and cassava-peanut inter cropping. III. Nutrient concentrations and removal. Agron J 78:441–444
Mazoyer M (1972) Développement de la production et transformation agricole marchande d'une formation agraire en Ivory Coast. Communication au Colloque sur les "Stratégies de Développement économiques, Afrique et Amérique Latine". UN, Institut Africain de Développement économique et de planification, Dakar, Sept 1972
Mbomda J (1985) Essai de classification des exploitations agricoles de la chefferie de Bafou. CUDS, IRA Dschang BP 99, Cameroun, 35 p
Mérot P (1976) Quelques données sur l'hydrologie de deux bassins versants élémentaires granitiques, bocager et ouvert. Table ronde CNRS "*les bocages*" Rennes, 1976
Meynard JM, Sébillotte M (1989) La conduit des cultures: vers une ingénierie agronomique. Econ Rural 192(193):35–41
Mhandawire ABC (1989) Fertilizer research in intercrops. In: Waddington SR, Palmer AFE, Edje OT (eds) Proceeding of a workshop on a cereal/legume intercropping in Eastern and Southern Africa. Lilongwe, 23–27 Jan 1989
Miche S (1986) Acacia albida and other multipurpose trees on the fur farmlands in the Jebel Marra highlands, Western Darfur, Sudan. Agroforest Syst 4:89–119
Michon G (1985) From forest dweller to tree growing farmer. Indonesian agro-forestry. PHD thesis. USTL. Montpellier, France, 273 p
Michon G, de Foresta H (1995) The Indonesian agro-forest model: forest resource management and biodiversity conservation. In: Halladay P, Gilmour DA (eds) Conserving biodiversity outside protected areas. The role of traditional agro-ecosystems. IUCN, Gland
Midmore DJ (1993) Agronomic modification of resource use and intercrop productivity. Field Crop Res 34:357–380
Mitsch WJ, Jorgensen SE (2003) Ecological engineering: a field whose time has come. Ecol Eng 20:363–377
Monzote FR, Lantinga EAM, vanKeulen H (2009) Conversion of specialized dairy farming systems into sustainable mixed farming systems in Cuba. Environ Dev Sust 11:765–783
Moreau R (1982) Evolution des sols sous différents modes de mise en culture, en Ivory Coast. *O.R.S.T.O.M.* Paris 14 p. Comm. In: symposium "Land clearing and development". I.I.T.A., Ibadan
Morelli C (2003) Evaluation des performances agronomiques des jardins au Vanuatu. Estimation de leur durabilité agro-écologique et proposition d'intensification par association aux cocoteraies. Mémoire de DAA Sol et Aménagement Rural ENSAR, Rennes, 57 pp + annexes
Morris RA, Garrity DP (1993) Resource capture and utilization in intercropping. Water Field Crop Res 34:303–317
Mungaï DN (1995) A microclimatological approach to understanding maize yield performance in alley cropping in the semi-arid areas of Machakos district, Kenya. In: Stigter CJ, Wang'ati FJ, Ng'ang'a JK, Mungai DN (eds) The TTMI-project and the "*Picnic*" model: an internal evalua-

tion of approaches and results and of prospects for TTMI-Units. -unités. Agricultural University, Wageningen, pp 111–123
Muoneka CO, Asiegbu JE (1997) Effect of okra planting and spatial arrangement in intercrop with maize on the growth and yield component species. J Agron Crop Sci 179:201–207
Murphy KM, Campbell KG, Lyon SR, Jones SS (2007) Evidence of varietal adaptation to organic farming systems. Field Crop Res 102:72–177
Mutuo P (2004) Potential of improved tropical legume fallows and zero tillage practices for soil organic sequestration. Ph.D. dissertation, Imperial College, University of London
Nair PKR (1979) Intensive multiple cropping with coconuts in India. Principles, programmes and prospects. Advances in agronomy and crop science, vol 6. Paul Parey ed., Berlin, 147 p
Nair PKR (1985) Classification of agroforestry systems. Agroforest Syst 3:97–128
Natarajan M, Willey RW (1986) The effects of water stress on yield advantages of intercropping systems. Field Crop Res 13:117–131
Naudin K, Gozé E, Balarabe O, Giller KE, Scope E (2009) Impact of no tillage and mulching practices on cotton production in North Cameroon: a multi-locational on-farm assessment. Soil Till Res 108(1–2), May–June 2010, 68–76
N'Goram K, Snoeck J (1987) Cultures vivrières associées au caféier en Ivory Coast. Food crops intercropping with coffee trees in Ivory Coast. Café Cacao Thé 31(2):121–133
Njoku BO, Igbokwe MC, Ohiri AC (1984) Leaching losses and recovery of fertilizer nitrogen in cassava/maize intercrop grown in lysimeter. In: Proceedings of the 6th symposium of International Society for Tropical Root Crops, Etude de la production Vivrière dans la ZAPI de Menguémé (Centre Sus du Cameroun). IRA Yaoundé. Document ronéoté. MD 206. 24p.
Noël B (2005) Le Bois Raméal Fragmenté – Plus de carbone pour nos sols. CTA de Strée, Belgique
Norman MJT, Pearson CJ, Searl PGE (1984) The ecology of tropical food crops. Cambridge University Press (2nd ed, 1995). 369 pp
Nouri M, Reddy KC (1990) Utilisation de l'eau par le mil et le niébé en association et en culture pure. In: Sivakumar MVK et al (ed) Soil water balance in the Sudano-Sahélian zone. Proceedings of an international workshop, Niamey. 18–19 Feb 1991. IAHS Publ. 199. International Association of Hydrological Sciences, Wallingford
N'tare BR, Serafini PG, Fussell LK (1987) Recent developments in millet/cowpea cropping systems for low rainfall areas of the Sudano-Sahelian zone of West Africa. In: Soil, crop and water management systems for rainfed agriculture in the Sudano-Sahelian Zone. ICRISAT, Sahelian Center Niamey, Niger, pp 277–290
Obedoni BO, Mensah JK, Isesele SO (2005) Effects of intercropping cowpea {vigna unguiculata (L) Walp} and tomato (lycopersicon esculentum Mill)) on their growth, yield and monetary returns. Indian J Agric Res 39(4):286–290
Odhiambo GD, Ariga ES (2001) Effect of intercropping maize and beans on striga incidence and grain yield. In: Proceedings of the 7th Eastern Southern Africa regional maize conference. 7:183–186
Odhiambo GD, Ransom JK (1993) Effect of dicamba on the control of *Striga hermonthica* in maize in western Kenya. Afr Crop Sci J 1:105–110
Odum HT (1975) Combining energy laws and corollaries of the maximum power principle with visual systems mathematics. In: Ecosystem analysis and prediction. In: Proceedings of the conference on ecosystems. SIAM Institute for Mathematics and Society, Alta, pp 239–263
Odum HT (1988) Self-organization, transformity and information. Science 242:1132–1139
Odum HT (1995) Energy systems concepts and self-organization: a rebuttal. Oecologia 104(4):518–522
Odum HT, Odum B (2003) Concepts and methods of ecological engineering. Ecol Eng 20(2003):339–36
Odurukwe SO (1986) Yam-maize intercropping investigations in Nigeria. Trop Agric Trin 63(1):17–21
Ofori F, Stern WR (1987) Cereal legume intercropping systems. Adv Agron 41:41–90

Ogindo HO, Walker S (2005) Comparison of measured changes in seasonal soil water content by rained maize-bean intercrop and component cropping in semi arid region in South. Phys Chem Earth 30:799–808

Okigbo BN, Greenland DJ (1976) Intercropping systems in tropical Africa. In: Papendick RI, Sanchez PA, Triplett GB (eds) Multiple cropping. ASA, Madison

Ong CK, Subrahmanyam P, Khan AAH (2001) The microclimate and productivity of a groundnut/millet intercrop during the rainy season. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru

Osseni B, N'Guessam A (1990) Etude des phénomènes de concurrence entre les cultures en association. Cas des cultures vivrières associées à l'ananas (sud de la Ivory Coast). Comm. Réunion Ananas. CIRAD- IRFA, BP 5035, Montpellier, 26 p

Othieno CO, Stigter CJ, Mwaampja AR (1985) On the use of Stigter's ratio in expressing the thermal efficiency of grass mulches. Exp Agric 21:169–174

Oxfam (2011) Échapper au cycle de la faim: Les chemins de la résilience au Sahel. Oxfam, Groupe de travail sur le Sahel, septembre 2011, 124 p

Ozier-Lafontaine H, Vercambre G, Tournebize R (1997) Radiation and transpiration partitioning in a maize-sorghum intercrop: a comparison of two models. Field Crop Res 49:127–145

Ozier-Lafontaine H, Lafolie F, Bruckler L, Tournebize R, Mollier A (1998) Modelling competition for water in intercrops: theory and comparison with field experiments. Plant Soil 204:183–201

Palapiapan SP (1988) Cropping systems in the tropic: principles and management. Wiley Eastern Ltd, New Delhi, India, 212 p

Pandita AK, Sham MH, Bali AS (2000) Effect of row ratio in cereal-legume intercropping systems on productivity and competition functions under Kashmir conditions. Indian J Agron 45:48–53

Papendick RI, Sanchez PA, Triplett GB (eds) (1976) Multiple cropping. ASA, Madison, Spec Publ 27, 378 pp

Pavé A (1997) Environnement et développement: approches scientifiques, structuration du domaine et co-évolution des recherches. Nat Sci Soc 1:50–63

Payne WA (1997) Managing yield and water use of pearl millet in the Sahel. Soil Sc Soc Am J 89:481–490

Pearce D (2001) The economic value of forest ecosystem. Ecosyst Health 7(4):284–296

Peichl M, Thevathasan NV, Gordon AM, Huss J, Abohassan RA (2006) Carbon sequestration potentials in temperate tree-based intercropping systems, southern Ontario, Canada. Agroforest Syst 66:243–257

Piraux M, Buldgen A, Steyaert P, Dieng A (1997) Intensification agricole en région sahélo-soudanienne: 2. Productivité économiques et risques. Biotechnol Agron Soc Environ 1(3):209–220

Planète (2012) "L'Afrique peut se nourrir et nourrir le monde". Planète, LE MONDE |09 Oct 2012 à 12h41

Prabhakar BS, Srinivas K (1989) Weighted income equivalent ratio for evaluating vegetable intercropping systems. S Indian Hortic 37:144–149

Prasad RB, Brook RM (2005) Effect of varying maize densities on intercropped maize and soybean in Nepal. Exp Agric 41:365–382

Rabot C (1982) Les jardins vivriers d'une petite région de la Guadeloupe. Approche agro-écologique des associations végétales. Mémoire ENITA-Dijon/CEAT, 105 p

Rachie KO, Roberts LM (1974) Grain legumes of the lowland tropics. In: Brady NC (ed) Advances in agronomy, vol 26. American Society of Agronomy, Academic Press, New York, pp 1–132

Rajvanshi I, Mathur BN, Sharma GL (2002) Effect of intercropping on incidence of *Heterodera avenae* in wheat and barley crops. Annu Plant Prot Sci 10:365–410

Rämert B, Lennartsson M, Davies G (2002) The use of mixed species cropping to manage pests and diseases theory and practices. Powel et al (eds) UK Organic Research 2002: proceeding of the COR conference, 26–28 mars 2002, Aberystwth, pp 207–210

Ransom JK (1989) Weed control in maize/legume intercrops. Research methods for cereal/legume intercropping. In: Waddington SR, Palmer AFE, Edje OT (eds) Proceeding of a workshop on

a cereal/legume intercropping in Eastern and Southern Africa. . Lilongwe, 23–27 Jan 1989, pp 42–45
Rao MR, Singh S (1988) Management practices for intercropping systems. In: Proceedings international workshop on intercropping. ICRISAT, Hydrabadpp 17–21
Rao MR, Nair PKR, Ong CK (1998) Biophysical interactions in tropical agro-forestry systems. Agroforest Syst 38:3–50
Ravignan de (1969) Etude de la production vivrière dans la ZAPI de Menguémé (Centre Sud du Cameroun). Doc. Ronéoté. MD 206, 24 p
Reddy MN, Ramanatha Chetty CK (1984) Staple land equivalent ratio for assessing yield advantage from intercropping. Exp Agr 20:171–177
Reddy MS, Willey RW (1981) Growth and resources use studies in an intercrop of pearl millet/groundnut. Projet Bututsi. Fields Crop Res 4:13–24
Renard C, Vandenbeldt RJ (1990) Bordure d'*Andropogon gayanus* Kunth comme moyen de lutte contre l'érosion éolienne au Sahel. L'Agronomie Tropicale 45(3):227–231
Risch SJ (1983) Intercropping as cultural pest control: prospects and limitations. Environ Manage 7:9–14
Rishirumuhirwa T (1996) Potentiel du bananier dans la gestion et la conservation des sols ferralitiques du Burundi. Cahier ORSTOM. Pédologie XXVIII(2):367–383
Rishirumuhirwa TH, Nyabuhwanya J (1993) Bananeraie, modes de paillis et restauration des sols acides. Bull 13:143–157. Réseau Erosion; ORSTOM, Montpellier
Ritz K, Young IM (2004) Interactions between soil structure and fungi. Mycologist, vol 18, Part 2, Cambridge University Press Printed in the United Kingdom, 52 p
Roger AF (2013) Echobio.fr/boutique magazine No 40 mars/avril 2013, pp 14–15
Roose E (1983) Ruissellement et érosion avant et après défrichement en fonction du type de culture en Afrique Occidentale. Cah O.R.S.T.O.M. sér Pédol XX(4):327–339
Roose E (1994) Introduction à la gestion conservatoire de l'eau, de la biomasse et de la fertilité des sols (GCES). Bulletin Pédologie de la FAO, Roma, Italia, 70, 420 p
Root RB (1973) Organization of a plant-arthropod association in simple and diverse habitats – fauna of collards (*Brassica oleracea*). Ecol Monogr 4:95–120
Rotillon G (2005) Economie des ressources naturelles. La Découverte, Paris
Rousseau GX, Deheuvels O, Rodriguez Arias I, Somarriba E (2012) Indicating soil quality in cacao-based agroforestry systems and old-growth forests: the potential of soil macrofauna assemblage. Ecol Indic 23:535–543
Salako FK, Tian G (2001) Litter and biomass from planted and natural fallows on a degraded soil in south-western Nigeria. Agroforest Syst 51:239–251
Salau OA, Opara-Nadi OA, Swennen R (1992) Effects of mulching on soil properties, growth and yield of plantain on a tropical ultisol in south eastern Nigeria. Soil Till Res 23:73–93
Salez P (1990) Maïs-légumineuses dans l'Ouest du Cameroun – relation entre espèces associées. In: Cereals of the semi-arid tropics. Regional seminar on cereal of the semi-arid tropics (Garoua, Cameroun). 1989-09-12/1989-09-16. 3(Réunion) CIRAD-IRAT IFS (Stockholm, Suede)
Samson C, Autfray F (1985) Effet de la géométrie de plantation sur la production d'une association maïs-soja dans l'Ouest Cameroun. Miméo, Station IRA, BP 44 Dschang, 7 p
Sanchez PA, Palm CA, Davey CB, Scott LT, Russell CE (1985) Trees as soil improvers in the humid tropics? In: Cannell MGR, Jackson JE (eds) Attributes of trees as crops plants. Institute of Terrestrial Ecology (NERC), Abbots Ripton, pp 327–358
Sans FX, Altieri MA (unpublished) Effects of intercropping and fertilization on weed abundance, diversity and resistance to invasion. www.ub.es/agroecologia/pdf
Saucke H, Ackermann K (2005) Weed suppression in mixed cropped grain peas and false flax (Camelina sativa). Weed Res 46:453–461
Schmidtke K, Neumann A, Hof C, Rauber R (2004) Soil and atmospheric nitrogen uptake by lentil (Lens culinaris Medik) as monocrops and intercrops. Field Crop Res 87:245–256

Schoeny A, Jumel S, Rouault F, Lemarchand E, Tivoli B (2010) Effect and underlying mechanisms of pea-cereal intercropping on the epidemic development of ascochyta blight. Eur J Plant Pathol 126:317–331

Schroth G, Harvey C, Vincent G (2004) Complex agroforests: their structure, diversity and potential role in landscape conservation. In: Schroth G, da Fonseca GAB, Harvey C, Gascon C, Vasconcelos HL, Izac AM (eds) Agroforestry and biodiversity conservation in tropical landscapes. Island Press, Washington, DC

Scopel E, Findeling A, Chavez Guerra E, Corbeels M (2005) Impact of direct sowing mulch-based cropping systems on soil carbon, soil erosion and maize yield. Agron Sust Dev 25:425–432

Séguy L (2003) Rapport de mission à Madagascar. 19-avril-7 mars 2003. Cirad, Montpellier, 35 p

Séguy L, Silva JL, Ribeiro DA, Bouzinac S (1982) L'amélioration variétale du riz pluvial dans les systèmes de production manuels pratiqués par les petits paysans de la région du Cocais au Maranhão, Nord-Est du Brésil, 1979–1988. EMAPA, Saõ Luis, 51 p

Séguy L, Bouzinac S et al (1994) Gestion des sols et des cultures dans les zones de frontières agricoles des cerrados humides du centre-ouest. Année agricole 1993/94. Document interne CIRAD-CA, Montpellier, 256 p

Séguy L, Bouzinac S, Brésiliens (2008) La symphonie inachevée du semis direct dans le Brésil central: Le système dominant dit de "semis direct". Limite et dégâts, éco-solutions et perspectives: la nature au service de l'agriculture durable. Cirad-Uepg-Embrapa-Facual- 214 p

Sekamatte BM, Ogenga-Latigo M, Russell-Smith A (2003) Effects of maize-legume intercrops on termite damage to maize, activity of predatory ants and maize yields in Uganda. Crop Prot 22:87–93

Seran TH, Brintha I (2009) Study on biological and economic efficiency of Radish (Raphanus sativus L.) intercropped with vegetable amaranthus (*Amaranthus tricolor* L.). Open Hortic J 2:17–21

Seran TH, Jeyakumaran J (2009) Effect of planting geometry on yield of capsicum (Capsicum annum L.) intercropping with vegetable cowpea (Vigna unguiculata L.). J Sci 6:11–19

Shetty SVR (1987) Design and evaluation of alternative production systems: pearl millet/maize and cereal/groundnut systems in Mali. In: Soil, crop and water management systems for rainfed agriculture in the Sudano-Sahelian Zone. ICRISAT, Sahelian Center Niamey, Niger

Sieffert A, Truong HXP (1992) Mode de production et stratégies paysannes des communautés rurales de la zone forestière dans l'Est Cameroun. Diagnostic pour le Projet d'Aménagement Pilote Intégré. Diplôme d'Ingénieur d'Agronomie Tropicale. CNEARC-ENGREF-Ministère de la Coopération et du développement, France, 158 p. 12 cartes

Sikirou R, Wydra K (2008) Effect of intercropping cowpea with maize or cassava on cowpea bacterial blight and yield. J Plant Dis Prot 115:145–151

Singh M, Joshi NL (1994) Performance of pearl millet-based intercropping systems under drought conditions. Arid Soil Res Rehabil 8(3):277–283

Singh SK, Hene YL, Reddy MV (1990) Influence of cropping systems on *Macrophimina phaseolina* populations in soil. Am Phytopathol Soc, ETATS-UNIS, St. Paul, 74(10):812–814

Sinha AK, Nathan AK, Sing AK (1985) Radiation climate and water-use studies in intercropping systems. J Nucl Agric Biol 14(2):64–69

Sissoko F, Autfray P, Rapidel B (2003) Effet du labour en culture attelée et de système à couverture végétale sur la disponibilité de l'eau en début de saison des pluies au Mali. IER, Sikasso Mali-CIRAD/IER BP 1813 Bamako, Mali-CIRAD, Montpellier. Document obtenu sur le site Cirad du réseau. http://agroecologie.cirad.fr

Skerman PJ (1982) Tropical forage legumes. FAO: Plant production and protection series no 2. Food and Agriculture Organisation (FAO), Rome, 609 pp

Smith ME, Francis CA (1986) Breeding for multiple cropping systems. In: Francis CA (ed) Multiple cropping systems. MacMillan Publishing Company, New York

Snoeck D, Lacote R, Keli ZJ, Doumbia A, Chapuset T, Jagoret P, Gohet E (2013) Association of hevea with other tree crops can be more profitable than hevea monocrop during first 12 years. Ind Crop Prod 43:578–586

SOYNICA- Nicaragua. CD sur la technique de la fabrication des extraits foliaires: jacques.subtil@yahoo.fr

Steiner KG (1985) Cultures associées dans les petites exploitations agricoles tropicales; en particulier en Afrique de l'Ouest. GTZ, Eschborn, 347 p
Stigter CJ (1984) Wind protection in traditional microclimate management and manipulations examples from East Africa. Grace NJ (ed) Progress in biometeorology; vol 2: The effect of the shelter on the physiology of plants and animals. Swetz and Zeitlinger, Lisse (Th), pp 145–155.e Netherlands
Stigter CJ (1994) Management and manipulation of microclimate. In: Griffiths JF (ed) Hanbook of agricultural meteorology. Oxford University Press, New York, pp 273–284
Szumigalski A, Rene V (2005) Weed suppression and crop production in annual intercrops. Weed Sci 53:813–825
Tajuddin I (1986) Integration of animals in rubber plantation. Agroforest Syst 4:55–66
Tardit MC (1961) Les Bamilékés de l'Ouest-Cameroun. Berger-Levrault, Paris. Coll. " l'Homme d'Outre-Mer". Nle Série. T. IV
Tardieu M (1970) Tentative dans la fertilisation des cultures associées. Séminaire de la Fondation Ford/IRAT (Institut de Recherche Agronomique Tropical -France)/IITA (International Institute of Tropical Agriculture) sur les systèmes traditionnels de l'agriculture africaine et leur amélioration. IITA-IBADAN, Nigéria, 16–20 Nov, 1970
Tétio Kagho (1994) Impact du système de culture associée mixte sur l'agriculture durable : cas des environs de Dschang dans les Hauts Plateaux de l'Ouest. Séminaire Régional sur les Systèmes Agraires et Agriculture Durable en Afrique sub-saharienne. Cotonou, 1994-02-07/1994-02-11 IFS (Stockholm)
Thé C, Calba H, Horst WJ, Zonkeng C (2001) Three years performance of a tolerant and a susceptible maize cultivar on non-amended and amended acid soil. In: Plant nutrition: food security and sustainability of agro-ecosystems through basic and applied research. Kluwer, Dordrecht, pp 984–985. International plant nutrition colloquium. 14, 27 Jul–3 Aug 2001. Hanovre, Allemagne
Theunissen J (1997) Intercropping in field vegetables as an approach to sustainable horticulture. Outlook Agr 26:95–99
Thior P (2002) Test de refertilisation et de cultures associées dans les communautés rurales de Dya et Ndiébel (Région de Kaolack) Hivernage 2002. Recherche-action-formation en milieu paysan. Projet Autopromotion et Gestion des Ressources Naturelles au Sine Saloum (PAGERNA).GTZ & MEPN, 15 p
Thobatsi TH (2009) Growth and yield of maize (Zea mays L.) and cowpea (Vigna unguiculata) in an intercropping system. University of Natural and Agricultural Sciences. Department of Plant Production and Soil Science, University of Pretoria, 149 p
Tiessen H, Steward WB, Hunt HW (1984) Concepts of soil organic matter transformation in relation to organo-mineral practice size fraction. Plant and Soil 76:287–295
Torquebiau E (1992) Are tropical agro-forestry homegardens sustainable? Agr Ecosyst Environ 41:189–207
Torquebiau E (2000) A renewed perspective on agro forestry concepts and classification. Compte Rendu de l'Académie Scientifique. Paris, France, 1009
Torquebiau E, Penot E (2006) Ecology versus economics in tropical multistrata agroforests. In: Kumar BM, Nair PKR (eds) Tropical home gardens: a time-tested example of sustainable agroforestry. Springer, Berlin, pp 269–282
Torquebiau E, Mary F, Sibelet N (2002) Les associations agroforestières et leurs multiples enjeux: the multiple challenges of agro forestry associations. Bois etforêts des tropiques 271:23–35
Tourte R (1971) Thèmes légers et thèmes lourds, systèmes intensifs: voies différentes ouvertes au développement agricole du Sénégal. Agro Trop 42(4):258–268
Traoré S, Bagayoko M, Coulibaly BS, Coulibaly A (2004) Amélioration de la gestion de la fertilité des sols et celle des cultures dans les zones sahéliennes de l'Afrique de l'Ouest: une condition sine qua none pour l'augmentation de la productivité et de la durabilité des systèmes de culture à base de mil
Tremblay R (2006) Les Iroquoiens du St-Laurent - Éditions de l'Homme, France, pp 52–54
Trenbath BR (1975) Diversify or be damned. Ecologist 5:76–83

Trenbath BR (1976) Plant interactions in mixed crops communities. In: Papendick RI, Sabchez PA, Triplett GB (eds) Multiple cropping, vol 27. ASA Spec. Publi, Madison, USA, pp 129–170
Trenbath BR (1999) Multispecies cropping systems in India. Prediction of their productivity, stability, resilience and ecological sustainability. Agroforest Syst 45:81–107
Tsubo M, Walker S, Mukhala E (2001) Comparisons of radiation use efficiency of mono-/inter-cropping systems with different row orientations. Field Crop Res 71:17–29
Tsubo M, Mukhala E, Ogindo HO, Walker S (2003) Productivity of maize-bean intercropping in a semi-arid region of South Africa. Water SA 29(4):361–388
Ullah A, Bhatti MA, Gurmani ZA, Imran M (2007) Studies on planting patterns of maize (*Zea mays* L.) facilitating legumes intercropping. J Agric Res 45:113–118
USAID, CILSS, IRG (2002) Investir dans la forêt de demain: vers un programme de révitalisation de la foresterie en Afrique de l'Ouest. Washington/Ouagadougou, 35 p
Valentin C, Chevallier P, Fritsch E, Janeau JL (1990) Le fonctionnement hydrodynamique aux échelles ponctuelles. In: "HYP'ERBAV, 1990", pp 147–163. Etudes et Thèses, ORSTOM30, 7 p
Valet S (1968) Premiers résultats de la fertilisation minérale dans les conditions pédoclimatiques de l'Ouest-Cameroun. Miméo IRAT - BP 99, Dschang, Cameroun, 55 p
Valet S (1969) Besoin en eau et production végétale dans l'Ouest-Cameroun. Miméo IRAT Réunion de Programmation Bouaké, Ivory Coast. IRAT, BP 5045, 34032, Montpellier, France, 12 p
Valet S (1972) Bilan des expérimentations sur cultures associées dans l'Ouest-Cameroun. GERDAT-IRAT - BP 99, Dschang, Cameroun, 43 p. (Coll. Tardieu M, Praquin J, Séguy L)
Valet S (1974a) Note sur des observations et mesures de quelques facteurs climatiques, physiques et pédologiques et de leur incidence sur la production agricole à la station de Dschang (Cameroun). Agro Trop XXIX(12):1266–1287
Valet S (1974b) Observations et mesures sur des cultures associées traditionnelles en pays Bamiléké et Bamoun. Miméo IRAT- BP 99, Dschang, Cameroun, 30 p
Valet S (1976) Observations et mesures sur des cultures associées traditionnelles en pays bamiléké et bamoun. (Essais de fertilisation et de pré vulgarisation de fumures- Cameroun). IRAT, BP 99 Dschang-Cameroun. IRAT, BP 5045, 34032, Montpellier, France, 38 p
Valet S (1980) Notice explicative des cartes: Cartes de zonation géo-climatique (1/400 000), des pentes des paysages agro géologiques (1/200 000) et de mise en valeur agricole des paysages agro géologiques de l'Ouest-Cameroun (1/400 000). GERDAT-IRAT. BP 5035, Montpellier, France, 34032. 117 p.- 3 cartes
Valet S (1995) Concept de gestion et de valorisation agricole du report hydrique (Run on): éco-développement alternatif en région soudano-sahélienne. Colloque "Intensification agricole au Sahel". INSAH BP 1530 Bamako, Mali, 28 Nov–2 Déc 1995, 28 p
Valet S (1999) L'aménagement traditionnel des versants et le maintien des cultures associées traditionnelles: cas de l'Ouest-Cameroun. Colloque International "L'homme et l'Erosion". IRD-CIRAD, BP 5045, Montpellier, 34032, France, 12–15 Dec 1999. Yaoundé, 17 p
Valet S (2000) Nouvelle stratégie d'eco-développement durable par la gestion et la valorisation du report hydrique. SECHERESSE J Libbey eurotext, 127, ave. De la République, 92120, France. 11(4):239–247, 12 p
Valet S (2004) Effet de la sécheresse sur les associations culturales vivrières de l'Ouest-Cameroun. Secheresse (J. Libbey Eurotext, 127, ave. de la République, 92120), France, 11(4):239–247
Valet S (2007) Les associations culturales traditionnelles améliorées: Une alternative écologique à l'intensification agricole face au changement climatique, démographique et à la "mondialisation". In: Roose E, Albergel J, Laouina A, Sabir M (eds) Efficacité de la gestion de l'eau et de la fertilité des sols en milieux semi arides. Enfi-IRD-Au francophonie. Réseau E-GCES de l'AUF. Conférence ISCO Marrakech-Maroc. 14–19 mai 2006, pp 152–163
Valet S (2011a) Les cultures associées multi-étagées traditionnelles innovantes. Services écologiques: résilience et durabilité des éco-agro-systèmes. Colloque Production agricole: pour une réconciliation entre durabilité et rentabilité économique, 6–9 juin 2011- Université Ouverte de Ho Chi Minh, 19 p
Valet S (2011b) Techniques biophysiques traditionnelles innovantes de contrôle du ruissellement et de gestion agro forestière du report hydrique. Colloque "Production agricole: pour une

réconciliation entre durabilité et rentabilité économique". 6–9 juin 2011- Université Ouverte de Ho Chi Minh, 8 p

Valet S, Motelica-Heino M (2010) Les cultures associées traditionnelles à l'échelle du champ: Une technique biophysique raisonnée de lutte contre les tempêtes et la dégradation des agro-systèmes. Colloque international: Effets des techniques antiérosives sur la productivité des terres tropicales, Port-au-Prince (Haïti), 19–24 octobre 2010 (*accepté*)

Valet S, Ozier-Lafontaine H (2013) Again water scarcity, use agro ecological systems and bio pratices. Conference on desertification and Land dégradation. EGU (European Geoscience Union)- (17–18 juin 2013) Ghent Belgium. Universiteit Gent-Gent BC (big in creativity) -International Centre for Eremologie (UNESCO). Poster

Valet S, Sar PS (1999) Concept de report hydrique superficiel (Runon): III) Sa gestion et sa valorisation pour un éco-développement durable l'échelle de la parcelle en zone soudano-sahélienne. 24èmes Journées Scientifiques du GFHN, 23–24 Nov 1999. Strasbourg. Mécaniques des fluides, IFARE, ENGEES, ULP, CNRS, 2 p

Valet S, Motélica-Heino M, Le Coustumer PH, Sarr PS (2008) The Sudan-Sahelian grove: a multi-scale ecological alternative to climatic change. XIIIème Congrès Mondial de l'Eau. Changements Globaux et Ressources en Eface à des pressions toujours plus nombreuses et diversifiées. 1 au 4 septembre 2008. Montpellier, 34032 France

Vance CP, Uhde-Stone C, Allan DL (2003) Phosphorus acquisition and use: critical adaptations by plants for securing a non renewable resource. New Phytol 157:423–447

Vandermeer J-H (1986) Intercropping. In: Carrol CR, Vandermeer JH, Rosset PM (eds) Agroecology. McGraw-Hill, New York, pp 481–516

Vandermeer JH (1989) The ecology of intercropping. Cambridge University Press, Cambridge

Van Duivenbooden N, Pala M, Studer C, Bielders CL, Beukes DJ (2000) Cropping systems and crop complementarity in dryland agriculture to increase soil water use efficiency: a review. Koninklijke Landbouwkundige Vereniging (KLV) Published by Elsevier B.V. NJAS – Wageningen J Life Sci 48(3):213–236

Van Noordwijk M, Lawson G, Groot JJR, Hairiah K (1996) Root distribution in relation to nutrients and competition. In: Ong CK, Huxley PA (eds) Tree- crop interactions – a physiological approach. CAB International, Wallingford, pp 319–364

Vilich-Meller V (1992) Mixed cropping of cereals to suppress plant diseases and omit pesticide applications. Biol Agr Hort 8:299–308

Vlachostergios DN, Roupakias DG (2008) Response to conventional and organic environment of thirty-six lentil (*Lens culinaris* Medik.) varieties. Euphytica 163:449–457

Vlachostergios DN, Lithourgidis AS, Roupakias DG (2010) Adaptability to organic culture system of lentil (*Lens culinaris* Medik) varieties developed from conventional breeding programs. J Agr Sci. doi:10.1017/S002185961000050X

Wakindiki IIC, Ben-Hur M (2001) Indigenous soil and water conservation techniques: effects on runoff, erosion, and crop yields under semi-arid conditions. Aust J Soil Res 40(3):367–379

Weber J-L (2007) Implementation of land and ecosystem accounts at the European Environment. Agency Ecol Econ 61(4):695–707, 15 Mar 2007

Weber JL (2008) Au-delà du PIB, à la recherche d'indicateurs synthétiques. Les relations entre environnement et développement durable. Comptabilité des écosystèmes et de leurs services. -12ème colloque de l'Association de Comptabilité Nationale Paris, 4–6 juin 2008

Webert J (1977) Structures agraires et évolution des milieux ruraux : le cas de la région cacaoyère du Centre-Sud Cameroon. Cahiers ORTOM, Série Sciences Humaines XIV(2):113–141

Weil RW, McFadden ME (1991) Fertility and weed stress on performance of maize/soybean intercrop. Agron J 83:717–721

Welsh JP, Philipps L, Bulson HAJ, Wolfe M (1999) Weed control for organic cereal crops. In: Proceedings of the Brighton crop protection conference – Weeds, Brighton, pp 945–950

Whitmore AP (2000) The biological management of soil fertility project. Neth J Agric Sci 48:115–122

Whitmore AP, Schroder JJ (2007) Intercropping reduces nitrate leaching from under field crops without loss of yield: a modelling study. Eur J Agron 27:81–88

Whitmore AP, Cadisch G, Toomsan B, Limpinuntana V, Van Noordwijk M, Purnomosidhi P (2000) An analysis of the economic value of novel cropping systems in N.E. Thailand and S. Sumatra. Neth J Agric Sci 48:105–114

Wilken GC (1972) Microclimate management by traditional farmers. Geogr Rev 62:544–566

Willey RW (1979) Intercropping – its importance and research needs. Part I: competition and yield advantage; Part II: agronomy and research approaches. Field Crop Abstr 32(1) (2):1–10

Willigen de P, Van Noordwijk M (1987) Roots, plant production and nutrient use efficiency, Ph.D. thesis, Agricultural University, Wageningen, 281 p

Wolfe MS, Baresel JP, Desclaux D, Goldringer I, Hoad S, Kovacs G, Löschenberger F, Miedaner T, Østergård H, Lammerts van Bueren ET (2008) Developments in breeding cereals for organic agriculture. Euphytica 163:323–346

Zegada-Lizarazu W, Izumi Y, Iijima M (2006) Water competition of intercropped pearl millet with cowpea under drought and soil compaction stresses. Plant Prod Sci 9(2):123–132

Zhang F, Li L (2003) Using competitive and facilitative interactions in intercropping systems enhances crop productivity and nutrient-use efficiency. Plant Soil 248:305–312

Zhen L, Routray JK, Zoebisch MA, Chen G, Xie G, Cheng S (2005) Three dimensions of sustainability of farming practices in the North China Plain; a case study from Ningjin County of Shandong Province, PR China. Agr Ecosyst Environ 105:507–522

Zhu Z (1991) Evaluation and model optimisation of Paulownia intercropping system – a project report, agroforestry systems in China. Chinese Academy of Forestry, IDRC, pp 30–43

Zougmoré R, Kambou F, Ouattara K, Guillobez S (1998) The cropping system of sorghum/cowpea in the prevention of runoff and erosion in the Sahel of Burkina Faso. In: Buckless D, Eteka A, Osiname O, Galiba M, Galiano G (eds) Cover crops in West Africa: contributing to sustainable agriculture. International Development Research Centre, Ottawa, pp 217–224

Zougmoré R, Kambou F-N, Ouattara K, Guillobez S (2000) Sorghum-cowpea intercropping: an effective technique against runoff and soil erosion in the Sahel (Saria, Burkina Faso). Arid Land Res Manag 14:329–342

Agroecological Engineering to Biocontrol Soil Pests for Crop Health

Marie Chave, Marc Tchamitchian, and Harry Ozier-Lafontaine

Abstract Feeding a growing population and ensuring food security whilst protecting ecosystems and natural resources are crucial priorities in times of global changes. Agroecology promotes innovative drivers of change for a smart agriculture that meets the specifications of ecological transition. Managing soil interactions offer largely unexplored potential to increase agricultural yields and reduce pressures on the environment. Crop losses of 10 % are due to soil-borne pests causing root rot, root blackening, wilt, stunting or seedling damping-off. One promising approach is to encourage pest regulation provided by soil interactions to decrease the inputs of pesticides. However, limited success of this approach in field applications raises questions as to how this might be best accomplished.

Here we review advances in plant protection against soil-borne pests and implications for disease-suppressive agrosystems design. Root infection processes are increasingly understood. Plants protect themselves by naturally engineering the composition of their rhizosphere. They fight soil pests both by root production of toxic chemicals and by favoring pest enemies. The analysis of the chemical dialogue offers new perspectives to enhance biocontrol effectiveness of disease-suppressive soils and antagonists. High throughput technologies provide unprecedented knowledge on rhizosphere interactions and implications for crop health. Agroecological

M. Chave (✉)
INRA, UR1321, ASTRO AgroSystèmes Tropicaux, 97170 Petit-Bourg, France

CIRAD, UPR 103, HORTSYS, 97285 Le Lamentin, France
e-mail: Marie.Chave@antilles.inra.fr

M. Tchamitchian
INRA, UR0767, Ecodéveloppement, 84000 Avignon, France

H. Ozier-Lafontaine
INRA, UR1321, ASTRO AgroSystèmes Tropicaux, F-97170 Petit-Bourg, France

H. Ozier-Lafontaine and M. Lesueur-Jannoyer (eds.), *Sustainable Agriculture Reviews 14: Agroecology and Global Change*, Sustainable Agriculture Reviews 14,
DOI 10.1007/978-3-319-06016-3_8,

engineering approaches overcome the limitations of conventional protection strategies by promoting multi-functional practices harnessing rhizosphere bioprotection. Breeding crop cultivars which capitalize on plant-microbiome interactions or associating plants and biocontrol agents early in their life offers innovative ways to contribute to disease-suppressive agroecosystems design. Integrating interacting species with strong ability to recruit beneficial microorganisms or secrete toxic compounds in mixed cropping systems is a key issue. Based on functional biodiversity management, these systems will provide underpinning ecosystem services and enhance global resiliency of agroecosystems.

Keywords Agroecology • Integrated pest management • Rhizosphere bioprotection • Mixed cropping systems

Introduction

Maximizing long-term crop production, while minimizing resource use, is a crucial challenge to ensure sustainable world food security in the context of global changes and global demand. Major worldwide crop losses are due to soil-borne pets: fungi, oomycetes, bacteria, arthropods and nematodes (Figs. 1 and 2). In 2001–2003, 7–15 % of the potential harvest was lost, according to Oerke (2006), and an average loss of 10 % is often quoted (Raaijmakers et al. 2009). Soil microbial communities represent the greatest reservoir of biological diversity in the world (Berendsen et al. 2012), and plant-microorganism interactions are essential for ecosystems (Van der Heijden et al. 2008). Although numerous agricultural practices and landscape management strategies aim to control aerial pests via biodiversity, the effects on soil pests barely have attracted attention (Hiddink et al. 2010). The soil is a complex environment that is the site of multiple interactions across a variety of space and time scales. Soil biodiversity can only be managed indirectly, and the options for such management are not obvious (Brussaard et al. 2007).

The rhizosphere, the narrow zone of soil that is influenced by root secretions, can contain up to 100 billion (10^{11}) microbial cells per gram root (Berendsen et al. 2012) and more than 30,000 prokaryotic species (Mendes et al. 2011). The rhizosphere is considered as one of the most complex ecosystems on earth (Jones and Hinsinger 2008; Raaijmakers et al. 2009). Plant roots exude up to 21 % of their photosynthetic compounds (Marschner 1995), not only as nutrients for soil microbes but also as signal molecules in plant-microbe interactions. Roots are involved in attracting beneficial microorganisms and soil pests to the immediate environment of the plant.

Over the past decade modern tools such as genomics have revolutionized description and understanding of belowground biodiversity, including the functional roles of assemblages of microorganisms important to agriculture. Tomich et al. (2011) highlighted the need to anticipate and benefit this imminent, unprecedented wave of

Fig. 1 Damages caused by root-knot nematodes *Meloidogyne* on greenhouse lettuces. *Left*: central rows show limited development symptoms. *Right*: galls on the roots (caused by the infestation by J2 Meloidogyne for their reproduction) disrupting the physiological and nutritional functions of the roots to the plant

Fig. 2 Example of pathogenic saprophytic fungi found in the soil: *Sclerotinia sclerotiorum* infecting an open-field grown lettuce. *Left*: first symptoms on the plant, wilting of leaves; fungi mycelium becomes visible. *Center*: advanced symptoms, rotten leaves; fungi mycelium and sclerotia are visible. *Right*: rotten roots; fungi mycelium colonize the soil

information. What might the applications of that knowledge bring to crop protection management? What agroecological methods will prove practical to manage below-ground biodiversity? (Tomich et al. 2011).

Here, our aim is to review current advances in understanding how plants protect themselves against soil pests colonization and how this ability can be used in the design of disease-suppressive agroecosystems. Indeed, the agroecological design of crop systems can benefit from mimicking this natural phenomenon, as advocated by Doré et al. (2011).

We first analyze how recent advances in the study of plant-microorganism interactions in the rhizosphere have highlighted their importance for plant health. Next, we investigate how the use of root ecological functions helps overcome the limitations of current soil-borne pests management through an agroecological engineering framework. Finally, we highlight management practices to design disease-suppressive production systems.

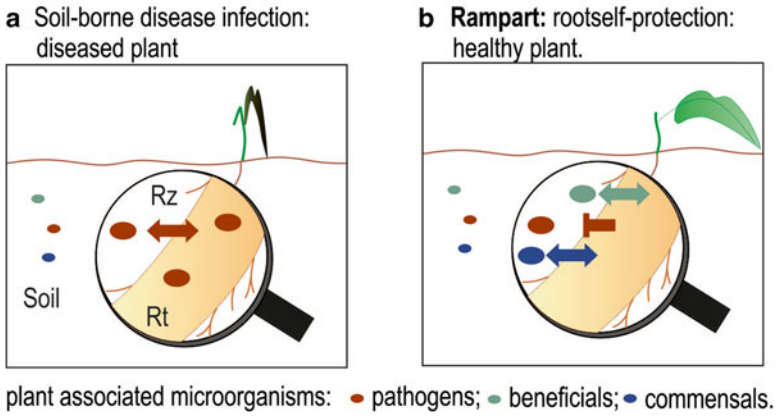


Fig. 3 Natural engineering of root microbiome by plants for self-protection. (**a**) Diseased plant: pathogens (in *red*) colonize and infect roots. (**b**) Self-protected healthy plant: beneficials microorganisms (in *green*) and commensals (in *blue*) are recruited and toxic compounds are secreted (T in *red*) to create a living rampart. *Rz* rhizosphere, *Rt* root

Rhizosphere Interactions and Plant Health

Root Microbiome and Soil-Borne Pests

The vast surface area provided by roots is an extraordinarily diverse habitat for bacteria, fungi, oomycetes, nematodes, protozoa, algae, viruses, archaea and arthropods (Mendes et al. 2013). A huge assortment of microorganisms range from transient epiphytic saprophytes to epiphytic commensals, mutualistic symbionts, endophytes, and pathogens (Fig. 2).

Soil-borne pathogens reside in the soil for brief or extended periods, and survive on plant residues or as resting organisms until root exudates reach them and allow them to grow. They then escape competition with other microorganisms by penetrating the roots (Fig. 3a). Plants infected by soil-borne pathogens suffer from root rot, root blackening, wilt, stunting or seedling damping-off (Haas and Defago 2005).

Cross-communication between roots and pathogens and mobility of pathogens are essential processes in root infection (Bais et al. 2006). Regarding bacteria, an early step in the establishment of interactions is the attachment to plant roots, which can lead to microbial biofilm formation (Fig. 4). As specific regulation of bacterial pathogenicity depends on bacterial cell density, the process of "quorum sensing" allows bacteria to assess their local population density via the secretion and detection of small, diffusible signal molecules (Bais et al. 2006; Kievit and Iglewski 2000). It is only when high cell densities have been reached that the bacteria are able to successfully compete with the plant host defenses.

Roots provide a carbon-rich environment that initiates colonization, a key step in the infection process by soil-borne pests. However roots also develop self-protection.

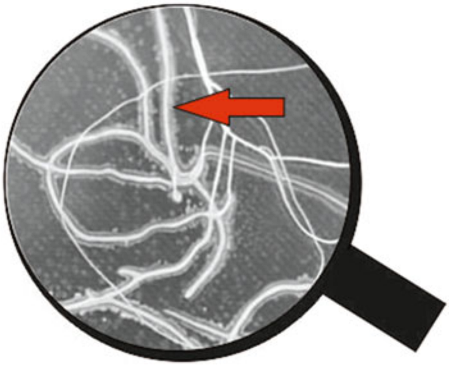


Fig. 4 Tomato rhizosphere colonization by the phytopathogenic *Ralstonia solanacearum* is a key step in the infection process. Development of a biofilm (*red arrow*) of the bacteria *Ralstonia solanacearum* in the rhizosphere of tomato Heat Master

Root Self-Protection

Roots secrete repellent and toxic compounds (Fig. 3b). The survival of physically vulnerable root cells depends on "underground chemical warfare" mediated by plant secretion of phytoalexins produced in response to attack or phytoanticipins produced prior to attack, defense proteins, and other as yet unknown chemicals (Bais et al. 2006). Some plant species also contain unique antimicrobial metabolites in their exudates (Berg et al. 2005). Interfering with quorum-sensing compounds also enables the plant to manipulate gene expression in associated bacterial communities (Berendsen et al. 2012). Allelopathy is defined as any biochemical interaction among plants, including those mediated by microorganisms, resulting in either detrimental or beneficial effects on the interacting plants (Wu et al. 2001).

Plants are able to shape the root zone environment with substrates that encourage the development of cultivar-specific, plant-beneficial, microbial communities (Lugtenberg et al. 2001). Living under continuous attack from soil-borne pests, plants protect themselves by naturally engineering the composition of rhizosphere populations (Ryan et al. 2009). Plants recruit beneficial microorganisms for help against attacks by other microorganisms (Fig. 3b). For example, plants select and support populations of antibiotic-producing bacterial strains (Ryan et al. 2009). Recent studies showed that, upon attack by a fungal root pathogen, plants exploit the microbial consortia from soil for protection against infections, not through taxonomic diversity, but via functional diversity (Mendes et al. 2011; Berendsen et al. 2012). Similarly, some plants recruit the help of auxiliary organisms to protect themselves, a natural biological protection strategy: upon attack of roots of *Thuja occidentalis* by larvae of a weevil, these roots release chemicals and thus attract a parasitic nematode, which preys on weevil larvae (Van Tol et al. 2001).

Plants fight soil pests both by root production of toxic chemicals and by favoring microbial pests enemies. Roots create or modify microbial community habitats and support large microbial populations that provide to roots a basal level of protection against pests, simply through their metabolic activity. Many antagonistic microorganisms naturally present in soil exert a certain degree of biological control over plant pests, regardless of human activities (Garbeva et al. 2004). Therefore, plants modify the chemical and physical space in which other species live. Their impacts differ from biotic interactions as their effects can last longer than their lifetime. Roots act as ecological engineers (Hastings et al. 2007).

Plants, like mammals and insects, rely on specific constituents of the microbial community for protection against attacks by soil pests. These interactions are based on a chemical dialogue.

Rhizosphere Signaling Molecules

Plant roots initiate communication with soil microbes by producing signals that are recognized by the microbes, which in turn produce signals that initiate colonization. Chemical attraction of soil microbes was demonstrated in pathogenic and symbiotic plant-associated bacteria (Berg et al. 2005).

Isolation and identification of plant signaling molecules open up new ways for studying plant-microorganism interactions. Flavonoids, for example, depending on their structure have been shown to stimulate or inhibit plant-rhizobium symbiosis, inhibit root pathogens, stimulate mycorrhizal spore germination and hyphal branching, mediate allelopathic interactions between plants, affect quorum sensing, and chelate soil nutrients (Hassan and Mathesius 2012). Major progress is being made on signaling between roots and arbuscular mycorrhiza fungi (Akiyama et al. 2005). Strigolactones are plant hormones that stimulate the branching and growth of symbiotic arbuscular mycorrhiza fungi, increasing the probability of contact and establishment of a symbiotic association between the plant and fungus. Strigolactones also inhibit plant shoot branching, and trigger germination of parasitic plant seeds (Akiyama et al. 2005).

Root exudates initiate various positive and negative interactions. Their analysis in natural conditions is just at the beginning. Disease-suppressive soils and antagonists of soil-borne plant pathogens illustrate these interactions.

Disease-Suppressive Soils

Disease-suppressive soils provide some of the best examples in which plants protect themselves against soil-borne pathogens by "naturally engineering" the composition of rhizosphere microbial populations (Ryan et al. 2009). Disease-suppressive soils are exceptional ecosystems in which crop plants suffer less from specific soil-borne pathogens than expected due to the activities of other soil microorganisms (Mendes et al. 2011). General soil suppressiveness is the capacity of the total microbial biomass to suppress the growth or activity of deleterious organisms, whereas specific soil suppressiveness generally depends on a single organism with the ability to antagonize a specific pathogenic species or genus (Weller et al. 2002). Virtually, all soils possess some biological capacity to restrict disease progression. Indeed, disease severity incited by an introduced pathogen is consistently less severe in a native soil than in the same soil that has been pasteurized prior to pathogen introduction (Mazzola 2004).

Development of disease suppression in soils has been reported for a variety of diseases, such as those resulting from infection with *Pythium spp.* (Manici et al. 2005), *Rhizoctonia solani* (Ghini and Morandi 2006), and *Fusarium spp.* (Borrero et al. 2006). Diversity has been suggested to be an important attribute of healthy soils and a contributor to disease suppression (Postma et al. 2008). However, the identification of specific microorganisms responsible for disease suppression has relied mainly on cultivation-dependent techniques (Manici et al. 2005; Borrero et al. 2006).

However, for most disease-suppressive soils, the microbes and mechanisms involved in pathogen control remain unknown. Long-standing suppression is a biological condition naturally associated with soil. Its origin is not known, and it appears to persist in the absence of plants. This observation supports the hypothesis that plants do not only directly interact with microorganisms, but that their action as ecosystem engineers outlives them. Research related to suppressive soils may be hampered by an overemphasis on pathogen-antagonist interactions, with little consideration of other microbial and plant interactions (Weller et al. 2002; Kinkel et al. 2011) although the key aspect determining this relationship may not be taxonomic, but rather functional diversity (Chaparro et al. 2012; Postma et al. 2008). Hence, although specific processes can be attributed to specific microorganisms, it is the total microbiome and its interactions that affect plant health.

Identification of the biological properties contributing to the function of suppressive soils is a necessary first step to the management of such systems for use in the control of soil-borne diseases. Suppressive soils have provided a wealth of microbial resources that have subsequently been applied for the biological control of soil-borne plant pathogens (Mazzola 2004).

Soil-Borne Pathogens' Antagonists

Each plant selects its specific antagonistic microorganisms (Berg et al. 2005). Several bacterial and fungal groups have been identified as antagonists of soil-borne plant pathogens; these groups employ a variety of mechanisms for this process, including competition, niche exclusion, parasitism, induction of systemic resistance, production of antifungal or antibiotic compounds, and production of lytic enzymes (Bais et al. 2006; Berendsen et al. 2012).

Interactions between the different elements of rhizosphere communities have been studied in relation to biological control of plant pathogens. Fluorescent pseudomonas produce antifungal antibiotics, elicit induced systemic resistance in the host plant or interfere specifically with fungal pathogenicity factors. Before engaging in these activities, biocontrol bacteria go through several regulatory processes at the transcriptional and post-transcriptional levels (Haas and Defago 2005).

Studies on biological control of plant diseases have focused, during the last decade, on Induced Systemic Resistance (ISR), because ISR is effective against a wide range of pathogens and thus offers serious potential for practical applications in crop protection. Induced resistance responses in host plants mediated by selected strains of rhizosphere microorganisms such as AMF is widely recognized (Pozo and Azcon-Aguilar 2007). Such applications may however affect microbial communities associated with plant roots and interfere with the functioning of the root microbiota (Doornbos et al. 2012).

Disease suppressive soils and soil-borne pathogens's antagonists constitute naturally occurring plant protection processes. The development of new approaches to study and implement interactions between plants and their associated communities is crucial to design disease-suppressive agroecosystems.

Towards Disease-Suppressive Agroecosystems

New Approaches to Assess Root Ecological Processes

Tools are now available to increase our understanding of rhizospheric ecological processes and their consequences. Assessing whether and how plants recruit beneficial soil microorganisms for protection against infections can be elucidated via microbial and genetic markers (Mendes et al. 2011). Assessing rhizosphere interactions is possible with the development of innovative techniques such as functional metagenomics (Bais et al. 2006; Berendsen et al. 2012; Mazzola, 2004; Neumann et al. 2009), enabling the exploration of promising strategies for providing rhizosphere bioprotection against colonization.

Mendes et al. (2013) reviewed available technologies to identify gene transcripts, proteins, or metabolites and provide a more detail insight into the genes and functions expressed in the rhizosphere microbiome. Developments in genomics, proteomics and metabolomics provide new tools to study genotype x environment molecular interactions (Welbaum et al. 2004). The new generation of PhyloChip that contains 60,000 bacterial operational taxonomic units (Mendes et al. 2013) facilitates the assessment of qualitative and quantitative shifts in microbial communities and the molecular interplay of plant–microbe interactions (Doornbos et al. 2012). These tools are being used on model plant species, but their application to a broader range of crops is essential if we are to develop new approaches in the management of agroecosystems.

Increasing the fitness of beneficial microorganisms, whether antagonists or commensals is now possible by increasing the densities, the frequencies, the antagonistic abilities or the diversities of indigenous consortia in soil (Kinkel et al. 2011).

Moreover, the manipulation of the exudates pathway to specifically synthesize certain products is an avenue to improve root–rhizosphere interactions. As an example, possible strategies to alter flavonoid exudation are considered. However the

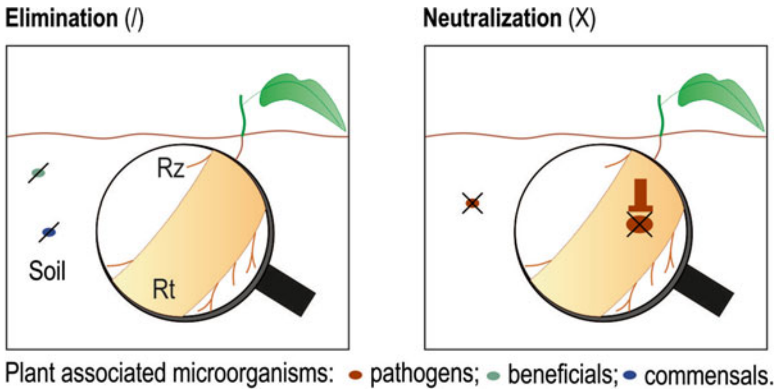


Fig. 5 Plant protection against soil-borne disease infection in managed systems. *Left*: **Elimination (/)** of soil inoculum (pesticide, heat treatment, sanitation). *Right*: **Neutralization (X)** of the pathogen (resistant cultivar, grafting, natural defense elicitation) (*Rz* rhizosphere, *Rt* root)

overlapping functions of many flavonoids as stimulators of functions in one organism and inhibitors of another suggests caution in attempts to manipulate flavonoid rhizosphere signals (Hassan and Mathesius 2012).

Similar to those existing for above-ground, our rapidly increasing knowledge of belowground tritrophic interactions is expected to provide opportunities to implement naturally occurring plant-soil feedbacks in plant management systems.

Current Crop Protection Management and Rhizosphere Bioprotection

Current crop protection management seldom capitalizes on disease-suppressive root processes presented in the previous section. The difficulties of studying rhizosphere interactions in situ until now may explain these observations.

As compared with plants in natural systems, crops are fast-growing and short-lived, which makes it difficult for them to develop root-protective mechanisms. Many practices prevent plants from engaging in self-protection in intensive agricultural systems, including monoculture, short life spans, tillage, periods of bare soil, high input levels, and the presence of microorganisms characterized by high growth rates. Moreover plants are placed in non-native habitats with generally low soil biodiversity and are deprived of co-evolutionary antagonists (Badri and Vivanco 2009). Bakker et al. (2012) highlights possible effects of disrupting plant-microbiome coadaptation on sensitivity to subsequent disease. A plant growing with a microbiome which has no shared history or adaptation is less effective at preventing pathogen establishment.

Plant protection strategies mainly focus on breeding to exploit host resistance (Mazzola 2004) or on sanitizing methods to decrease soil inoculum (Fig. 5). These strategies do not generally take into account rhizosphere interactions and have their limitations at present. Plant resistance against many soil-borne pathogens is hardly available and when it is, it can create resistance bypass (Hiddink et al. 2010). Decreasing soil inoculum via chemical, physical, or cultural techniques does not always result in the desired effect, in addition to harming the environment in some cases. Rhizosphere bioprotection is mainly implemented through biocontrol agent inoculation.

Rhizosphere Bioprotection and Biocontrol Agents Inoculation

We addressed rhizosphere bioprotection strategies on the case study of two major soil-borne pathogens of tomato (*Lycopersicon esculentum* L.): *Fusarium oxysporum* f. sp. *radicis lycopersici* (FORL) and *Ralstonia solanacearum* (RS). We searched the literature for studies that experimentally assessed tomato Fusarium or Bacterial wilt management based on rhizosphere processes thereby excluding the many practices that aim to reduce the amount of inoculum in the soil or exploit the plant resistance (Table 1).

Fusarium oxysporum f. sp. *radicis lycopersici* (FORL) is a soil-borne fungus, which invades the plants through the roots and causes tomato foot and root rot, and one of the worldwide yield limiting factors of tomato. *Ralstonia solanacearum* is one of the world's most important phytopathogenic bacteria due to its lethality, persistence, wide host range and broad geographic distribution (Denny 2006). Due to the soil-borne nature of these diseases, the use of chemicals in controlling the wilt is hardly successful. Although the use of resistant cultivars against Fusarium or Bacterial wilt is a viable option, the occurrence and development of new pathogenic races is a continuous problem (Srivastava et al. 2010; Wicker et al. 2007).

Rhizosphere bioprotection is addressed via inoculation of biocontrol agents (BCA) in 36 papers among the 39 papers we reviewed. Inoculation of BCA is associated with good results in the laboratory and in greenhouse experiments. Unfortunately, results in the field have been less consistent, probably because of non-ecological persistence of the inoculant in the soil due to unfavorable conditions and competition (Cetintas and Dickson 2004; Chave et al. 2008; Collange et al. 2011; Rumbos et al. 2008). The conditions for maintaining the BCA are not assessed and provided. Complementary practices likely to drive and sustain rhizospheric processes are rarely implemented although combining the benefits of BCA with the utilization of plant species diversity shows great promise (Hage-Ahmed et al. 2013). Possible ecological processes mentioned by the authors in the 39 reviewed papers are antagonism (33 papers), induction of systemic resistance (10) and allelopathy (6). Some current agricultural practices, especially soil amendments and plant functional diversification, make contributions to rhizosphere protection through antagonism and allelopathy (Posas and Toyota 2010; Yu 1999).

There are few examples of efficient rhizosphere bioprotection in fields as the persistence of biocontrol agents is not guaranteed. Enhancing rhizosphere bioprotection must be part of an integrated soil pests management.

Table 1 Management options for promoting rhizosphere bioprotection against *Fusarium oxysporum* f. sp. *radicis lycopersici* (FORL) and *Ralstonia solanacearum* (RS), agents of tomato Fusarium and Bacterial wilt. Ecological processes proposed by the authors are antagonism (ANT), allelopathy (ALL) and induction of systemic resistance (ISR)

Management of rhizosphere bioprotection		Ecological process			Pathogen		
BCA type	Other strategies	Ant.	All.	ISR	FORL	RS	References
Mycorrhiza/*T. harzanium*		×			×		Datnoff et al. (1995)
Pseudomonas fluorescens		×		×	×		M'Piga et al. (1997)
Non-pathogenic *Fusarium*				×	×		Fuchs et al. (1997)
Pseudomonas fluorescens/non pat. *Fusarium*		×		×	×		Duijff et al. (1998)
Pseudomonas chlororaphis		×			×		Chin-A-Woeng et al. (1998)
Inocula from suppressive soils		×				×	Shiomi et al. (1999)
–	Intercropping		×			×	Yu (1999)
Pseudomonas spp.		×			×	×	Bolwerk et al. (2003)
Bacillus pumilus/*Pseudomonas putida*	ASM/soil amendment	×		×		×	Anith et al. (2004)
Mycorrhiza				×		×	Zhu and Yao (2004)
Mycorrhiza/*Pseudomonas fluorescens*		×		×	×		Akköprü and Demir (2005)
Pseudomonas fluorescens		×	×		×		Kamilova et al. (2008)
Inocula from suppressive soils		×				×	Irikiin et al. (2006)
Mixed culture of bacteria		×				×	Lwin and Ranamukhaarachchi (2006)
Mycorrhiza mixture		×		×	×		Utkhede (2006)
Streptomyces griseoviridis	Solarization	×			×		Minuto et al. (2006)
Pseudomonas fluorescens/*Bacillus subtilis*…		×				×	Lemessa and Zeller (2007)
–	Soil amendment	×				×	Posas et al. (2007)
Mycorrhiza	Soil amendment	×			×	×	Taïwo et al. (2007)
Pseudomonas spp., etc.		×			×		Validov et al. (2006)
Mycorrhiza			×		×		Lioussanne et al. (2008)
Pythium oligandrum				×		×	Hase et al. (2008)

(continued)

Table 1 (continued)

Management of rhizosphere bioprotection		Ecological process			Pathogen		
BCA type	Other strategies	Ant.	All.	ISR	FORL	RS	References
Burkholderia nodosa		×			×	×	Nion and Toyota (2008)
Non-pathogenic *Fusarium*			×		×		Steinkellner et al. (2008)
Bacillus megaterium, *Enterobacter cloacae*…		×				×	Nguyen and Ranamukhaarachchi (2010)
Mycorrhiza		×		×	×		Ren et al. (2010)
Mycorrhiza/*Pseudomonas fluorescens*/*Trichoderma harzanium*	Soil amendment	×		×	×		Srivastava et al. (2010)
–	Soil amendment	×				×	Posas and Toyota (2010)
Bacillus amyloliquefaciens	Soil amendment	×				×	Weï et al. (2011)
Pseudomonas fluorescens		×			×		Barahona et al. (2011)
Endophytic bacteria		×				×	Tan et al. (2011)
Bacillus spp.	ASM/hymexazol	×			×		Myresiotis et al. (2012)
Pseudomonas alcaligenes		×			×		Widnyana et al. (2013)
Bacilus subtilis		×	×			×	Chen et al. (2013)
Acinetobacter/Enterobacter		×				×	Xue et al. (2013)
Mycorrhiza	Intercropping	×	×		×		Hage-Ahmed et al. (2013)
Cyanobacteria	Soil amendment	×			×		Prasanna et al. (2013)
Ralstonia pickettii		×				×	Wei et al. (2013)
Bacilus amyloliquefaciens		×				×	Tan et al. (2013)

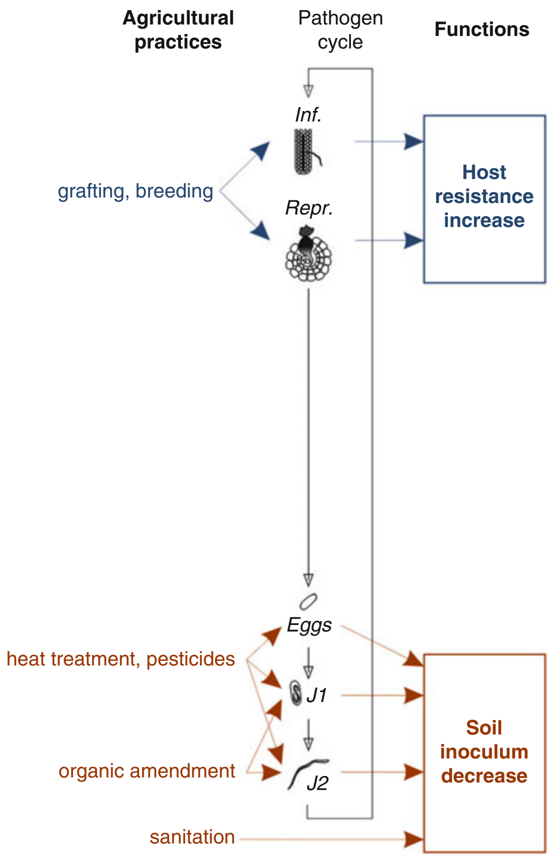


Fig. 6 From agricultural practices to biological functions in the current protection system: an illustration on root-knot nematode control (Inf.: root infestation, Repr.: egg laying, J1: first stage juvenile, J2: infective second stage juvenile). Agricultural practices are chosen according to the service they perform, with some considerations to the pathogen cycle

Agroecological Design

To overcome the limitations of conventional protection strategies, many agroecological practices such as soil amendments, plant-induced resistance stimulation, and plant species diversity have been assessed. Applying a single control measure is often ineffective, as the action of a chemical input cannot be replaced by the stimulation of a single ecological process (Lopez-Escudero and Mercado-Blanco 2011). A holistic approach is the best strategy to effectively control soil-borne pathogens by integrating biological, chemical, physical, and crop-management approaches (Collange et al. 2011; Oka 2010).

To date, we have been able to implement agroecological approaches. For example, Tchamitchian et al. (2011) used a multicriteria approach to link the design of a vegetable cropping system to its sanitary properties (Navarette et al. 2010). They first grouped the several present pathogens, root-knot nematodes, soil-borne fungi according to their management traits (Moonen and Barberi 2008), then grouped the practices according to their effects on these traits (Fig. 6). Finally, they

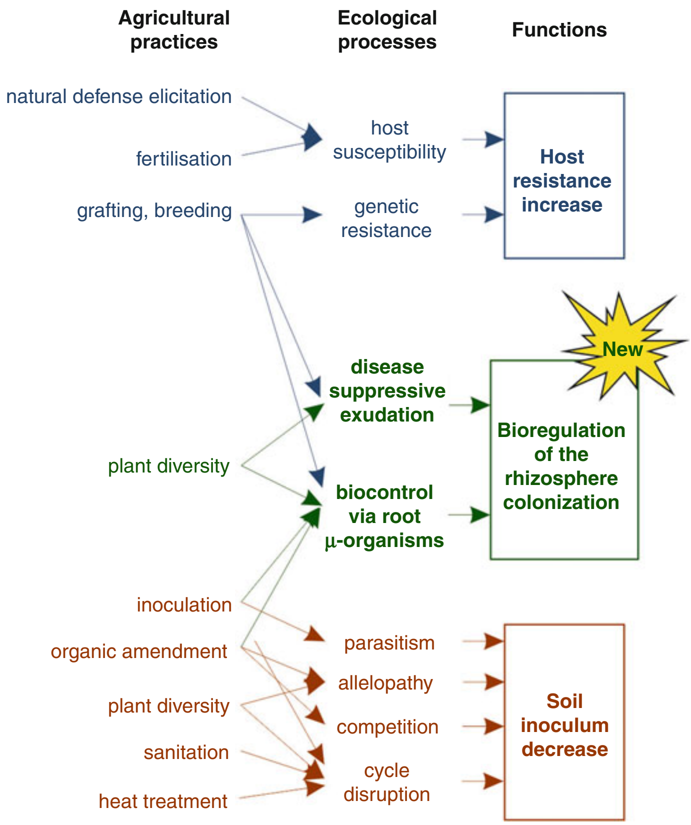


Fig. 7 From agricultural practices to biological functions in the proposed agroecological framework for plant protection and health. Protection services are sustained by ecological processes which in turn are driven by agricultural practices. Notice the new function, bioregulation of the rhizosphere colonization and associated ecological processes and agricultural practices (in comparison to Fig. 6)

evaluated the properties of the cropping system, taking into account the interactions between the techniques. This approach allows to consider contradictory effects in practices combinations on the development of the different addressed pests and diseases (Navarrete et al. 2013). This example shows that it is possible to associate agricultural practices with functions thanks to the agroecological approach described here. This approach mobilized both plant-resistance increase and reduction of the inoculum. However, to date, plant protection seldom considered the regulation of rhizosphere colonization.

The rhizosphere bioprotection is now part of the design phase of the cropping system based on the combination of multi-functional practices. The design of these disease-suppressive systems is based on the mobilization of ecological processes to provide three functions: the elimination of the inoculum, the resistance of the plant and rhizospheric bioprotection. An agroecological engineering framework encompassing a holistic rhizosphere approach based on the three functions is presented in Fig. 7. Agricultural practices modify not one but many ecological processes at the same time. It is critical to understand the interactions between these processes as well as the interactions between these practices. Combining the ecological processes triggered by the implemented practices will likely produce dynamic synergies and achieve trade-offs. The risk of emergence of new disease in agroecological systems must be taken into account.

Our ability to more fully exploit plant-rhizosphere interactions for agroecosystem productivity depends not only on our understanding of these complex processes but also on their sustainable mobilization in agroecological engineering approaches.

Harnessing Rhizosphere Interactions and Disease-Suppression Strategies

Multi-functional practices to capitalize on plant-microbiome beneficial interactions are presented in Fig. 8 and addressed in the present section.

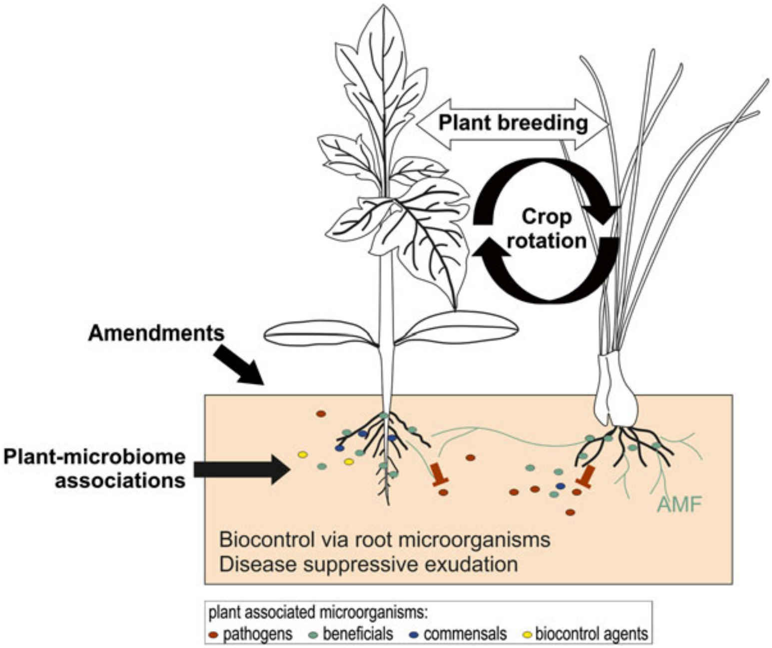


Fig. 8 Disease-suppression strategies to harness rhizosphere interactions. Plant breeding, soil amendments, plant-microbiome associations (i.e. *AMF* arbuscular mycorrhizal fungi), crop rotation and mixed cropping systems favor rhizospheric processes: biocontrol of soil-borne pathogens (in *red*) via indigenous (in *green* and *blue*) or introduced (in *yellow*) root microorganisms and disease suppressive exudation (T in *red*)

Plant Breeding

The collective genome of microbial communities is much larger than a plant genome, and is referred to as the plant's second genome (Berendsen et al. 2012). Plants can be viewed as superorganisms that rely in part on their microbiome for specific functions and traits (Mendes et al. 2013). Databases of plant traits, such as TRY (Kattge et al. 2011), gather information on morphological, physiological, biochemical, and other characteristics of plants and their organs. In the future, a major challenge will be the extension of these databases to microbial and microbial-suppressive characteristics of roots. The Banking Rhizosphere Micro-Organisms European - Russian Initiative (BRIO 2010) is the first initiative to set up a network of rhizosphere microbiological resources centers.

The ability of crops to select their specific antagonistic microorganisms could be exploited in breeding strategies as it is already done for the resistance against pathogens (Bakker et al. 2012; Berg and Smalla 2009). Utilization of crop genotypes with an elevated capacity to select for specific functional microbial genotypes appears to be a viable means to enhance crop disease tolerance and ultimately productivity. Breeding of crops that exudates allelopathic compounds or quorum-sensing mimics could lead to the same benefits (Ryan et al. 2009). The development of crop cultivars that are bred specifically to capitalize on beneficial plant-microbial associations will increase the numbers of breeding options and selection criteria available to plant breeders (Welbaum et al. 2004). However Bakker et al. (2012) stated that currently there is no known breeding program that evaluates plant lines for their broad interaction with soil microbiome. These authors stressed that the variability of plant-microbiome interactions across environments, soil types and microbial communities will represent one of the difficulties for breeders.

The capacity to modulate resident soil microbial populations in a plant genotype dependent manner induces soil suppressiveness. Although the body of work consists primarily of studies conducted in controlled environments, plant genotype-dependent selection of specific resident soil microorganisms having a functional role in disease suppression has been reported. The vast majority of works addressing the impact of plant genotype on selection of microbial antagonists has focused on fluorescent Pseudomonas spp. strains producing the antibiotic 2,4-diacetylphloroglucinol (2,4-DAPG) which is active against numerous soil-borne plant pathogens (Haas and Defago 2005). Mazzola and Gu (2000) showed that soil suppressiveness towards *Rhizoctonia* root rot in response to repeated cultivation of wheat has been found to be wheat genotype dependent. The capacity of a wheat genotype to induce disease suppression was associated with enhancing rhizosphere populations of specific fluorescent pseudomonas genotypes, thus demonstrating antagonistic activity towards *Rhizoctonia solani*. Cultivation of wheat genotypes that did not modify the fluorescent pseudomonas population in this manner did not elicit a disease suppressive soil.

Although the vast majority of studies on potential source of antagonists have focused on the saprophytic bacterial community, there is also evidence that plant species differentially support root colonization by fungi, such as *Trichoderma spp.*, *Penicillium spp.*, and non-pathogenic *Fusarium* spp., with potential to suppress plant pathogens (Berg et al. 2005; Duijff et al. 1998; Fuchs et al. 1997; Larkin et al. 1996; Rengel and Marschner 2005). Larkin et al. (1996) showed that *Fusarium* wilt suppressive soils in response to repeated cultivation of watermelon was only observed when cultivars resistant to *Fusarium oxysporum f. sp. niveum* were cropped, and was associated with increases in specific populations of non-pathogenic *Fusarium oxysporum*.

However, direct selection for rhizosphere traits remains an exception, either because few suitable traits have been identified to date or because the expression of such traits are prone to variation depending on growth stages or environmental conditions. Much could be gained if phenotypic evaluations were replaced by selection for molecular markers tightly linked with the trait of interest. Considerable effort has therefore been invested in mapping quantitative trait loci (QTLs) associated with rhizosphere traits (Wissuwa et al. 2009).

Soil Amendments

Soil amendments have the capacity to enhance disease suppression, though the biological modes of action may vary from that initially resident in the soil. In most cases soil amendments are used for their biotoxic properties for the pathogen in the soil and their ability to stimulate the growth of the plants (Radwan et al. 2009; Wachira et al. 2009). However soil amendment can enhance the fitness of root-associated beneficial communities, a process that allows the selection of bacterial consortia that interfere with bacterial pathogens. Increasing nutrient availability can both enhance the feasibility of making antibiotics or other costly antagonistic compounds for the main crop and contribute to increase the fitness of beneficial microorganisms. Thus, the potential for achieved benefits or disease suppression is enhanced.

Initial community density, diversity, composition may be one source of the variation in the effectiveness of organic inputs in enhancing antagonistic activities in soil (Kinkel et al. 2011). Enhancing the level of organic matter in soil is often correlated with increased suppressiveness towards plant pathogens such as *Pythium* (Mazzola 2004). In large part, these amendments appear to function though enhancing overall microbial activity, or general suppressiveness. Mazzola (2004) suggests that the persistence of the disease-suppressive state operating though a biological mechanism will be greater if the organic amendment is functioning through enhanced activity of the resident soil microbial community rather than through the introduction of a novel active community.

Focusing the studies of disease suppression singly as a response to nutrient inputs may miss important steps or benchmarks in the development of disease-suppressive potential. Sustained management of nutrient inputs should focus on supporting high community densities and diversities while providing consistent resources to enhance capacities for antagonistic phenotypes (Kinkel et al. 2011). During the decomposition of organic matter in soil, the soil ecosystem is subjected to the increase of the ratio of oligotrophic (K-strategist) to copiotrophic (r-strategist) organisms in microbial succession (Van Bruggen and Semenov 2000). The range of this ratio has been associated with general disease suppression. Some authors proposed that the microbial community structure and the time required to return to the initial state after application of various disturbances or stress could be characteristic for disease suppression in soil (Garbeva et al. 2004).

Kinkel et al. (2011) proposed a co-evolutionary framework for inducing natural disease suppressiveness of soils. Co-evolution is the process of reciprocal genetic change between interacting populations. Co-evolution of plants and rhizosphere microorganisms has been reviewed by Lambers et al. (2009). Kinkel et al. (2011) propose, for example, to identify the nutrient conditions under which the microbial communities follow an antagonistic trajectory. They suggest a new focus on the impacts of initial microbial density and diversity on the success of disease suppression management strategies.

Plant-Microbiome Associations

Terms of the Associations

Beneficial microorganisms that protect the host plant against infection are introduced into soil or onto seeds (seed coating) or planting material. To overcome the constraints related to the implementation of inoculation, tissue culture techniques provide a great opportunity for the uptake of selected microbial strains and/or strain combinations by sterile plant propagules. In vitro and ex vitro bacterization and mycorrhization of vegetatively propagated material is explored as an efficient way to improve production practices of high value horticultural crops (Nowak and Shulaev 2003). The successful introduction of endophytic pseudomonas into tissue culture plantlets to improve transplant establishment and early vigor has also been found to increase resistance to biotic stress (Sturz et al. 2000).

Despite extensive investigation on soil or seed inoculation with beneficial microorganisms, the full potential for the utilization of these natural allies has not been achieved yet. Inconsistencies in biocontrol under varying environmental conditions have been a common limitation of many biocontrol agents. When introduced in new environments, many microbial strains do not survive or cannot establish densities in the rhizosphere that are necessary to control soil-borne pathogens (Raaijmakers et al. 2009; Verbruggen et al. 2012). The first and most crucial prerequisite for an effective use of biological control agents is the continuous confirmation of strain identity and activity. Monitoring microbial inoculants and their impact on rhizosphere microbial communities is necessary to guarantee safe and reliable application, but that was not possible until now.

Inocula Composition

Instead of the “one-microorganism” approach, Bakker et al. (2012) highlight the use of assemblages of different microorganisms with complementary or synergistic traits. In most of the studies published to date, as shown on the examples of *Ralstonia solanacearum* and FORL biocontrol, combinations of microorganisms usually consisted of strains (bacterial, fungal) that were effective on their own (Duijff et al. 1998, Lwin and Ranamukhaarachchi 2006, Srivastava et al. 2010).

Srivastava et al. (2010) assessed arbuscular mycorrhizal fungi, fluorescent *Pseudomonas* and *Trichoderma harzianum* formulation against *Fusarium oxysporum f. sp. lycopersici* for the management of tomato wilt by seed bio-priming. All these bioagents significantly reduced the incidence of wilt in pot and field trials and combinations of bioagents were more effective than single isolate treatments. The combination of fluorescent *Pseudomonas, T. harzianum* and arbuscular mycorrhizal fungi provided significantly better control than the non-inoculated treatment, reducing disease incidence and severity by 74 % and 67 % in pots and field, respectively. The combination treatments also increased yield by 20 %. Addition of compost further reduced disease and improved yield in all treatments. In comparison to the control, the combination of all three bioagents with compost significantly reduced disease by 81 % and 74 % in pots and field, respectively, and enhanced the yield by 33 %. Other authors have stressed the importance of adding compost combined with the inoculation of biocontrol agents for the management of *Fusarium* and Bacterial wilt (Prasanna et al. 2013; Taïwo et al. 2007; Wei et al. 2013).

However designing a consortium of microorganisms for controlling soil-borne pathogens is very complex as each member of the consortium is affected by the identity of the other members. Mendes et al. (2013) proposed to design a ‘core microbiome’ that is effective against soilborne pathogens in different agro-ecosystems. They define the core rhizosphere microbiome in the context of plant health as the set of microorganisms that are needed to effectively protect plants from soilborne pathogens. They suggest that the core microbiome may be different for the different groups of soil-borne plant pathogens that are bacteria, fungi, oomycetes and nematodes. They propose to assemble the core microbiome more from a functional perspective than based on taxonomic classification only. This proposal is a trade-off between a high functional diversity on one hand and a high establishment of a given antagonist on the other hand.

Crop Rotation

Crop rotation is the practice of growing crops on the same field sequentially in time. Crop rotation using non-host species has long been employed as the densities of both soil-borne pathogens and antagonistic microorganisms are affected. Effective crop rotation results in the lack of positive selection of the pathogen and provides time needed for the biological control of the pathogen inoculum by antagonists residing in soil. Moreover, cropping sequences could be designed to select specific elements of the resident microbial community that contribute to disease suppression (Mazzola 2004).

The concept of "soil priming" interpreted as setting the "readiness" of a specific soil to receive a selected crop with "primer plants" has been proposed by Welbaum et al. (2004). For example, the integration of legumes, which secrete compounds recognized as signal molecules by rhizobacteria, into life-mulch induces the bacterial production of factors essential for the establishment successful N2-fixing legume-rhizobia symbiosis. Submicromolar concentrations of these compounds induce physiological changes in both host (legume) and an array of non-host plants by enhancing seed germination and early seedling growth (Prithviraj et al. 2003).

Larkin (2008) assessed the effects of biological amendments and crop rotations on soil microbial communities and soil-borne diseases of potato. Their results indicate that some rotations were more able to support the added beneficial organisms from amendments and enabled more effective biological control.

Although crop rotation, if properly designed, is the most efficient cultural practice to reduce the incidence and severity of soil-borne diseases, diversified and multiyear crop rotations can have lower interest from an economic point of view (Hiddink et al. 2010). This reinforces the interest of the soil-priming concept and the necessity to organize the complementarity between crop rotations and the other methods discussed here.

Mixed Cropping Systems

Mixed cropping is defined as the cultivation of a mixture of at least two crops together in the same field (Trenbath 1976). Although mixed cropping systems are applied primarily for their impact on overall yield and their frequent agronomic advantages (Figs. 9 and 10), one benefit of this practice is disease control (Hiddink et al. 2010). Boudreau (2013) reviewed 206 studies comparing disease in monocropping and intercropping systems. Intercropping reduced disease by 86 % for rots and wilts, 100 % for bacteria, 37 % for nematodes. Identification of strongly interacting species that recruit beneficial microorganisms or exude toxic compounds opens new paths to manage soilborne disease in mixed cropping systems.

Hiddink et al. (2010) reviewed different type of mixed cropping systems: (1) strip mixed cropping, the strip-wise simultaneous cultivation of multiple crops in rows, wide enough to permit independent cultivation but still sufficiently narrow to interact agronomically; (2) relay mixed cropping, the simultaneous cultivation of multiple crops during only part of their field period; (3) row mixed cropping, the production of multiple crops alternatively planted in rows; and (4) multi-storey mixed cropping, the cultivation of tall perennials combined with shorter biannual or annual crops, practiced in orchards, tree nurseries and agroforestry. These different types of mixed cropping systems and their characteristics often determine if

Fig. 9 Enhancing agronomic performance intercropping corn with manioc (INRA, Guadeloupe)

Fig. 10 Mixed cropping systems in Guadeloupe (INRA)

soilborne diseases can be suppressed and what mechanisms can be held for disease suppression (Hiddink et al. 2010). In 30 out of 36 publications, mixed cropping resulted in a significant reduction of soil-borne disease while in 6 it resulted in no or in an aggravation of the disease incidence or severity.

Host dilution appeared to be the most important mechanism of disease suppression although Hiddink et al. (2010) highlight that allelopathy and antagonism should be better managed to optimize disease-suppressive effects. To be effective in inhibiting rhizosphere-inhabiting pathogens, allelopathic substances should be present at sufficiently high concentrations in the micro-sites where the pathogen is located, and roots of mixed crops should be in close proximity (Hiddink et al. 2010).

Abdel-Monaim and Abo-Elyousr (2012) showed the suppressive effect of intercropping cumin, anise, onion and garlic with lentil on damping-off and root rot disease caused by *Rhizoctonia solani* and *Fusarium solani*. Roots exudates of intercropping partners reduced mycelial dry weight of the tested fungi in vitro. Marigolds

Fig. 11 Enhancing nematoregulation intercropping *Canavalia sp.* with banana *Musa spp* groupe AAA cv Grande Naine (INRA, Petit-Bourg, Guadeloupe)

(*Tagetes spp.*) have been demonstrated to reduce nematode infestation, especially those caused by the root-knot nematode *Meloidogyne incognita*, in tomatoes, when used as an intercrop or cover crop (Hooks et al. 2010; Kumar et al. 2005). In another example, *Canavalia sp.* produces allelopathic compounds that reduce nematodes and benefit banana crops (Fig. 11) (Damour 2004).

In mixed crops, increased plant diversity leads to more diverse root exudates and consequently to a more diverse rhizosphere-inhibiting microbial community (Kowalchuk et al. 2002). Rhizosphere of mixed crops support different bacterial and fungal communities compared to the corresponding single-crop rhizospheres (Hiddink et al. 2004; Bainard et al. 2012).

Mixed cropping plants that recruit and transfer beneficial microorganisms or secrete allelopathic compounds can provide sustainability and resilience. Some plants could favor symbiotic microorganisms such as arbuscular mycorrhizal fungi which act for roots bioprotection through different processes (Azcón-Aguilar and Barea 1997). Arbuscular mycorrhizal fungi and their bioprotective effect are of great importance for the management of plant disease in an environmentally compatible agriculture. As illustrated in Fig. 12, some plants favor arbuscular mycorrhizal fungi, which provide root bioprotection. This system is based on the multiplication of natural mycorrhiza due to the planting of a mycorrhizal plant (chives) associated with a second crop (tomato), which benefits from the increased mycorrhizal density.

Fig. 12 Enhancing arbuscular mycorrhizal fungi biocontrol effect against soilborne disease intercropping tomato *Lycopersicon esculentum* with chive *Allium fistulosum* (Soufriere, Santa-Lucia)

Hage-Ahmed et al. (2013) tested arbuscular mycorrhizal fungi against *Fusarium oxysporum* F. sp. *Lycopersici* with tomato intercropped with leek, cucumber, basil, fennel or tomato itself. The bioprotective effects resulting in the decrease of *F. oxysporum* wilt disease severity depended on the intercropping partner more than on the degree of mycorrhizal colonization. A combination of the bioprotective effects of arbuscular mycorrhizal fungi and intercropping partners can be considered as a new potential strategy against soilborne pathogens and would be of high significance for sustainable agriculture.

Conclusion

Harnessing the plant's ability to mobilize beneficial rhizosphere interactions is a promising strategy to include in the design of innovative disease-suppressive agroecosystems. Such strategy will address the defense against several pests at once, therefore benefiting plant health and productivity. It allows reducing the dependence on pesticides and decreases the risk of the emergence of resistant pests. Although we have shown how promising such strategies would be, based on the opportunities offered by the current knowledge, the knowledge on the rhizospheric interactions is yet too scarce to design such strategies in an effective and economically feasible way. Linking agricultural practices to these interactions requires more detailed investigation, especially in mixed cropping systems.

Identifying interacting species with strong ability to recruit beneficial microorganisms or secret toxic compounds is a key and paramount issue. A framework based on smart usage of databases implemented to inventory plant-induced functional traits will be useful to predict disease-suppressive capacities and will be of great help to the agroecosystems designers. Plants would be associated with their second genomes and enlarged rhizosphere compartments of associated microorganisms. Specific investigations should focus on understanding how biotic versus abiotic conditions can be manipulated to generate appropriate compound profiles.

Harnessing rhizosphere interactions is one of the innovative ways to design disease-suppressive agroecosystems. Pest regulation and crop yield are supplied by biodiversity rather than by anthropogenic inputs. Several other underpinning ecosystem services such as weed control, soil formation and nutrient cycling may also be boosted. For successful management of multiple services, decision-making and developing management interventions will need to promote synergies between below and above-ground interactions. Smart management of functional biodiversity will lead to disease-suppressive agroecosystems and enhance their resiliency. Long-term crop production and resource preservation will ensure sustainable food security in the context of global changes and global demand.

References

Abdel-Monaim MF, Abo-Elyousr KA (2012) Effect of preceding and intercropping crops on suppression of lentil damping-off and root rot disease in New Valley–Egypt. Crop Prot 32:41–46

Akiyama K, Matsuzaki K, Hayashi H (2005) Plant sesquiterpenes induce hyphal branching in arbuscular mycorrhizal fungi. Nature 435:824–827

Akköprü A, Demir S (2005) Biological control of Fusarium wilt in tomato caused by *Fusarium oxysporum* f. sp. *lycopersici* by AMF *Glomus intraradices* and some rhizobacteria. J Phytopathol 153:544–550

Anith KN, Momol MT, Kloepper JW, Marois JJ, Olson SM, Jones JB (2004) Efficacy of plant growth-promotin-rhizobacteria, acibenzolar-S-methyl, and soil amendment for integrated management of bacterial wilt on tomato. Plant Dis 88:669–673

Azcón-Aguilar C, Barea JM (1997) Arbuscular mycorrhizas and biological control of soil-borne plant pathogens–an overview of the mechanisms involved. Mycorrhiza 6:457–464

Badri DV, Vivanco JM (2009) Regulation and function of root exudates. Plant Cell Environ 32:666–681

Bainard LD, Koch AM, Gordon AM, Klironomos JN (2012) Temporal and compositional differences of arbuscular mycorrhizal fungal communities in conventional monocropping and tree-based intercropping systems. Soil Biol Biochem 45:172–180

Bais HP, Weir TL, Perry LG, Gilroy S, Vivanco JM (2006) The role of root exudates in rhizosphere interactions with plants and other organisms. Annu Rev Plant Biol 57:233–266

Bakker MG, Manter DK, Sheflin AM, Weir TL, Vivanco JM (2012) Harnessing the rhizosphere microbiome though plant breeding and agricultural management. Plant soil 360:1–13

Barahona E, Navazo A, Martinez-Granero F, Zea-Bonilla T, Perez-Jimenez RM, Martin M, Rivilla R (2011) A *Pseudomonas fluorescens* F113 mutant with enhanced competitive colonization ability shows improved biocontrol activity against fungal root pathogens. Appl Environ Microbiol 77:5412–5419

Berendsen RL, Pieterse CMJ, Bakker PAHM (2012) The rhizosphere microbiome and plant health. Trends Plant Sci 17:478–486

Berg G, Smalla K (2009) Plant species and soil type cooperatively shape the structure and function of microbial communities in the rhizosphere. FEMS Microbiol Eco 68:1–13

Berg G, Zachow C, Lottmann J, Götz M, Costa R, Smalla K (2005) Impact of plant species and site on rhizosphere-associated fungi antagonistic to *Verticillium dahliae* Kleb. Appl Environ Microbiol 171:4203–4213

Bolwerk A, Lagopodi A, Wijfjes A, Lamers G, Chin-A-Woeng TFC, Lugtenberg B, Bloemberg G (2003) Interactions in the tomato rhizosphere of two *Pseudomonas* biocontrol strains with the phytopathogenic fungus *Fusarium oxysporum* f. sp. *radicis-lycopersici*. Mol Plant Microbe In 16:983–993

Borrero C, Ordovas J, Trillas MI, Aviles M (2006) Tomato Fusarium wilt suppressiveness. The relationship between the organic plant growth media and their microbial communities as characterised by Biolog (R). Soil Biol Biochem 38:1631–1637

Boudreau MA (2013) Diseases in intercropping systems. Annu Rev Phytopathol 51:499–519

BRIO project – Banking rhizosphere micro-organisms European – Russian Initiative. FP7-KBBE.2010.1.4-06: EU-Russia Partnership initiative in Microbes-Plant Biodiversities

Brussaard L, de Ruiter PC, Brown GG (2007) Soil biodiversity for agricultural sustainability. Agr Ecosyst Environ 121:233–244

Cetintas R, Dickson DW (2004) Persistence and suppressiveness of *Pasteuria penetrans* to *Meloidogyne arenaria* race 1. J Nematol 36:540–549

Chaparro JM, Sheflin AM, Manter DK, Vivanco JM (2012) Manipulating the soil microbiome to increase soil health and plant fertility. Biol Fert Soil 48:489–499

Chave M, Dabert P, Brun R, Godon JJ, Poncet C (2008) Dynamics of rhizoplane bacterial communities subjected to physicochemical treatments in hydroponic crops. Crop Prot 27:418–426

Chen Y, Yan F, Chai Y, Liu H, Kolter R, Losick R, Guo JH (2013) Biocontrol of tomato wilt disease by Bacillus subtilis isolates from natural environments depends on conserved genes mediating biofilm formation. Environ Microbiol 15:848–864

Chin-A-Woeng TFC, Bloemberg GV, van der Bij AJ, van der Drift KMGM, Schripsema J, Kroon B, Scheffer RJ, Keel C, Bakker PAHM, Tichy HV, de Bruijn FJ, Thomas-Oates JE, Lugtenberg BJJ (1998) Biocontrol by phenazine-1-carboxamide-producing *Pseudomonas chlororaphis* PCL1391 of tomato root rot caused by *Fusarium oxysporum* f. sp. *radicis-lycopersici*. Mol Plant Microbe In 11:1069–1077

Collange B, Navarrete M, Peyre G, Mateille T, Tchamitchian M (2011) Root-knot nematode (Meloidogyne) management in vegetable crop production: the challenge of an agronomic system analysis. Crop Prot 30:1251–1262

Damour G (2004) Analyse et modélisation des interactions pour l'eau et bilan de services dans une association banane-canavalia. MS thesis, Institut National Agronomique Paris-Grignon, Paris

Datnoff LE, Nemec S, Pernezny K (1995) Biological control of *Fusarium* crown and root rot of tomato in Florida using *Trichoderma harzianum* and *Glomus intraradices*. Biol Control 5:427–431

Denny TP (2006) Plant pathogenic Ralstonia species. In: Gnanamanickam SS (ed) Plant-associated bacteria. Springer, Dordrecht, The Netherlands, pp 573–644

Doornbos RF, van Loon LC, Bakker PAHM (2012) Impact of root exudates and plant defense signaling on bacterial communities in the rhizosphere. A review. Agron Sust Dev 32:227–243

Doré T, Makowski D, Malezieux E, Munier-Jolain N, Tchamitchian M, Tittonell P (2011) Facing up to the paradigm of ecological intensification in agronomy: revisiting methods, concepts and knowledge. Eur J Agron 34:197–210

Duijff BJ, Pouhair D, Olivain C, Alabouvette C, Lemanceau P (1998) Implication of systemic induced resistance in the suppression of Fusarium wilt of tomato by *Pseudomonas fluorescens WCS417* and by nonpathogenic *Fusarium oxysporum Fo47*. Eur J Plant Pathol 104:903–910

Fuchs JG, Moënne-Loccoz Y, Défago G (1997) Non-pathogenic *Fusarium oxysporum* Fo47 induces resistance to *Fusarium* wilt in tomato. Plant Dis 81:492–496

Garbeva P, Van Veen JA, van Elsas JD (2004) Microbial diversity in soil: selection of microbial populations by plant and soil type and implications for disease suppressiveness. Annu Rev Phytopathol 42:243–270

Ghini R, Morandi MAB (2006) Biotic and abiotic factors associated with soil suppressiveness to Rhizoctonia solani. Sci Agric 63:153–160

Haas D, Defago G (2005) Biological control of soil-borne pathogens by fluorescent pseudomonads. Nat Rev Microbiol 3:307–319

Hage-Ahmed K, Krammer J, Steinkellner S (2013) The intercropping partner affects arbuscular mycorrhizal fungi and *Fusarium oxysporum* f. sp. *lycopersici* interactions in tomato. Mycorrhiza 23:543–550

Hase S, Takahashi S, Takenaka S, Nakaho K, Arie T, Seo S, Ohashi Y, Takahashi H (2008) Involvement of jasmonic acid signalling in bacterial wilt disease resistance induced by biocontrol agent *Pythium oligandrum* in tomato. Plant Pathol 57:870–876

Hassan S, Mathesius U (2012) The role of flavonoids in root–rhizosphere signalling: opportunities and challenges for improving plant–microbe interactions. J Exp Bot 63:3429–3444

Hastings A, Byers JE, Crooks JA, Cuddington K, Jones CG, Lambrinos JG, Talley TS, Wilson WG (2007) Ecological engineering in space and time. Ecol Lett 10:153–164

Hiddink GA, Termorshuizen AJ, Raaijmakers JM, van Bruggen AHC (2004) Effect of mixed cropping on rhizosphere microbial communities and plant health. In: Book of abstracts international congress rhizosphere 2004, Munich, 12–17 Sept 2004

Hiddink GA, Termorshuizen AJ, van Bruggen AHC (2010) Mixed cropping and suppression of soilborne diseases. Sust Agric Rev 4:119–146

Hooks CR, Wang KH, Ploeg A, McSorley R (2010) Using marigold (*Tagetes* spp.) as a cover crop to protect crops from plant-parasitic nematodes. Appl Soil Ecol 46:307–320

Irikiin Y, Nishiyama M, Otsuka S, Senoo K (2006) Rhizobacterial community-level, sole carbon source utilization pattern affects the delay in the bacterial wilt of tomato grown in rhizobacterial community model system. Appl Soil Ecol 34:27–32

Jones DL, Hinsinger P (2008) The rhizosphere: complex by design. Plant Soil 312:1–6

Kamilova F, Lamers G, Lugtenberg B (2008) Biocontrol strain *Pseudomonas fluorescens* WCS365 inhibits germination of *Fusarium oxysporum* spores in tomato root exudate as well as subsequent formation of new spores. Environ Microbiol 10:2455–2461

Kattge J, Díaz S, Lavorel S et al (2011) TRY – a global database of plant traits. Glob Chang Biol 17:2905–2935

Kievit TR, Iglewski BH (2000) Bacterial quorum sensing in pathogenic relationships. Infect Immun 68:4839–4849

Kinkel LL, Bakker MG, Schlatter DC (2011) A coevolutionary framework for managing disease-suppressive soils. Annu Rev Phytopathol 49:47–67

Kowalchuk GA, Buma DS, De Boer W, Klinkhamer PGL, van Veen JA (2002) Effects of above-ground plant species composition and diversity on the diversity of soil-borne microorganisms. Anton Leeuw 81:509–520

Kumar N, Krishnappa K, Reddy BMR, Ravichandra NG, Karuna K (2005) Intercropping for the management of root-knot nematode, *Meloidogyne incognita* in vegetable-based cropping systems. Ind J Nematol 35:46–49

Lambers H, Mougel C, Jaillard B, Hisinger P (2009) Plant-microbe interactions in the rhizosphere: an evolutionary perspective. Plant Soil 321:83–115

Larkin RP (2008) Relative effects of biological amendments and crop rotations on soil microbial communities and soilborne diseases of potato. Soil Biol Biochem 40:1341–1351

Larkin RP, Hopkins DL, Martin FN (1996) Suppression of Fusarium wilt of watermelon by nonpathogenic Fusarium oxysporum and other microorganisms recovered from a disease-suppressive soil. Phytopath 86:812–819

Lemessa F, Zeller W (2007) Screening rhizobacteria for biological control of *Ralstonia solanacearum* in Ethiopia. Biol Control 42:336–344

Lioussanne L, Jolicoeur M, St-Arnaud M (2008) Mycorrhizal colonization with *Glomus intraradices* and development stage of transformed tomato roots significantly modify the chemotactic response of zoospores of the pathogen *Phytophthora nicotianae*. Soil Biol Biochem 40:2217–2224

Lopez-Escudero FJ, Mercado-Blanco J (2011) Verticillium wilt: a case study to implement an integrated strategy to control a soil-borne pathogen. Plant Soil 344:1–50

Lugtenberg BJ, Dekkers L, Bloemberg GV (2001) Molecular determinants of rhizosphere colonization by Pseudomonas. Annu Rev Phytopathol 39:461–490

Lwin M, Ranamukhaarachchi SL (2006) Development of biological control of Ralstonia solanacearum through antagonistic microbial populations. Int J Agri Biol 8:657–660

Manici LM, Caputo F, Baruzzi G (2005) Additional experiences to elucidate the microbial component of soil suppressiveness towards strawberry black root rot complex. Ann Appl Biol 146:421–431

Marschner H (1995) Mineral nutrition of higher plants. Academic Press, London, UK

Mazzola M (2004) Assessment of soil microbial community structure for disease suppression. Annu Rev Phytopathol 42:35–59

Mazzola M, Gu YH (2000) Impact of wheat cultivation on microbial communities from replant soils and apple growth in greenhouse trials. Phytopathol 90:114–119

Mendes R, Kruijt M, de Bruijn I, Dekkers E, van der Voort M, Schneider JHM, Piceno YM, DeSantis TZ, Andersen GL, Bakker PAHM, Raaijmakers JM (2011) Deciphering the rhizosphere microbiome for disease-suppressive bacteria. Science 332:1097–1100

Mendes R, Garbeva P, Raaijmakers JM (2013) The rhizosphere microbiome: significance of plant beneficial, plant pathogenic, and human pathogenic microorganisms. FEMS Microbiol Rev 37:634–663

Minuto A, Spadaro D, Garibaldi A, Gullino ML (2006) Control of soilborne pathogens of tomato using a commercial formulate of *Streptomyces griseoviridis* and solarization. Crop Prot 25:468–475

Moonen AC, Barberi P (2008) Functional biodiversity: an agroecosystem approach. Agr Ecosyst Environ 127:7–21

M'Piga P, Belanger RR, Paulitz TC, Benhamou N (1997) Increased resistance to *Fusarium oxysporum f. sp. radicis-lycopersici* in tomato plants treated with the endophytic bacterium *Pseudomonas fluorescens* strain 63–28. Physiol Mol Plant Pathol 50:301–320

Myresiotis CK, Karaoglanidis GS, Vryzas Z, Papadopoulou-Mourkidou E (2012) Evaluation of plant growth promoting rhizobacteria, acibenzolar-S-methyl and hymexol for integrated control of Fusarium crown and root rot on tomato. Pest Manag Sci 68:404–411

Navarette M, Tchamitchian M, Aissa Madani C, Collange B, Taussig C (2010) Elaborating innovative solutions with experts using a multicriteria evaluation tool. ISDA, Montpellier

Navarrete M, Collange B, Montfort F, Mateille T, Tavoillot J, Martiny B, Tchamitchian M (2013). Alternative cropping systems can have contrasting effects on various soil-borne diseases: relevance of a systemic analysis in vegetable cropping systems. Crop Prot. (in press)

Neumann G, Timothy SG, Plassard C (2009) Strategies and methods for studying the rhizosphere – the plant science toolbox. Plant Soil 321:431–456

Nguyen MT, Ranamukhaarachchi SL (2010) Soil-borne antagonists for biological control of bacterial wilt disease caused by *Ralstonia Solanacearum* in tomato and pepper. J Plant Pathol 92:395–406

Nion AA, Toyota K (2008) Suppression of bacterial wilt and fusarium wilt by a *Burkholderia nodosa* strain isolated from Kalimantan soils, Indonesia. Microbes Environ 23:134–141

Nowak J, Shulaev V (2003) Priming for transplant stress resistance in in vitro propagation. In vitro Cell Dev-Pl 39:107–124

Oerke EC (2006) Crop losses to pests. J Agric Sci 144:31–43

Oka Y (2010) Mechanisms of nematode suppression by organic soil amendments-a review. Appl Soil Ecol 44:101–115

Posas MB, Toyota K (2010) Mechanism of tomato bacterial wilt suppression in soil amended with lysine. Microbes Environ 25:83–94

Posas MB, Toyota K, Islam TMD (2007) Inhibition of bacterial wilt of tomato caused by *Ralstonia solanacearum* by sugars and amino acids. Microbes Environ 22:290–296

Postma J, Schilder MT, Bloem J, van Leeumen-Haagsma WK (2008) Soil suppressiveness and functional diversity of the soil microflora in organic farming systems. Soil Biol Biochem 40:2394–2406

Pozo MJ, Azcon-Aguilar C (2007) Unraveling mycorrhiza-induced resistance. Curr Opin Plant Biol 10:393–398

Prasanna R, Chaudhary V, Gupta V, Babu S, Kumar A, Shivay YS, Nan L (2013) Cyanobacteria mediated plant growth promotion and bioprotection against Fusarium wilt in tomato. Eur J Plant Pathol 136:337–353

Prithviraj B, Zhou X, Souleimanov A, Kahn WM, Smith D (2003) A host-specific bacteria-to-plant signal molecule (Nod factor) enhances germination and early growth of diverse crop plants. Planta 216:43–445

Raaijmakers JM, Paulitz TC, Steinberg C, Alabouvette C, Moënne-Loccoz Y (2009) The rhizosphere: a playground and battlefield for soilborne pathogens and beneficial microorganisms. Plant Soil 321:341–361

Radwan MA, El-Maadawy EK, Kassem SI, Abu-Elamayem MM (2009) Oil cakes soil amendment effects on *Meloidogyne incognita*, root-knot nematode infecting tomato. Arch Phytopathol Plant Prot 42:58–64

Ren L, Lou Y, Sakamoto K, Inubushi K, Amemiya Y, Shen Q, Xu G (2010) Effects of arbuscular mycorrhizal colonization on microbial community in rhizosphere soil and Fusarium wilt disease in tomato. Com Soil Sci Plan 41:1399–1410

Rengel Z, Marschner P (2005) Nutrient availability and management in the rhizosphere: exploiting genotypic differences. New Phytol 168:305–312

Rumbos CI, Mendoza A, Sikora R, Kiewnick S (2008) Persistence of the nematophagous fungus *Paecilomyces lilacinus* strain 251 in soil under controlled conditions. Biocontrol Sci Technol 18:1041–1050

Ryan PR, Dessaux Y, Thomashow LS, Weller DM (2009) Rhizosphere engineering and management for sustainable agriculture. Plant Soil 321:363–383

Shiomi Y, Nishiyama M, Onizuka T, Marumoto T (1999) Comparison of bacterial community structures in the rhizoplane of tomato plants grown in soils suppressive and conducive towards bacterial wilt. Appl Environ Biol 65:3996–4001

Srivastava R, Khalid A, Singh US, Sharma AK (2010) Evaluation of arbuscular mycorrhizal fungus, fluorescent *Pseudomonas* and *Trichoderma harzianum* formulation against *Fusarium oxysporum f. sp. lycopersici* for the management of tomato wilt. Biol Control 53:24–31

Steinkellner S, Mammerler R, Vierheilig H (2008) Germination of *Fusarium oxysporum* in root exudates from tomato plants challenged with different *Fusarium oxysporum* strains. Eur J Plant Pathol 122:395–401

Sturz AV, Christie BR, Nowak J (2000) Bacterial endophytes: potential role in developing sustainable systems of crop production. Crit Rev Plant Sci 19:1–30

Taïwo LB, Adebayo DT, Adebayo OS, Adediran JA (2007) Compost and *Glomus mosseae* for management of bacterial and Fusarium wilts of tomato. Int J Veg Sci 13:49–61

Tan H, Zhou S, Deng Z, He M, Cao L (2011) Ribosomal sequence-directed selection for endophytic streptomycete strains antagonistic to *Ralstonia solanacearum* to control tomato bacterial wilt. Biol Control 59:245–254

Tan S, Jiang Y, Song S, Huang J, Ling N, Xu Y, Shen Q (2013) Two Bacillus amyloliquefaciens strains isolated using the competitive tomato root enrichment method and their effects on suppressing *Ralstonia solanacearum* and promoting tomato plant growth. Cop Prot 43:134–140

Tchamitchian M, Collange B, Navarrete M, Peyre G (2011) Multicriteria evaluation of the pathological resilience of in-soil vegetable protected cropping systems. Acta Hortic 893:1239–1246

Tomich TP, Brodt S, Ferris H, Galt R, Horwath WR, Kebreab E, Leveau J, Liptzin D, Lubell M, Merel P, Michelmore R, Rosenstock T, Scow K, Six J, Williams N, Yang J (2011) Agroecology: a review from a global-change perspective. Ann Rev Environ Resour 36:193–222

Trenbath BR (1976) Plant interactions in mixed crop communities. In: Papendick RI, Sanchez PA, Triplett GB (eds) Multiple cropping. ASA, SSSA, CSSA, Madison, 27:129–169

Utkhede R (2006) Increased growth and yield of hydroponically grown greenhouse tomato plants inoculated with arbuscular mycorrhizal fungi and Fusarium oxysporum f. sp. radicis-lycopersici. Biocontrol 51:393–400

Validov S, Kamilova F, Qi S, Stephan D, Wang JJ, Makarova N, Lugtenberg B (2006) Selection of bacteria able to control *Fusarium oxysporum* f. sp. *radicis lycopersici* in stonewool substrate. J Appl Microbiol 102:461–471

Van Bruggen AHC, Semenov AM (2000) In search of biological indicators for soil health and disease suppression. Appl Soil Ecol 15:13–24

Van der Heijden MGA, Bardgett RD, van Straalen NM (2008) The unseen majority: soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. Ecol Lett 11:296–310

Van Tol RWHM, Van Der Sommen ATC, Boff MIC, Van Bezooijen J, Sabelis MW, Smits PH (2001) Plants protect their roots by alerting the enemies of grubs. Ecol Lett 4:292–294

Verbruggen E, van der Heijden M, Rillig MC, Kiers ET (2012) Mycorrhizal fungal establishment in agricultural soils: factors determining inoculation success. New Phytol 197:1104–1109

Wachira PM, Kimenju JW, Okoth SA, Mibey RK (2009) Stimulation of nematode-destroying fungi by organic amendments applied in management of plant parasitic nematode. Asia J Plant Sci 8:153–159

Wei Z, Yang XM, Yin SX, Shen QR, Ran W, Xu YC (2011) Efficacy of Bacillus-fortified organic fertiliser in controlling bacterial wilt of tomato in the field. Appl Soil Ecol 48:152–159

Wei Z, Huang JF, Tan SY, Mei XL, Shen QR, Xu YC (2013) The congeneric strain *Ralstonia pickettii* QL-A6 of *Ralstonia solanacearum* as an effective biocontrol agent for bacterial wilt of tomato. Biol Control 65:278–285

Welbaum GE, Sturz AV, Dong Z, Nowak J (2004) Managing soil microorganisms to improve productivity of agro-ecosystems. Crit Rev Plant Sci 23:175–193

Weller DM, Raaijmakers JM, Gardener BBM, Thomashow LS (2002) Microbial populations responsible for specific soil suppressiveness to plant pathogens. Annu Rev Phytopathol 40:309–348

Wicker E, Grassart L, Coranson-Beaudu R, Mian D, Guilbaud C, Fegan M, Prior P (2007) *Ralstonia solanacearum* strains from Martinique (French West Indies). Exhibiting a new pathogenic potential. Appl Environ Microbiol 73:6790–6801

Widnyana IK, Suprapta DN, Sudana IM, Temaja IGRM (2013) *Pseudomonas alcaligenes*, potential antagonist against *fusarium oxysporum f. sp. lycopersicum* the cause of fusarium wilt disease on tomato. J Biol Agric Health 3:163–169

Wissuwa M, Mazzola M, Picard C (2009) Novel approaches in plant breeding for rhizosphere-related traits. Plant Soil 321:409–430

Wu H, Pratley J, Lemerle D, Haig T (2001) Allelopathy in wheat (*Triticum aestivum*). Ann Appl Biol 139:1–9

Xue QY, Ding GC, Li SM, Yang Y, Lan CZ, Guo JH, Smalla K (2013) Rhizocompetence and antagonistic activity towards genetically diverse *Ralstonia solanacearum* strains – an improved strategy for selecting biocontrol agents. Appl Microbiol Biotech 97:1361–1371

Yu JQ (1999) Allelopathic suppression of *Pseudomonas solanacearum* infection of tomato (*Lycopersicon esculentum*) in a tomato-Chinese chive (*Allium tuberosum*) intercropping system. J Chem Ecol 25:2409–2417

Zhu HH, Yao Q (2004) Localized and systemic increase of phenols in tomato roots induced by *Glomus versiforme* inhibits *Ralstonia solanacearum*. J Phytopathol 152:537–542

Agroecological Resources for Sustainable Livestock Farming in the Humid Tropics

Harry Archimède, Gisèle Alexandre, Maurice Mahieu, Jérôme Fleury, Dalila Petro, Gary W. Garcia, Audrey Fanchone, Jean-Christophe Bambou, Carine Marie Magdeleine, Jean-Luc Gourdine, Eliel Gonzalez, and Nathalie Mandonnet

Abstract Agroecological farming practices require a change in the evaluation and management of plant and animal resources. The goal is to increase the feed self-sufficiency of farms to reduce the negative environmental footprint linked to imported feed. There is a very large diversity of potentially valuable biomass for livestock. The profile of available feeds depends on the characteristics of farms, that is livestock farm versus mixed crop-livestock farm. Whatever the degree of farm specialisation, plant resources should be adapted to soil and climatic conditions in order to reduce inputs such as water, fertilisers and pesticides. Dual crops, that is food and feed, are strategic resources. In mixed farming systems, co-products from these dual crops should be valued as a first step before the incorporation of specialised feeds in the livestock diet. The choice of feeds, as well as the cultures, must be reasoned upon several criteria: multi-functionality, feed value, and environmental impact.

H. Archimède (✉) • G. Alexandre • M. Mahieu • A. Fanchone • J.-C. Bambou
C.M. Magdeleine • J.-L. Gourdine • N. Mandonnet
INRA, UR143, Unité de Recherches Zootechniques,
Domaine Duclos Prise d'eau, 97170 Petit-Bourg, Guadeloupe (FWI), France
e-mail: Harry.Archimede@antilles.inra.fr

J. Fleury
INRA, UE1294 Plateforme Tropicale de recherche sur l'Animal,
Domaine Duclos Prise d'eau, 97170 Petit-Bourg, Guadeloupe (FWI), France

D. Petro
INRA, UR01321, Unité de Recherches des AgroSystèmes Tropicaux,
Domaine Duclos Prise d'eau, 97170 Petit-Bourg, Guadeloupe (FWI), France

G.W. Garcia
UWI, Faculty of Food and Agriculture, University of the West Indies,
St. Augustine, Trinidad and Tobago

E. Gonzalez
INRA, UMR0868 Systèmes d'Elevage Méditerranéens et Tropicaux,
2 place Viala, F-34060 Montpellier, France

H. Ozier-Lafontaine and M. Lesueur-Jannoyer (eds.), *Sustainable Agriculture Reviews 14: Agroecology and Global Change*, Sustainable Agriculture Reviews 14,
DOI 10.1007/978-3-319-06016-3_9,

A major principle of agro-ecology is the use of animal species and genotypes adapted to their environmental conditions rather than adapting breeding conditions regarding livestock susceptibility. This contributes to the survival of animals and their welfare, their overall productivity, and the reduction of inputs. The choice of animal species should be conditioned by the characteristics of the biomass available on the farm and the greater or lesser efficiency of the species regarding this biomass. A compromise between productivity and adaptation capacity is then required. Within a species, the choice of genotype will depend on its adaptation to the different potential stresses of the humid tropical environment, such as temperature, humidity, diseases and feed quality. In an agroecological approach, qualities required of the right animal include: acceptability to farmers; adaptation to environments including climatic, nutritional and management; resistance to the common diseases of the area; and good reproductive and growth performances.

Keywords Crops • Livestock • Agroecology

Introduction

As in the North, the green revolution in humid tropics was based on specialised farms using "improved" genotypes of crops and livestock, and a high amount of inputs. The main difference was probably the gap between the theoretical potential of resources (crops and livestock) and the performances observed, because of the depressive effect of the environment. The agro-ecology concept has mainly been developed for the crop farming system and has existed as an on-going concept for the livestock farming system. However, agro-ecology practices have been implemented in low input farming under the tropics (Herrero et al. 2010) and recently some authors have theorised the application of agro-ecology in livestock systems (Preston 2009; Thornton 2010; Altieri and Nicholls 2012; Dumont et al. 2013). The development of agro-ecology in humid tropical areas must take into account the specificities of this environment. The climate (temperature, humidity) impacts heavily and often negatively on the main biological functions of plants and animals, such as photosynthesis, thermoregulation, reproduction and nutrition. (Thornton et al. 2009). In addition, in the humid tropics, there is a high prevalence of many diseases for plants and animals (Mandonnet et al. 2011). Agro-ecology should also anticipate new constraints linked to global warming (Thornton 2010).

Management of plant and animal resources in an agro-ecological approach involves taking into account numerous criteria including: the preservation of biodiversity; promotion of the multi-functionality of plants and livestock; proper management of plants and animals taking into account the constraints of the breeding environment and the multi-functionality of resources; trade-off between the physiological functions of adaptation to the environment and productive functions; and finally the economics of agricultural inputs, including water. Management must also evolve to be more consistent in using the logic of efficiency rather than maximisation. This involves choices that include policies of genetics, nutrition and reproduction.

Agro-ecology implies the autonomy of farms in feeding livestock in order to reduce the environmental cost of animal products. Feed self-sufficiency must be achieved in a competitive context for the use of land to feed humans and animals. Land requirements for livestock products vary largely: 1–2, 4–7, 5–7, 6–8, 15–45 m^2 per kg product for milk, egg, broiler, pork, and beef, respectively (Hermansen et al. 2013). The environmental impacts of livestock production also vary greatly. Thus, in an agro-ecological approach, the classical mono-criterion evaluation of plants should be substituted for a multi-criteria evaluation for multiple uses of biomass on farms. The concept of food feed fuel is on-going (Preston 2009, see also Chap. 2 by Preston and Rodriguez in this book).

The objective of this paper is to identify and discuss components of strategies for managing plants and livestock for animal production in humid tropical areas following an agro-ecological approach.

Enhancement of the Plant Biodiversity and Biomass Available on Farms

Livestock convert vegetal biomass into animal products such as meat and milk with variable yields (2.5–30 kg DM/kg of meat), according to the animal species and feed used. Biomasses are valued by livestock with different environmental impacts. In the humid tropics, livestock are localised on specialised farms or mixed crop-livestock farms which are more or less integrated (Herrero et al. 2010). The potential to feed animals is closely related to the profile of crops on these farms. Some biomasses, coming from dual plants, are not produced specifically for livestock but exist because of the presence of crops for human food or industries. The valuation of these biomasses is strategic; it helps reduce the concurrency of land utilisation between food-crops and livestock. It contributes to intensifying land utilisation without input increase. Further, the development of such resources (dual plants) is an important lever for agro-ecology in farms.

The supply of some amino acids to humans can be partially achieved by some food-crops (e.g., grain-legumes). The efficiency of production of these amino acids is higher than that from livestock. This supports a holistic approach to food-crop and livestock production to produce proteins for human consumption. The optimisation of land use (food-crops versus animals-feed) could include a protein-livestock/protein-vegetable ratio consistent with nutrition and human health.

Agro-ecology must take into account: (1) the seasonal variability in biomass and feed availability; and (2) the high environmental cost of seasonal breeding strategies (e.g., irrigation, GMO) which is not based on the valuation of indigenous biodiversity and those appropriate resources for an agro-climatic production environment.

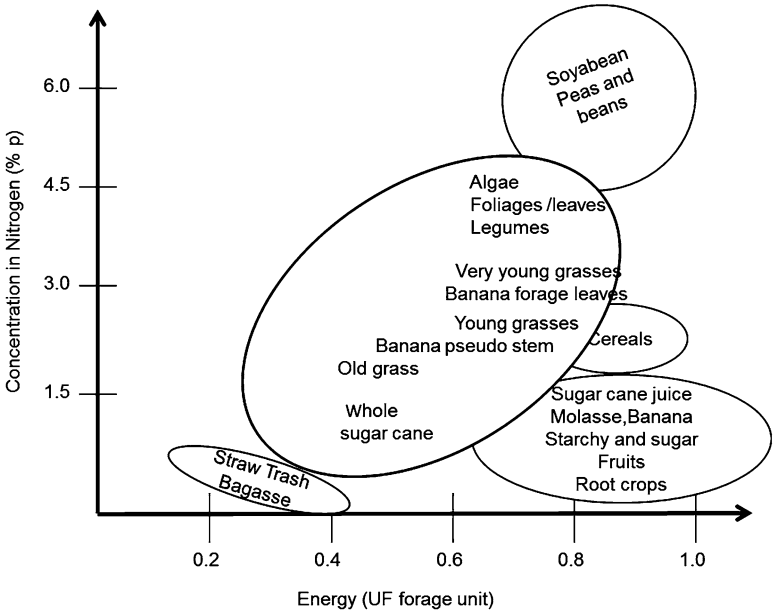


Fig. 1 Diversity of plant resources valuable par livestock

Feeds and Biodiversity

There is a large diversity of resources available for animal feed, as illustrated in Fig. 1 (Wanapat 2009; Archimède et al. 2011b). These resources can be classified as: (1) feed consumable only by livestock; (2) feed consumable by humans or livestock; and (3) co-products of crops or agro-industries. These products could also be classified as: (1) wild resources vs. breeding resources; (2) conventional resovurces vs. unconventional resources; and (3) specialised resources vs. multi-use resources (feed, food, energy). The chemical composition of resources largely varies inside and inter groups of resources, illustrating the diversity of management (or technology treatment) and product characteristics. Taking into account an agro-ecological point of view, advantages and disadvantages could be reported for each resource. The ideal resources use low inputs, have low impact on land use, low environmental impact and have high feed value.

Feeds Consumable Only by Livestock

Feed used only by livestock does not compete with human food from a nutritional point of view. However, competition can exist on land use unless the latter is not cultivable (very rough surface, thin soils, low rains). This family of biomass includes herbs (grasses and legumes), crop co-products and co-products of the agro-industry. These products are often characterised by the high level of fibre consumed mainly by ruminants.

Grass

Tropical grasses are C4 plants adapted to warm environments. There is a great diversity of tropical grasses. They are found both in spontaneous dry savannah grassland and intensive grassland in humid areas. They are adapted to different environments of soil and rainfall (Sotomayor and Pitman 2001). The productivity of grasses, 5–30 ton/dry matter/ha/year, largely varies depending on environmental conditions, level of inputs and plant species. Cultivated grasslands are generally based on less than 20 breeding grasses. Selection has been based on productivity, long durability and nutritional value (Roberge and Toutain 1999).

The areas occupied by native grasses are seven times higher than the breeding grasses. These native grasses are widely present in inadequate or marginal areas for crops because of low rains and soil characteristics. Grasslands have the ability to store almost as much carbon as forests and cultivated areas (Blanfort et al. 2011). Some strategic grasses, like sugarcane, provide a high carbon sink. Moreover, sugarcane enriches the soil with organic matter and it is a strategic plant in crop rotations (tubers, cereals, vegetable crops). In terms of water consumption, growth of sugarcane biomass occurs during the 6 months corresponding to the rainy season. After, there is an accumulation of sugars that contribute to maintaining its nutritional value. Sugarcane, the most productive crop, is also an energy bank for livestock in production systems with dry season shortages (Picture 1).

Herbaceous Legumes

Herbaceous legumes are on average richer in protein than grasses, while the energy value is lower (Minson 1990). Productivity of herbaceous legumes is 12–24 ton dry matter/ha/year, depending on environmental conditions, level of inputs, and plant species. Comparative to grasses, which are characterised by adaptation to widely contrasting environments, herbaceous legumes are adapted to more localised and specific biotope (Sotomayor and Pitman 2001). Legumes are a strategic resource for agro-ecological livestock production because they have multiple functions, including saving soil nitrogen. The production of methane from ruminants consuming legumes is lower than that of animals ingesting grass (Tiemann et al. 2008; Beauchemin et al. 2009). The potential of legumes to reduce methane production comes from the presence of secondary compounds (tannins, saponins) (Rochefort et al. 2008; Archimede et al. 2011a). These secondary metabolites are also strongly present in some leaves of trees and shrubs that give their anthelmintic properties (Marie-Magdeleine et al. 2010). Many other positive breeding properties are associated with these secondary metabolites (Rochefort et al. 2008).

Picture 1 Creole cattle of Guadeloupe on pasture. In the background, a sugarcane crop used as an energy bank to enter the dry season. Like numerous native livestock, Creole cattle has good productivity in good feeding condition

Fibrous Co-products

Fibrous co-products of food-crops, dual plant, are valuable to herbivores, especially ruminants. Fibrous co-products are a heterogeneous group of feed. Their feed value varies greatly within and between resources. Straws (cereals, sugar cane), the most abundant fibrous co-products, are characterised by a low energy and protein value, low vitamin and mineral content, and low intake and digestibility. When straws are the only ingredient in the diet, maintenance requirements by adult ruminants are covered. Rice straw differs from that of other cereals by its low lignin content and high silica content (Van Soest 2006). The leaf/stem ratio of straw highly influences its feed value. This ratio varies with growing conditions, species and varieties. Supplementation (energy, nitrogen and mineral) of straws is useful to increase ruminant performance.

Some fibrous co-products are much richer than the straws. For example, sweet potato, foliage leaves of cassava, groundnut foliage, and seed-legume foliage; after harvesting the tubers or seeds are similar to that of herbaceous legumes. Some resources, such as cassava, however, can require wilting to eliminate anti-nutritional factors. These co-products are available on mixed crop-livestock systems. The availability of fibrous co-products can be up to 5 ton dry matter/ha of crop. There are many potential uses of fibrous byproducts causing some pressure on this resource. They can be valued as organic mulch, bedding for animals, and biomass for energy production at the farm. Some highly lignified biomasses are preferentially used for energy production, such as sugarcane bagasse, and woody fraction of cassava foliage.

Cassava and sweet potato leaves are rich in protein and total essential amino acids content in the protein. Dry cassava leaves and sweet potato vines can replace 70 % of the crude protein from fish meal in diets and provide 35 % of the total crude protein without a depressive effect on the performance (450 g/day) and carcass traits of the Large White × Mong Cai pigs in Central Vietnam (Preston 2006).

Tree and Shrub Foliage

Trees and shrubs are multi-use plants that provide great interest from agro-ecological perspectives. They help to recycle nutrients (nutrient uptake in the deep soil horizons provided to the surface via the decomposition of leaves). These trees are carbon sinks and thus contribute to the fight against greenhouse gasses. They protect the soil against erosion from water and wind.

Tree and shrub foliage used as animal feed originates from a large botanical diversity (Speedy and Pugliese 1992). Generally the foliage is mostly used in very small farms, "cut and carry" following scenarios from dry season to permanent feed. Foliage is high value feed, often used as a supplement (protein and minerals) for poor roughage (Patra 2008, 2009). The optimal use of leaves is based on fractionation of biomass in two parts: digestible fraction (consumed by livestock) and indigestible fraction that can be converted into energy by various methods including firewood and pyro-combustion.

Apart from providing feed for the animals, trees and shrubs have other functions: fencing materials and construction, sources of pharmacological molecules and other foods (fruits) for humans, green manure and mulch, shelter and shade, habitat for wildlife, and landscape value.

Among the fodder trees, mulberry foliage (*Morus alba*) is largely used for ruminants and monogastric animals (Sanchez 2002). The protein content is high (15–28 % depending on the variety) in the leaves and young stems, with a good essential amino acid profile. No anti-nutritional factors or toxic compounds have been reported. Mineral content is high. The leaves are used as supplements, replacing concentrates for dairy cattle, providing a main feed for goats, sheep and rabbits and as an ingredient in monogastric diets (Leterme et al. 2009). Recently, in a study of the intake and digestion of several foliages, Régnier (2011) concluded that, due to their high fill unit and low digestibility, their contribution should not exceed 25 % of the total dry matter intake in growing pigs to avoid penalising their growth. Non-protein nitrogen, usable by pigs, contributes 25–30 % of the total nitrogen content in the foliages. The digestibility of amino acids varied from 15 to 45 %. Leterme et al. (2009, 2010) concluded similarly, but indicated that compared to growing pigs, sows were better at digesting these resources.

Aquatic Plants

Several aquatic plants such as duckweed (monocotyledon), azolla and salvinia (ferns), spirulina (algae) can be used in animal feed. Duckweeds (*Lemna* spp.) are small floating aquatic plants found worldwide. They are monocotyledons of the botanical family Lemnaceae and form dense mats over large areas of the water surface. Duckweeds are free-floating and do not have stems or typical leaves. The protein content of duckweed varies; in the sewage water of Australia, the protein content of duckweed increased from 20–25 to 35–40 % in dry matter when N in the water increased from <5–15 mg/l (Leng et al. 1995). In this same trial, the yields of duckweed dry matter were in the range of 10–30 tons/ha/year, equivalent to protein yields of duckweed as high as 10 tons/ha/yr. Duckweed can be used as a non-conventional protein source to completely replace soya bean meal and could be the sole source of protein in diets – with cassava meal and sugar – for ducks (Anh and Preston 1997).

Biomasses Consumable by Humans and Livestock

The Energy-Rich Foods on the Farm: Grains Versus Tubers

Maize and sorghum grains are the main cereals used in animal feed. They are introduced in animal diets because of their high energy value and average protein value. Maize accounts for 50–70 % of the main components of industry formulated major livestock feed. Maize and sorghum are C4 grasses, well adapted to the tropical area. However, maize in particular has become the main crop for the intensification of livestock feeding system production in the tropics, as in temperate areas. In the absence of this crop, maize is imported with a negative carbon footprint. In Africa and other tropical areas, cereals such as maize and sorghum grain are also strategic ingredients for human food. Consequently, there is contention regarding the use of such resources to feed animals or humans. Moreover, intensive single-cereal farming, as in the North, is unsustainable even with genotypes adapted to tropical areas; maize and sorghum require high inputs of water, fertilisers and pesticides. An alternative could be the integration of cereals in mixed crop systems or a mixed crop livestock system to restore fertility to soils (Preston 1995).

Some alternatives for cereals, such as roots and tubers, starchy fruits, sugarcane and palm oil, have been the subject of experiments in the humid tropics (Machin and Nyvold 1992; Preston 1995; Pérez 1997). The main specificity of these alternative feeds, compared with cereals, is their protein deficiency. Production can reach 5–10 ton dry matter/ha depending on growing conditions. These alternative crops (cassava, sweet potatoes) require lower inputs compared with cereals but the disadvantages of single-crops and competition with human food remains and therefore their sustainability must be questioned (Picture 2).

Picture 2 Brahman cattle feeding unmarketed bananas fruit as an energetic supplement during dry season

Protein-Rich Foods on the Farm: Alternative to Soybeans

Some foliage, seeds and fruits from protein-rich plants are excellent sources of protein (Archimède et al. 2011c). The high efficiency of photosynthesis in the tropics is an asset. In addition, there is a great diversity of such plants rich in proteins which are potentially valuable to animals (Fig. 2). This biodiversity contradicts the low number of resources actually used as feed. Soybean is the main protein source used in animal feed in intensive livestock production and it is also well balanced in amino acids. The mains producers of soybean are localised in a few countries of the world: United States, China, Brazil, and Argentina. The trade of soybean is important on the international market. It is well balanced in protein and energy and can be well valued by livestock. Although soybean is a legume, it is associated with unsustainable crops because of its mode of production. Its development in the South is at the expense of areas occupied by peasant agriculture and forestry. The main soybean varieties cultivated today are genetically modified (GMO). Soybean production is mainly in single crop and is accompanied by high water consumption and pesticides.

Protein-rich foods/feeds could be defined as resources containing more than 20 % protein/dry matter. However, the value of a resource is not based only on its content of protein, the amino acid profile and digestibility are also key factors. Tropical biodiversity contains many resources, legumes or otherwise, with protein contents ranging from

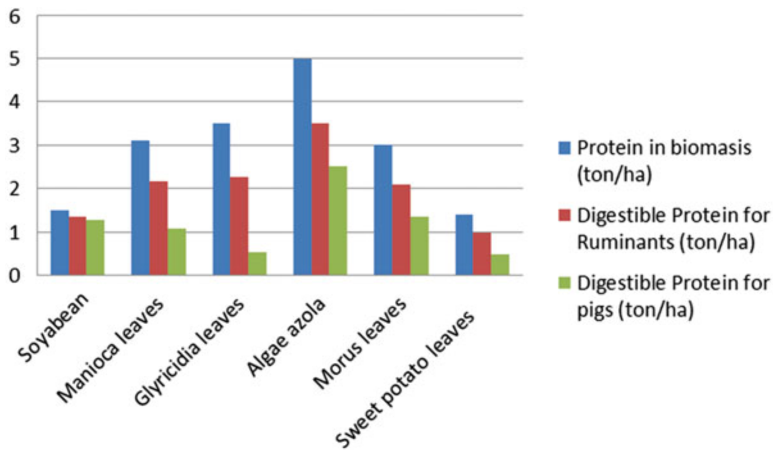


Fig. 2 Comparative digestion of protein of some protein-rich plants (Archimède et al. 2011c)

20 to 50 % protein (Mekbungwan 2007). The presence or absence of anti-nutritional elements must be taken into account. The main anti-nutritional factors in legumes are protease inhibitors, lectins and tannins. Some non-starch polysaccharides may also penalise the feed value. Technological treatments, before consumption, are sometimes useful to destroy anti nutritional factors and increase the feed value. Seed legume are also consumed by humans and livestock. The high cost of seeds on local markets sometimes disqualifies them as feed. Legumes, soybeans and peanuts occupy a special position because their co-product (meal) can be used by animals after oil extraction.

The target animal species that may be considered regarding the use of plants such as soybean as an alternative resource are very variable because of the specific features of their digestive physiologies. The ability of some animal species (i.e. ruminants) to digest fibre and synthesise some essential amino acids because of the presence of a large microbial population in their digestive tract gives them a clear advantage. Consequently, differences have to be considered between herbivores (ruminants, horses, rabbits) and other animal species (i.e. non-ruminants or mono-gastrics like pigs or poultry). Globally, herbivores are able to valorise all plant fractions (foliage, seeds and fruits). Non-herbivores will be able to valorise mainly seeds, fruits and low fibre content foliage.

Forage and Crop Management

Forage

Plant management determines the quantity and quality of the biomass produced. On grassland, the productions of forage curvilinearly increase with regrowth age whereas feed quality (protein and energy value) decreases, as illustrated in Fig. 3. Similar impacts of management are reported with dual feed-food plants like cassava and sweet potatoes.

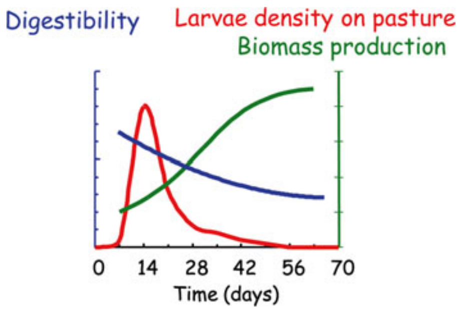


Fig. 3 Relative evolution of biomass production and grass quality (total tract digestibility larvae density) with regrowth age

Cassava and Sweet Potatoes

Cassava and sweet potatoes produce foliage and roots/tubers during a cycle crop. Foliage and roots/tubers can be used as feed for humans and livestock. These crops can be managed for optimising overall production (green leaves, roots or tubers) and adapting the density of plantations and strategies of defoliation (Wanapat 2009). Foliage production of sweet potatoes of 4,2, 5,2, and 4,8 (ton DM/ha) is reported for defoliation at harvest (4 months), at 2 months and harvest, and at 3 months and harvest (Ruiz et al. 1980).

Sugarcane System

Sugarcane is a strategic resource because it is productive and multiuse. If the farm only has ruminants, the whole sugarcane with its leaves can be fed (dry season feeding to ruminants). If pigs or poultry (particularly ducks and geese) are to be fed, it is best to reserve the sugarcane tops with the uppermost quarter of the stalk, which is unripened and has less sugar for the ruminants (Fig. 4), while the juice extracted from the remainder of the stalk will be of higher value and a better feed for pigs.

Banana System

Banana by-products (leaves, pseudostem and nonmarketable fruits) are potential feed resources for livestock. Alternative farming systems with the purpose of transforming monoculture banana farms into mixed farming systems with ruminants, feeding banana by-products and forage from the fallow land, have been tested using a mechanistic model (Archimède et al. 2012). One hectare monoculture shifted into a mixed farming system allows a stocking rate of 1,184, 285, and 418 kg of live weight per hectare for cattle, goats and sheep, respectively (Fig. 5).

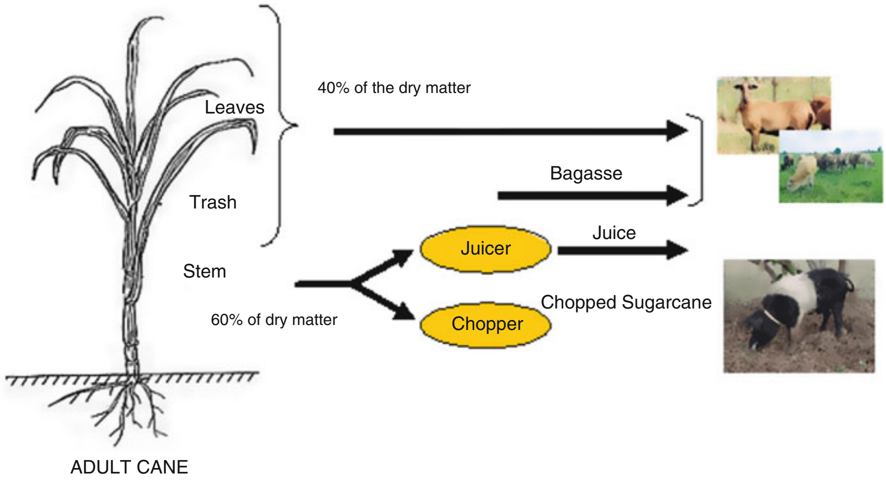


Fig. 4 Fractionning sugar cane to feed ruminants and non ruminants livestocks

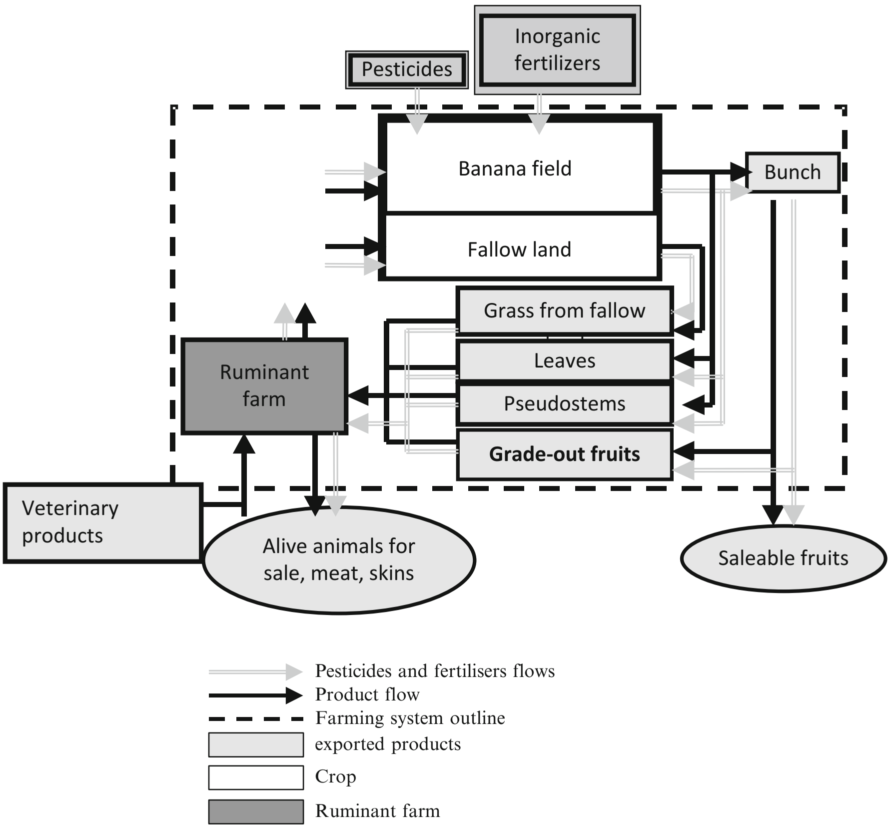


Fig. 5 Diagrammatic representation of a mixed farming system based on the integration of banana crops, fallow land and small or large ruminant production (Archimède et al. 2012)

Picture 3 Association of livestock on farm: Feces of poultry (geese, ducks, chickens …) are used as nutrients for aquatic plants eaten by herbivorous fish

Integrated Livestock Fish Crop Farming System, Other Alternative Systems

As in some Asian integrated farming systems, fish species can be included into the cycle with a multi-species breeding approach; fish are fed algae grown with fertiliser from livestock (pork, poultry) excreta. Fish are also consumed by humans or included in livestock diets (Picture 3).

Protein availability can be a diet limiting factor, mainly for non-herbivore livestock. To mitigate this limiting factor, small-scale worm productions are developed for poultry nutrition. Until now, this kind of technology has mainly been associated with small farms.

There is an ongoing concept of the farming of insects for food. The rearing of crickets for human consumption has been developed in Laos, Thailand and Vietnam (Van Huis et al. 2013). The environmental benefits of rearing insects are founded on the high feed conversion efficiency of insects. For example, 1 kg of cricket bodyweight gain requires only 2 kg of feed. Moreover, insects can be reared on organic side-streams, including animal waste. This can help reduce the environmental footprint.

Livestock Adapted to the Environment

Adaptation to the Environment

A major principle of agro-ecology is the use of animal species and genotypes adapted to their environmental conditions rather than adapting breeding conditions regarding livestock susceptibility. This contributes to the survival of animals and/or their welfare, their overall productivity, and the reduction of inputs. The adaptability of an animal is defined by its ability to survive and reproduce within a given environment or the degree to which the animal remains/becomes adapted to a wide range of environments by physiological or genetic means (Mirkena et al. 2010). Under the tropics, livestock often live in harsh environments which may be hot and dry, hot and humid, or cold at high altitudes. Livestock environments can also be characterised by high disease pressure, scarce feed and water resources and by large seasonal and annual variations of resources and diseases. Livestock adaptation to environments is mainly based on genetic mechanisms. Native animals in a breeding environment are often more suitable than introduced exotic animals. Livestock breeds and populations that have evolved over the centuries in diverse, stressful tropical environments have a range of unique adaptive traits (e.g. disease and heat resistance, water scarcity tolerance and the ability to cope with poor quality feed) which enable them to survive and be productive in these environments (Mirkena et al. 2010).

Impact of the Environment on Biological Functions

The stress induced by climate (temperature and humidity) has a direct impact on the welfare of animals, but also depreciates the main biological functions of nutrition, reproduction and lactation. When the temperature rises above the thermo neutral zone (depending on species and genotype) the regulatory mechanisms (thermogenesis reduction/increased thermolysis) are saturated and the animal is no longer able to maintain a constant internal temperature.

In poultry, chronic thermal stress reduces feed consumption 24 % between 22 and 32 °C in broiler chickens between 4 and 6 weeks of age (Geraert et al. 1993). However, the effect of temperature on the decreased feed consumption is curvilinear and is highly correlated to an increase in internal temperature (Picard et al. 1993). A degree of ambient temperature increase between 30 and 35 °C induces reduced consumption four times higher than that observed by the degree of increase between 10 and 20 °C. Similar observations are reported for pigs (Gourdine et al. 2006, 2007).

Under the tropics, with high producing dairy cows, high temperatures and humidity cause decreased survival of gametes, a decrease in fertilisation and a decrease in the survival of embryos during the first two weeks of gestation (Gauthier and Thimonier 1985; Berbigier 1988; Putney et al. 1989). A high decrease of feed intake is also registered (Berbigier 1988).

It is necessary to maintain a balance between the functions of adaptation and production, which are often negatively correlated. According to resource allocation theory (production vs. fitness traits), under selection within a particular environment the resources used by the animal are optimally distributed between traits for breeding and production within that environment (Beilharz et al. 1993). Consequently, any additional selection mediated increase in the performance of a production trait without a concurrent increase in resources, must lead to declines in other traits, due to reallocation of resources (Mignon-Grasteau et al. 2005). In livestock production, negative correlations are observed between production and fitness-related traits, such as fertility and health (Rauw et al. 1998).

Adaptation to Climate

The ability of animal species and genotypes to adapt to climate stress largely varies. Several examples exist throughout the world; concerning cattle, marked genetic distinction is reported between taurine and zebu. Under the humid tropical climate, the Creole cattle support higher temperatures than crossed, because they are more effective at regulating their internal temperature (Gauthier et al. 1984; Mandonnet et al. 2011). The variation of the relative humidity following the season would be a determining factor of thermal discomfort. The greatest adaptation of zebu to high temperatures, compared to taurine, can be explained by hide, skin, hematological characteristics, form, growth, and physiological aspects which are unique genetic attributes compared to Bos Taurus cattle. Zebu cattle are smooth coated, have primary hair follicles, and have better developed sweat and sebaceous glands than Bos Taurus cattle and can lose more moisture by evaporation; hence they have the ability to maintain a thermal equilibrium that is a necessary factor for normal function and performance (Mirkena et al. 2010).

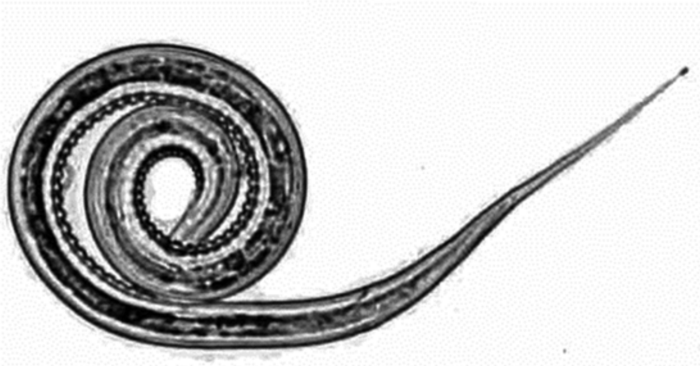
Monogastric smaller animals are generally less sensitive to heat because they have a better relationship surface/volume, which facilitates the removal of body heat by sensitivity (Dauncey and Ingram 1986; Renaudeau et al. 2012). Generally, slow growth animals are less sensitive to heat as fast growth has a relationship with a lower production of metabolic heat (Renaudeau et al. 2012). This effect is explained in the pig by reducing maintenance requirements and the energy cost of filing the body (relative protein deposition/deposit fat) (Noblet et al. 1999). The literature shows that high temperatures decrease intake and growth of pigs and that this effect was more pronounced in heavier pigs (Renaudeau et al. 2011). Some authors comparing pig breeds in similar experimental conditions reported that the productivity of indigenous tropical breeds is generally lower than that of exotic livestock breeds. However, in very harsh conditions (hot climate and/or poor nutritional resources or livestock management), the use of indigenous breeds would likely be most successful in improving production levels (Renaudeau et al. 2012). Cross between thermal tolerance of local breeds and exotic breed can be used in order to improve performance level by taking advantage of specific abilities (Renaudeau et al. 2012). Whatever the species, selection for improved performance has led to increased metabolic heat production, which increases their susceptibility to heat stress. Nevertheless, inside of breeds there is variability for hot tolerance that can be used to select animals with a tradeoff between adaptation and production (Picture 4).

Picture 4 Creole pigs of Guadeloupe. Comparing with an exotic breed (large white), growing Creole pigs are well adapted to hot climate maintaining good performance (500 g average daily gain)

Adaptation to Diseases

The resistance of animals to pathogens of the breeding environment is an important lever for agro-ecological practices. The fight against these pathogens, based on the use of chemical molecules, is expensive. In addition, the developing resistance of pathogens to chemical molecules could lead, in the medium term, to deadlock of some productions. In tropical areas the main diseases are parasitic diseases (endoparasites) and bacterial diseases. There are major diseases prevalent for intra-and inter-species livestock in tropical regions. Many data are reported for herbivores, whereas confined animals in livestock buildings (monogastrics) are less affected by diseases due to the artificial breeding environment (disinfection). However, differences between breeds were highlighted in systems with more extensive husbandry, for example resistant gastrointestinal strongyles in native poultry (Schou et al. 2007; Kaufmann et al. 2010).

The variability of character resistance to disease is often observed when exotic livestock are introduced in traditional breeding areas where the indigenous populations show no apparent pathological signs. This variability between populations is the result of the natural selection to which local populations have been submitted. In livestock, genetic diversity with respect to disease resistance is an important tool. Generally, if a new strain of a disease or a new disease occurs in a country, animals



Picture 5 Gastro-intestinal parasite: *Haemonchus contortus*

with a narrow genetic base may all be affected whereas in genetically diverse livestock, there is an increased chance that some animals will survive, when others die (Mirkena et al. 2010) (Picture 5).

Some native livestock are less affected by worms and ticks than imported ones. Gastrointestinal nematodes are a major pathogen in the tropics. The main mechanisms set up for the host to withstand these endoparasites are intended to prevent the establishment of parasites and/or eliminate the parasite burdens. Many breeds and population of sheep in different tropical regions are resistant to gastrointestinal nematodes: Red Maasai breed in Africa; West African Djallonke sheep; the Garole sheep in India; and Barbados Blackbelly sheep in the Caribbean. The evidence for genetic variation of resistance to endoparasites among goat breeds is more limited. Genetic variation has been reported for resistance by Small East African goats in Kenya (Baker and Gray 2004), and the Creole goat in the French West Indies (Picture 6).

Adaptation to Under Nutrition

In a tropical environment where rainy seasons alternate with dry seasons that are long and characterised by low quantity and quality of pasture, the ability to store fat during favourable seasons, and its subsequent use for maintenance, pregnancy and lactation during unfavourable seasons is an essential strategy for survival (Picture 7).

Some genotypes have developed strategies to adapt to low feed availability: low metabolic requirement, low metabolism, high digestive efficiency, the ability to utilise high-fibre feed, and the deposition of fat as a feed reserve. Adapted tropical genotypes recycle nutrients more efficiently and reduce their basic metabolism during periods of weight loss, compared with improved temperate breeds (Bayer and Feldmann 2003). Requirement per kg weight of body tissue in small mammals, a function of body mass$^{0.75}$, is higher than that in large mammals. Consequently, small mammals cannot meet their metabolic requirements with rich fibre diets. Thus, small

Picture 6 Creole goats of Guadeloupe. Variability of resistance to gastrointestinal strongyles was observed in Creole goats. A breeding program incorporating criteria of productivity, resistance to gastrointestinal strongyles, economic, is underway in Guadeloupe farms

Picture 7 Creole cattle of Guadeloupe are adapted to high temperature and low nutrition. During dry season where grasses availability is low, it may lose up to 20 % weight without affecting its reproductive capacity and weight of calves at birth

ruminants have to balance their comparatively higher energy requirements by eating higher nutritional value feed. However, small desert breeds such as the black Bedouin goat, which is an efficient exploiter of high-fibre low quality roughage, has a lower energy requirement than that predicted from their body mass in comparison to relatives from non-desert areas (Silanikove 1986, 2000).

Some mammals maintain steady body weights under less energy intakes than theoretical requirements. This ability may vary from species to species or among breeds; it is explained by their ability to reduce metabolism. Fed with high quality forage, temperate and desert goats reduce their intake by 20–30 and 50–55 % respectively, without weight loss (Silanikove 2000). A similar capacity to adjust to a low energy intake by reducing energy metabolism exists in zebu cattle and llama (Silanikove 2000). The digestive efficiency of livestock and their ability to utilise high-fibre feed varies between species and genotypes. Goats have better digestive efficiency than other ruminants consuming high-fibre low quality forages because of a longer mean retention time in the rumen (Devendra 1990). Some goat breeds native to semi-arid and arid areas are able to valorise low quality high-fibre feed more efficiently than other types of indigenous or exotic goat breeds (Silanikove et al. 1993).

Management of Livestock

Matching Livestock Species and Available Biomass

In an agro-ecological approach for the tropics, the right animal is not always the one that produces the most. It might not even be a “conventional” species or breed (Wilson 2009) (Picture 8).

Recent policies for protein sovereignty have been based on fast-growing livestock species such as poultry and pigs. However, the feed requirements of these species are close to that of humans. This choice of agricultural policy is probably not optimal in an agro-ecological perspective because it does not allow efficient valorisation of available primary biomass. Within this biomass, there are large amounts of rich fibre resources which are efficiently recoverable by some animal species (Fig. 6). The optimal choice to achieve protein sovereignty is probably a combination of animal species phasing with the characteristics of the primary biomass available.

High-fibre resources (over 35 % NDF) are under valorised by non-herbivore monogastrics; the presence of fibres penalises energy and protein supplies. There are also intra-species differences linked to physiological stages. As an example, compared to growing pigs, adult pigs extract 5–15 % more metabolic energy from high fibre feed due to a more developed distal gut. Among herbivores, rabbits appear as bad cell wall digesters due to a too rapid digestive transit of the diets. Caecotrophy only partially offsets this handicap. Low lignified fibre is easily digested by livestock. In ruminants, microorganisms of the rumen are able to synthesise their own proteins from non-protein sources. Microbial amino acids can cover on average 2/3 of the protein requirements of ruminants. With low quality diets (less than 12 % crude

Picture 8 None conventional livestock (Agouti, Guinea pig, Peccary). Some of these livestock are very productive (Guinea pig) and valorise "low" quality feed

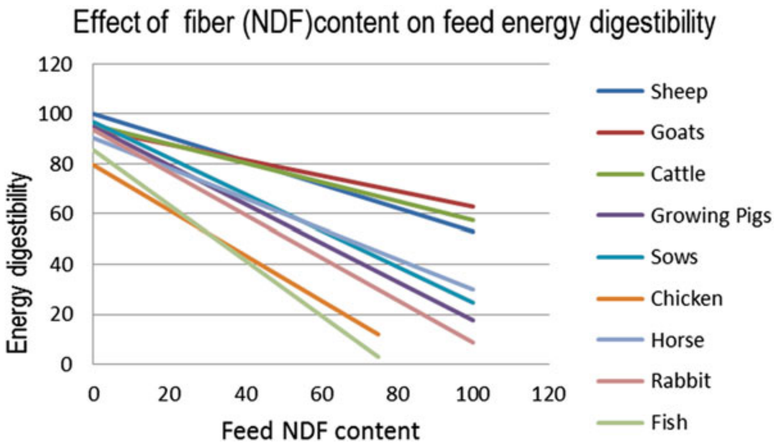


Fig. 6 Effect of fiber (NDF) content of biomass on its digestion by livestock (Modified from Sauvant 2011 in Archimede et al.. 2011a)

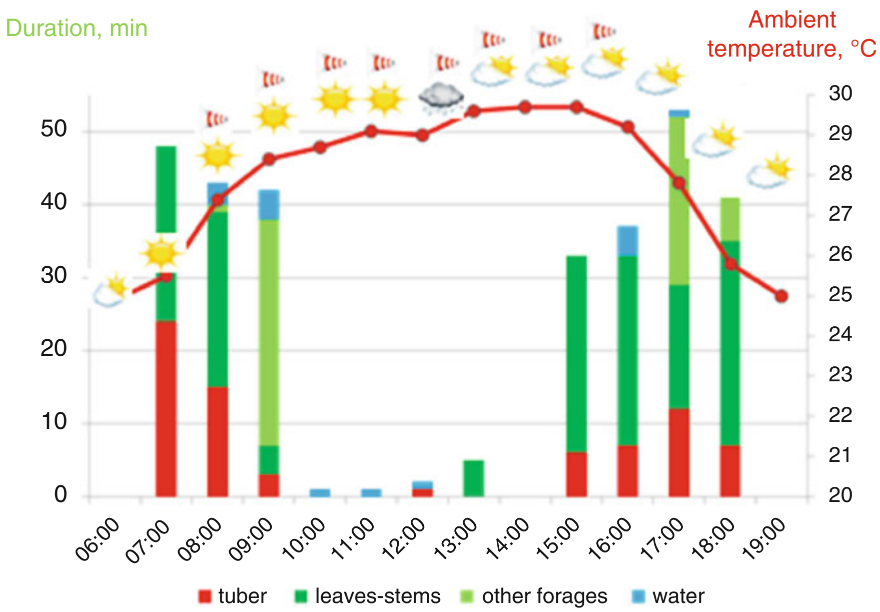


Fig. 7 Native Creole growing pigs daylight behaviour (duration of the consumption of leaves, stems and tubers) on a sweet potato pasture (Burel et al. 2013)

protein), common in the tropics, ruminants are able to recycle significant quantities of urea in the rumen to produce microbial protein (50 g protein per kg DM intake). Beyond a crude protein content of 12 %, less urea recycling occurs in the rumen, increasing nitrogen losses via elimination in the urine.

Animals can adapt to climate by changing their behaviour. Thus ruminants will mainly graze pasture during the fresh hours. Similarly, indoor pigs ingest more during the coolest hours compared to even the hottest hours. Creole pigs initially do well in livestock buildings and outdoor behaviour is adapted to their new environment (Fig. 7) (Burel et al. 2013).

Genetic Policy

Theoretically, there are a great variety of sources of animal protein from non-conventional animals (insects, small rodents) to animals of conventional farming (poultry, rabbits, pigs, ruminants) via fish and seafood. In an agro-ecological approach, qualities required of the right animal are: acceptability to farmers; adaptation to environments (climatic, nutritional, management); resistance to the common diseases of the area; good reproductive and growth performances; adequate yields of meat, milk, draught power and other products in relation to the prevailing management system, feed availability and veterinary services. Genetic policies should take into account and develop local resources rather than relying on the importation of

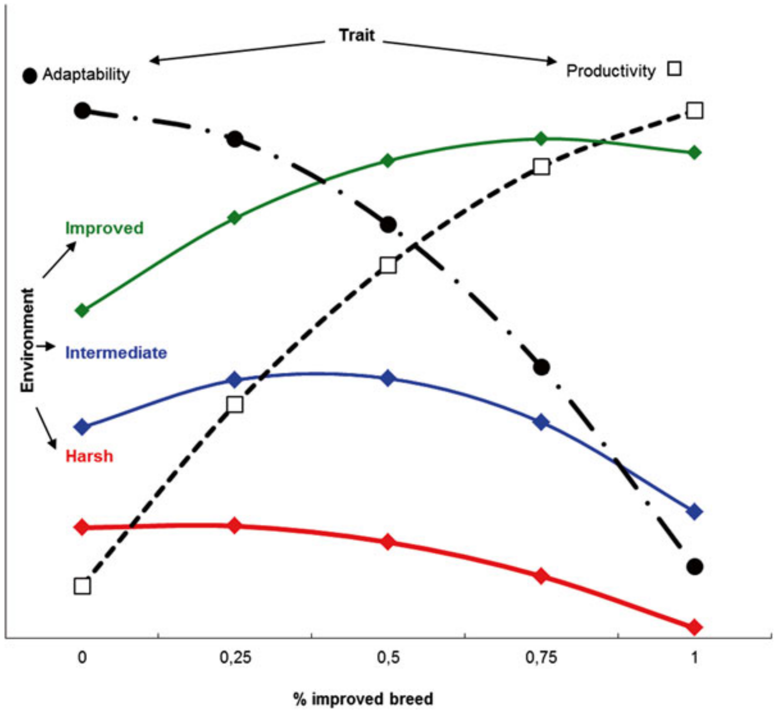


Fig. 8 Trade off between adaptative and productive abilities on improved livestocks depending on production environment

high potential livestock as advised by the green revolution. Agro-ecological strategies in humid areas are partly based on the use of native animal populations (Wilson 2009) and the selection of adaptive genes in the indigenous population or in specialised breeds (Mirkena et al. 2010). Local breeds of tropical areas are reservoirs of genes of high interest for the new challenges, including resistance to diseases and adaptation to stress climate (Hoffmann 2010). Genetic crosses (preserving the parental breeds) between breeds of interest is also a tool of genetic policy but optimum, variable depending on the production environment, must be taken into account (Fig. 8). There are several positive examples of each of these policies in the world.

Milking Production

Milk production in the humid tropics is an important issue in terms of food sovereignty, as the biological lactating function is very sensitive to hot environments. Therefore, the choice of dairy genotypes is an ongoing question. Several strategies have been put in place. In line with the green revolution, highly productive exotic breeds (mainly Holstein and Jersey) have been introduced. Whatever the genotype considered, performances (milk production and fertility of cows) observed were below the genetic potential of these animals. Generally, the best biological efficiency in tropical areas is 4,000–4,500 kg of milk per lactation. Attempts to push yields higher result in low efficiency in the use of feed energy (McDowell 1985). Higher milk productions have been observed by changing the environment, for example, buildings with cooling systems, and feed importation. This strategy is not in line with the agro-ecological approaches because of high input-consumption and non-valued biodiversity of local animals and vegetables.

The second strategy was to create new breeds adapted to hot environments. Several experiences could be reported. Jamaica Hope is a cross of "native" cows of mixed zebu blood, Sahiwal with Jersey bulls. Initially, the Jamaica Hope breed was analysed as a success story. In Jamaica, this breed was successful in low-input farming systems (forage with little supplements). Cows were milked once per day. On the large dairy enterprises, with a stocking rate of five cows per hectare, production was over 17,000 l of milk per hectare with supplementary feed at 0.4 kg per litre of milk. Several herds had averages of over 4,800 l per lactation while individual cows produced over 8,800 l of milk in 305 days, milking twice a day. Longevity and reproductive performance are good even under intensive commercial systems. The average number of lactations is over 5 with calving intervals of less than 13 months. In time, the performances decline because of poor management and feeding and a lack of enthusiasm by breeders. Because of an increase of inbreeding and the reduction of the effective population size a continuous loss of genetic variability was observed.

Other similar experiments were developed in Australia: Australian Friesian Sahiwal, Australian Milking Zebu, Gyr and Guzerat are products of breeding programmes for dairy Zebu breeds in Brazil. Zebu breeds have been selected due to their rusticity, thermo-tolerance, resistance to parasites and great capacity of gross roughage utilisation. Mean milk production of the Gyr and Guzerat cows are 3,300 and 2,200 kg/lactation respectively. The valuation of dual purpose cattle (cross-breeding) is another way to produce meat and milk in an agro-ecological approach. In the humid tropics, in intensive mixed farms especially, such systems enable better use to be made of available resources; they are well understood by farmers (who developed them in the first place) and they satisfy the demand ratio for milk and beef (Preston 1977). Maximum sustained yields from well-managed, fertilised and irrigated tropical pastures are 3,000–3,200 kg of milk. When feed resources are restricted to those that can be provided through forages produced on farms or from grazing natural grasslands and feeding crop residues, coupled with modest concentrate supplementation (<5 kg/day), milk yield is restricted to 2,000–2,500 kg (McDowell 1985).

Feeding Policy

To take into consideration these new challenges of agro-ecology in livestock production it is necessary to develop new concepts to evaluate feeds and the fed animal. Concerning feed value the objective is to optimise compromise between major constraints: (1) efficiency of biomass valuation for animal products and the quality of the products; (2) environmental impact of the use of the biomasses; and (3) impact of the use of biomass on health and animal welfare. In reality, it is to perform a multi-criteria evaluation of feed. Concerning animals, the traditional approach to feeding is to provide the nutrients to cover their production potential. In the agro-ecology approach, the objective is to optimise the use of biomass produced on the farm. Consequently, the objective will be to study multiple responses of live-stock to feeds (production, quality of products, feed efficiency, emissions in the environment, animal health and welfare). Antagonistic responses of livestock to dietary practices could be observed. For example, the welfare of sows increases with the fibre content of the diet whereas the dietary energy content and the animal performance decreases. The concentration of nitrogen in a feed also illustrates some antagonism; a high nitrogen content of diet maximises animal performance simultaneously with increasing emissions of nitrogen in the environment via faeces and urine. New potential responses to feed can be defined for example, in warm areas where the ability of the feed to allow the animal to better fight against the heat would be an important criterion. This would indicate that it is necessary to differentiate between feeds by their ability to induce extra heat, and their capacity to buffer the water balance and minerals related to sweating.

Integrated Management of Environmental Constraints on the Farm

In an agro-ecological approach the goal is to optimize the efficiency of production system. Consequently all the constraints have to be managed in an integrated approach and their control in the system must rely on various methods. Firstly the breeding environment can be managed to reduce some depressive effects. For example, agroforestry creates a microclimate that can reduce the depressive effect of heat on the production of livestock. In addition, herbaceous biomasses produced in this environment have better nutritional value than those grown under the direct effect of climate. Feeding small ruminants on shrub pasture rather than on herbaceous pasture limit the risk gastrointestinal parasitism. The evaluation of environmental effects on livestock production and the understanding of mechanisms and genetic control for adaptation traits are key-issues for an agro-ecological approach. However, farmers are concerned with choosing the most suitable animal (that is the most adapted one) considering the rearing conditions. From this point of view, under tropical climate, local breeds, submitted to long-standing natural selection and sometimes derived from former crossbreeding, have interesting abilities that must be evaluated regarding the production and multifunctional requirements of the farm. The farmer must design an integrated management of environmental constraints on the farm.

Management of reproduction is an important lever to control livestock productivity. The Reproduction programming by the farmer and therefore physiological status of livestock need should be synchronized with the seasonal variability of amounts and food qualities (grass, crop byproducts ....). Figure 9 illustrates the optimal

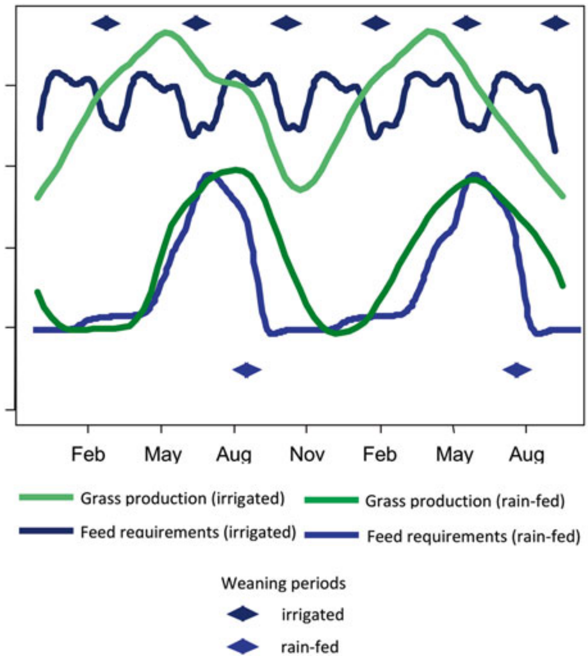


Fig. 9 Scheduling periods of reproduction and stocking rate of small ruminants on pasture to synchronize the needs of the dams-litter and feed availability on the basis of seasonal variability of biomass in irrigated and rain-fed system

synchronization for grazing animals. Wider, career management of animals must be adapted to environmental constraints. Thus, high prolific livestock such as pigs, rabbits mobilize their reserves to meet the needs of their offspring. Indeed, the diets nutritional density even with very high quality ingredients is not sufficient to meet the livestock requirement at the beginning of lactation. Livestock replenish these reserves with the physiological decrease of milk production and weaning. This ability range is variable depending on the genotype but it is in all cases penalized by accelerating reproduction rate typically implemented in intensive breeding since the objective is to increase individual performance. In an agro-ecological approach a tradeoff between animal crop and land performances is useful to optimize the efficiency of production system. As an example there may be a contradiction between individual production performance of livestock and that measured at the unit level surface that has been necessary to feed them.

Environmental effect of feeding strategies has to take into account too. Usually live livestock transforms nitrogen intake as animal protein with a poor performance which is potentially an environmental risk. Nitrogen excretion of ruminants via feces increases with indigestible dry intake and it is not linked to nitrogen intake. Mean value of 7.5 g Nitrogen/kg dry matter intake is reported for cows (Peyraud et al. 1995). In contrary, nitrogen excretion of ruminants via urine increase with nitrogen intake and is influenced by its nature. Urinary nitrogen comes from the metabolic turnover of protein and metabolic activity linked to protein synthesis (meat, milk) and any excess or imbalance of the contributions from the real needs. Dung nitrogen is slightly soluble in organic form and is practically not leachable. In contrast, the nitrogen in the urine is mainly in organic form quickly converts single mineral forms that can be leached away, volatilisable more easily but also more readily available to the plant. The «pollutant risk «of urine appears therefore much higher than dung, even though it is the most variable portion. The efficiency of the use of nitrogen per kg of meat or milk produced increases with animal potential due to a dilution of maintenance needs in total requirements. Reducing nitrogen fertilization on pastures, the amount of nitrogen exported in feces varies little in cows but, on the contrary, nitrogen excreted in urine is reduced. In an agro- ecological mixing crop and livestock and/or a recycling livestock excretion, feces and urine are used as organic fertilizer.

Feeding strategies to reduce ruminant methane emission is also a complex question. Really, feeding animals with high nonstructural carbohydrates (sugars, starch…) using ingredients like cereals, tubers, roots, and starchy fruits reduces methane emission compared with structural carbohydrate (cell wall) coming from roughages (grass and legumes, straws and others fibrous crops co-products). However, there is a high competition between human and livestock for the valuation of the first ingredients listed, which have also a strong environmental footprint.

The increase of animal production potential may be an interesting way to decrease environmental footprint of animal product evaluated on the basis of meat and milk produced by example. Nevertheless, even when the assumption that the climate is not a limiting factor is done, the nutritional density of rations to allow animals to express their potential requires the use of resources also directly usable by humans.

Efficiency of Feed Use by Livestock

Today, the increase of the efficiency of feed use by livestock is mainly based on use of human-edible crops. The challenge of agro ecology is to improve efficiency of resource use by matching available feeds to animal requirements and at the same time reduce reliance on human-edible foods (Wilkinson 2011). The increase of production and efficiency of use maximizing crop productivity seem to be too simplistic a goal. The optimization of land use across a more complex matrix of production, environmental and cultural factors should be a more appropriate strategy (Godfray et al. 2010).

There is a genetic variability of animal responses (daily growth, milk production, fat deposition, methane emission) to a similar (amount and quality) dry matter intake resulting from a variation in the efficiency of feed utilization. This variability named feed efficiency can be valued in an agro ecological approach. Some recent studies have been focused on this goal. Using selection for residual feed intake approach, some studies indicate that cattle that consume less dry matter intake, have improved feed conversion ratio and reduced enteric CH_4 emissions at equal levels of production, body size and body fatness (Basarab et al. 2013). Using multi-trait selection and a comprehensive record keeping system, rate of genetic change has been estimated to be 0.75–1.0 % per year compared with no selection for feed efficiency. There will be few, if any, antagonistic effects on growth, carcass quality, fertility and cow lifetime productivity (Basarab et al. 2013). Moreover, rearing several animal species may result in a better utilization of the available feed resources because complementarities in digestive abilities (Figs. 4 and 6) or in grazing behavior (Animut and Goetsch 2008; Celaya et al. 2007). Mixed grazing of cattle and small ruminants may also help in reducing parasitic diseases and the corresponding production losses (Mahieu, 2013) and veterinary costs, at least when epidemiological and behavioral knowledge are used properly.

Conclusions and Perspectives

The improvement of efficiency of resource use by matching available feeds to animal requirements and at the same time reduce reliance on human-edible feeds is a major challenge for soil crop and animal scientists researchers.

A reconsideration of the "modern" food consumption model based on the increasing consumption of animal products is an urgent issue. Livestock that are placed on top of the food chain transforms primary biomass in animal protein with a relatively low efficiency. Moreover, proteins of plant origin can substitute a portion of animal protein consumption without adversely impacting human health and development. A profile of the agricultural area should be achieved by optimising the needs of livestock and those of crops, including the contribution of the latter to supplying food protein. As a result, plant species such as legumes should be better represented in rotations. Production systems such as mixed crop-livestock farming systems and agro-forestry have strengths. The choice of crops and genotypes should, as far as possible, take into account the constraints of feeding humans and animals. As a result, dual plants i.e. those producing high quality co-products potentially usable as livestock feed, are preferable. Plant breeding which is now mainly based on the production of biomass eligible for human consumption should take into account this constraint. The choice of animal species and genotypes should be based on a better balance between cultural criteria, the expected multi services of livestock and the match between the characteristics of plant biomass available and the efficiency of animal species valuation.

Agro-ecology helps in giving identity to territories. It is a cultural revolution where the citizen consumer should firstly use products originating from its agro-climatic environment. This cultural revolution also includes new plant and animal resources management, where farmers react smartly on the basis of general guidelines rather than adopting a routine technically predefined route. Agro-ecology is a biotech approach valuing natural processes rather than an artificial modification of the environment of production. Proper plant and animal management should contribute to reducing environmental animal protein production by decreasing inputs (water, fertilisers, pesticides) and land utilisation, and increasing biodiversity and recycling.

The implementation of agro-ecology in farms must be accompanied by the development of eco-innovations. These innovations will be developed from the analysis of the relationships between living organisms in natural ecosystems, popular and scientific knowledge, and participatory research. Among popular knowledge, ethno-veterinary practices are an important tool because they are based on the valuation of local plant biodiversity. This empirical knowledge has greatly boosted the integrated fight against ruminants' internal nematodes, identifying plant resources which support research on active molecules (secondary metabolites). Other pathogens, like external parasites, are treated with ethno-veterinary practices. Popular empirical practices target other metabolic functions such as nutrition, reproduction, and lactation, necessitating scientific research. The increased use of natural substances in livestock production is urgent because of the biological limits of chemical products and legislation.

The feeding strategies of livestock should be based, as far as possible, on biomasses originating from the local environment and produced following agro-ecological conditions. In the humid tropics, when the goal is to increase meat production per unit area, the main ingredients of livestock diet remains cereals and oleaginous products like soybeans. Because of the high environmental footprint and the high prices of these ingredients, often imported, it is useful to develop feeding strategies based on alternative ingredients like sugar and starchy fruit, roots and tubers, high protein leaves, and legume grains. However, special attention should be given to strategies for the production of these ingredients which avoid setbacks linked to practices advocated by the green revolution. In this context, the dual crops (feed-food) have many advantages. The way in which the food chain connects different living organisms in natural ecosystems should be analysed to identify new recoverable resources of feed and secondary rights. Non-conventional animals (guinea pigs, insects, worms) can potentially contribute to these challenges, but require further research.

Characterisation of indigenous animal resources must be strengthened. Livestock populations that have evolved over the centuries in diverse, stressful tropical environments have a range of unique adaptive traits: disease and heat resistance, water scarcity tolerance, and the ability to cope with poor quality feed. These adaptive traits are a support for agro-ecology practices.

Finally, the optimization of agroecological systems relies on the knowledge on the interactions between the farmer, climate, soil, plants, animals, animal diseases, plant diseases and food webs, capitalized empirically by traditional farmers and enriched by more highly interdisciplinary scientific approaches.

References

Altieri MA, Nicholls CI (2012) Agroecology scaling up for food sovereignty and resiliency. Sustain Agric Rev 11:1. doi:10.1007/978-94-007-5449-2_1

Anh ND, Preston TR (1997) Evaluation of protein quality in duckweed (Lemnaspp.) using a duckling growth assay. Livest Res Rural Dev 9. http://www.lrrd.org/lrrd9/2/anh92.htm

Animut G, Goetsch AL (2008) Co-grazing of sheep and goats: benefits and constraints. Small Rumin Res 77:127–145

Archimède H, Eugène M, Marie Magdeleine C, Boval M, Martin C, Morgavi DP, Lecomte P, Doreau M (2011a) Comparison of methane production between C3 and C4 grasses and legumes. Anim Feed Sci Technol 166–167:59–64

Archimède H, Bastianelli D, Boval M, Tran G, Sauvant D (2011b) Ressources tropicales. Disponibilité et valeur alimentaire. INRA Prod Anim 24:23–40

Archimède H, Régnier C, Marie-Magdeleine Chevry C, Gourdine JL, Rodriguez L, Gonzalez E (2011c) The alternatives to soybeans for animal feed in the tropics, soybean – applications and technology, Tzi-Bun Ng (ed), ISBN: 978-953-307-207-4, InTech, New York. Available from: http://www.intechopen.com/books/soybean-applications-and-technology/the-alternatives-to-soybeans-for-animal-feed-in-the-tropics

Archimède H, Gourdine JL, Fanchone F, Tournebize T, Bassien-Capsa M, González-García E (2012) Integrating banana and ruminant production in the French West Indies. Trop Anim Health Prod 44:1289–1296

Baker RL, Gray GD (2004) Appropriate breeds and breeding schemes for sheep and goats in the tropics. In: Sani RA, Gray GD, Baker RL (eds) Worm control for small ruminants in tropical Asia. ACIAR monograph no. 113. ACIAR, Canberra, pp 63–96

Basarab JA, Beauchemin KA, Baron VS, Ominski KH, Guan LL, Miller SP, Crowley JJ (2013) Reducing GHG emissions through genetic improvement for feed efficiency: effects on economically important traits and enteric methane production. Animal 7:303–315

Bayer W, Feldmann A (2003) Diversity of animals adapted to smallholder system. Conservation and Sustainable Use of Agricultural Biodiversity. http://www.eseap.cipotato.org/UPWARD/Agrobio-sourcebook.htm

Beauchemin KA, McAllister TA, McGinn SM (2009) Dietary mitigation of entericmethane from cattle. CAB Rev Perspect Agric Vet Sci Nutr Nat Res 4:1–18

Beilharz RG, Luxford BG, Wilkinson JL (1993) Quantitative genetics and evolution: is our understanding of genetics sufficient to explain evolution? J Anim Br Gen 110:161–170

Berbigier P (1988) Bioclimatologie des ruminants domestiques en zone tropicale. INRA Editions, Versailles, 237p

Blanfort V, Doreau M, Huguenin J, Lazard J, Porphyre V, Soussana JF, Toutain B (2011) Impacts et services environnementaux de l'élevage en régions chaudes. INRA Prod Anim 24:89–122

Burel A, Archimède H, Mahieu M, Fanchone A, Gourdine JL (2013) Foraging behavior of Creole pigs kept outdoor under tropical conditions on sweet potatoes field. Communication présentée à 64th Annual Meeting of the European Federation of Animal Science (EAAP), Nantes, (2013-08-26 - 2013-08-30)

Celaya R, Olivan M, Ferreira LMM, Martinez A, Garcia U, Osoro K (2007) Comparison of grazing behaviour, dietary overlap and performance in non-lactating domestic ruminants grazing on marginal heathland areas. Livest Sci 106:271–281

Dauncey MJ, Ingram DL (1986) Acclimatization to warm or cold temperatures and the role of food intake. J Theor Biol 11:89–93

Devendra C (1990) Comparative aspects of digestive physiology and nutrition in goats and sheep. In: Devendra C, Imaizumi E (eds) Satellie symposium on ruminant physiology and nutrition in Asia, August 1989. Japanese Society of Zootechnological Science, Sendai, pp 45–60

Dumont B, Fortun-Lamothe L, Jouven M, Thomas M, Tichit M (2013) Prospects from agroecology and industrial ecology for animal production in the 21st century. Animal 7:1028–1043

Gauthier D, Thimonier J (1985) Variations saisonnières de la durée de l'inactivité ovulatoire post-partum et de la fertilité des vaches Françaises Frisonnes Pie Noires élevées en Guadeloupe. Ann Zootech 34:347–354

Gauthier D, Aumont G, Barre N, Berbigier P, Camus E, Lafortune E, Popescu P, Rulquin H, Xande A, Thimonier J (1984) Le bovin créole en Guadeloupe: caractéristiques et performances zootechniques. Rev Elev Med Vet Pays Trop 37:212–224

Geraert PA, Guillaumin S, Leclercq B (1993) Are genetically lean broilers more resistant to hot climate? Br Poult Sci 34:643–653

Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty J, Robinson S, Thomas S, Toulmin C (2010) Food security: the challenge of feeding 9 billion people. Science 327:812–818

Gourdine JL, Mandonnet N, Naves M, Bidanel JP, Renaudeau D (2006) Genetic parameters of rectal temperature in sows in a tropical humid climate and its association with performance during lactation: preliminary results. 8th World Congress on Genetics Applied to Livestock Production, Belo Horizonte, pp 16–29

Gourdine JL, Bidanel JP, Menendez-Buxadera A, Mandonnet N, Naves M, Renaudeau D (2007) Estimation des relations génétiques de la température rectale chez la truie en lactation en relation avec les performances. J Rech Porcine Fr 39:293–294

Hermansen JE, Knudsen MT, Kristensen T (2013) Role of animal products in feeding the planet. In: Oltjen JW, Kebreab E, Lapierre H (eds) Energy and protein metabolism and nutrition in sustainable animal production, EAAP publication no. 134. Wageningen Academic Publisher, Wageningen, pp 35–46

Herrero M, Thornton PK, Notenbaert AM, Wood S, Msangi S, Freeman HA, Bossio D, Dixon J, Peters M, van de Steeg J, Lynam J, Parthasarathy Rao P, Macmillan S, Gerard B, McDermott J, Seré C, Rosegran M (2010) Smart investments in sustainable food production: revisiting mixed crop-livestock systems. Science 327:822–825

Hoffmann I (2010) Climate change and the characterization, breeding and conservation of animal genetic resources. Anim Genet 41:32–46

Kaufmann F, Das G, Preisinger R, König S, Gauly M (2010) Genetic resistance to natural helminth infections in two chicken layer lines. 9th World Congress on Genetics Applied to Livestock Production, Leipzig, 1–6 Aug, p 337

Leng RA, Stambolie JH, Bell R (1995) Duckweed – a potential high protein feed resource for domestic animal and fish. Livest Res Rural Dev 7. http://www.lrrd.org/lrrd7/1/3.htm

Leterme P, Botero M, London AM, Bindelle J, Buldgen A (2009) Nutritive value of tropical tree leaf meals in adult sows. Anim Sci 82:175–182

Leterme P, Londono AM, Ordonez DC, Rosales A, Estrada F, Bindelle J, Buldgen A (2010) Nutritional value and intake of aquatic ferns (Azolla filiculoides Lam. and Salvinia molesta Mitchell.) in sows. Anim Feed Sci Technol 155:55–64

Machin D, Nyvold S (1992) Roots, tubers, plantains and bananas in animal feeding. FAO animal production and health paper, no. 95. In: Machin DH, Nyvold S (eds) Expert consultation on roots, tubers, plantains and bananas in animal feeding, Cali, 21–25 Jan 1991. FAO, Rome. http://www.fao.org/docrep/003/T0554E/T0554E00.HTM

Mahieu M (2013) Effects of stocking rates on gastrointestinal nematode infection levels in a goat/cattle rotational stocking system. Vet Parasitol 198:136–144

Mandonnet N, Tillard E, Faye B, Collins A, Gourdine JL, Naves M, Bastianelli D, Tixier-Boichard M, Renaudeau D (2011) Adaptation des animaux d'élevage aux multiples contraintes des régions chaudes. INRA Prod Anim 24:41–64

Marie-Magdeleine C, Mahieu M, Philibert L, Despois P, Archimède H (2010) Effect of cassava (Manihot esculenta) foliage on nutrition, parasite infection and growth of lambs. Small Rumin Res 93:10–18

McDowell RE (1985) Crossbreeding in tropical areas with emphasis on milk, health and fitness. J Dairy Sci 68:2418–2435

Mekbungwan A (2007) Application of tropical legumes for pig feed. Anim Sci J 78:342–350

Mignon-Grasteau S, Boissy A, Bouix J, Faure JM, Fisher AD, Hinch GN, Jensen P, Le Neindre P, Mormède P, Prunet P, Vandeputte M, Beaumont C (2005) Genetics of adaptation and domestication in livestock. Livest Anim Sci 93:3–14

Minson DJ (1990) Forage in ruminant nutrition. Academic, San Diego, 483 pp

Mirkena T, Duguma G, Haile A, Tibbo M, Okeyo AM, Wurzinger M, Solkner J (2010) Genetics of adaptation in domestic farm animals: a review. Livest Sci 132:1–12

Noblet J, Karege C, Dubois S, Van Milgen J (1999) Metabolic utilization of energy and maintenance requirements in growing pigs: effects of sex and genotype. J Anim Sci 77:1208–1216

Patra AK (2008) A meta-analysis on effects of supplementing low-quality roughages with foliages from browses and tree fodders on intake and growth in sheep. Livest Sci 121:239–249
Patra AK (2009) Effects of supplementing low-quality roughages with tree foliages on digestibility, nitrogen utilization and rumen characteristics in sheep: a meta-analysis. J Anim Physiol Anim Nutr 94:338–353
Perez R (1997) Feeding pigs in the tropics. In: Pérez R (ed) Animal production and health papers, no. 132. FAO, Rome. http://www.fao.org/docrep/003/w3647e/W3647E00.htm
Peyraud JL, Vérité R, Delaby L (1995) Rejets azotés chez la vache laitière: effets du type d'alimentation et du niveau de production des animaux. Fourrages 142:131–144
Picard M, Sauveur B, Fernadji F, Angulo I, Mongin P (1993) Ajustements technicoéconomiques possibles de l'alimentation des volailles dans les pays chauds. INRA Prod Anim 6:87–103
Preston TR (1977) A strategy for cattle production in the tropics. World Anim Rev 21:11–17
Preston TR (1995) Tropical animal feeding. FAO animal production and health paper, no. 126. FAO, Rome. http://www.fao.org/docrep/003/v9327e/V9327E14.htm
Preston TR (2006) Forages as protein sources for pigs in the tropics. In: Workshop-seminar "Forages for pigs and rabbits" MEKARN-CelAgrid, Phnom Penh, 22–24 Aug 2006. http://www.mekarn.org/proprf/preston.htm. Accessed 19 Dec 2006
Preston TR (2009) Environmentally sustainable production of food, feed and fuel from natural resources in the tropics. Trop Anim Health Prod 41:873–882
Putney DJ, Mullins S, Thatcher WW, Drost M, Gross TS (1989) Embryonic development in superovulated dairy cattle exposed to elevated ambient temperatures between the onset of estrus and insemination. Anim Reprod Sci 19:37–51
Rauw WM, Kanis E, Noordhuizen-Stassen EN, Grommers FJ (1998) Undesirable side effects of selection for high production efficiency in farm animals: a review. Livest Prod Sci 56:15–33
Régnier C (2011) Valorisation des ressources alimentaires tropicales (feuillages et tubercules) chez le porc. Thèse de doctorat, Université des Antilles et de la Guyane, 203p
Renaudeau D, Gourdine JL, St-Pierre NR (2011) A meta-analysis of the effects of high ambient temperature on growth performance of growing-finishing pigs. J Anim Sci 89:2220–2230
Renaudeau D, Collin A, Yahav S, de Basilio V, Gourdine JL, Collier RJ (2012) Adaptation to hot climate and strategies to alleviate heat strees in livestock production. Animal 6:707–728
Roberge G, Toutain B (1999) Cultures fourragères tropicales. Coll. Repères, Editions Quae, Paris, 369p
Rochefort S, Parker AJ, Dunshea FR (2008) Plant bioactives for ruminant health and productivity. Phytochemistry 69:299–322
Ruiz ME, Pezo D, Martinez L (1980) The use of sweet potato (Ipomoea batatas, (L.) Lam) in animal feeding. I Agronomic aspect. Trop Anim Prod 5:238
Sanchez MD (2002) Mulberry for animal production. In: Sánchez MD (ed) FAO animal production and health paper, no 147. FAO, Rome. http://www.fao.org/3/a-x9895e/index.html
Schou TW, Permin A, Juul-Madsen HR, Sorensen P, Labouriau R, Nguyen TLH, Fink M, Pham SL (2007) Gastrointestinal helminths in indigenous and exotic chickens in Vietnam: association of the intensity of infection with the major histocompatibility complex. Parasitology 134:561–573
Silanikove N (1986) Interrelationships between feed quality, digestibility, feed consumption, and energy requirements in desert (Bedouin), and energy requirements in desert (Bedouin) and non-desert (Saanen) goats. J Dairy Sci 69:2157–2162
Silanikove N (2000) The physiological basis of adaptation in goats to harsh environments: a review. Small Rumin Res 35:181–193
Silanikove N, Tagari H, Shkolnik A (1993) Comparison of rate passage, fermentation rate and efficiency of digestion of high fiber diet in desert black Bedouin goats as compared to Swiss Saanen goats. Small Rumin Res 12:45–60
Sotomayor-Rios A, Pitman WD (2001) Tropical forage plants: development and use. CRC Press LLC, Boca Raton, 391p
Speedy A, Pugliese P (1992) Legume trees and other fodder trees as protein sources for livestock. In: Speedy A, Pugliese P-L (eds) FAO animal production and health paper, no. 102. Expert Consultation, Kuala Lumpur, 14–18 Oct 1991. FAO, Rome. http://www.fao.org/docrep/003/t0632e/t0632e00.htm

Thornton PK (2010) Livestock production: recent trends, future prospects. Philos Trans R Soc B 365:2853–2867

Thornton PK, van de Steeg J, Notenbaert A, Herrero M (2009) The impacts of climate change on livestock and livestock systems in developing countries: a review of what we know and what we need to know. Agric Syst 101:113–127

Tiemann TT, Lascano CE, Wettstein HR, Mayer AC, Kreuzer M, Hess D, Zurich ETH (2008) Effect of the tropical tannin-rich shrub legumes Calliandra calothyrsus and Flemingia macrophylla on methane emission and nitrogen and energy balance in growing lambs. Animal 2:790–799

Van Huis A, Van Itterbeeck J, Klunder H, Mertens E, Halloran A, Muir G, Vantomme P (2013) Edible insects: future prospects for food and feed security. FAO forestry paper, no. 171. In: van Huis A, Van Itterbeeck J, Klunder H, Mertens E, Halloran A, Muir G, Vantomme P (eds). FAO, Rome. http://www.fao.org/docrep/018/i3253e/i3253e.pdf

Van Soest PJ (2006) Review. Rice straw, the role of silica and treatments to improve quality. Anim Feed Sci Technol 130:137–171

Wanapat M (2009) Potential uses of local feed resources for ruminants. Trop Anim Health Prod 41:1035–1049

Wilkinson JM (2011) Re-defining efficiency of feed use by livestock. Animal 5:1014–1022

Wilson TR (2009) Fit for purpose, the right animal in the right place. Trop Anim Health Prod 41:1081–1090

Agroecology for Farmers: The Linguistic Issue

Diane Le Hénaff and Zeynel Cebeci

Abstract Agroecology means that agriculture is a part of ecological systems. Agroecology thus promotes biodiversity and support multicultural production. Farmers are benefiting from the digital revolution that allow access to agroecological knowledge. Although internet access to information resources is becoming less problematic, the issue of language barrier is particularly critical. This chapter therefore focuses on the need for farmers to access useful information, with focus on language barriers. The linguistic issue is addressed using the Organic.Edunet experience (www.organic-edunet.eu). Organic.Edunet is a learning portal that provides access to high-quality and trusted digital learning resources on organic agriculture and agroecology. These resources are used by students, teachers and farmers, as well as the general public interested in the subject. Organic.Edunet is used in this chapter as a use-case for analysing the benefit of truly multilingual portal in the agroecological field. Automated multilingual services introduced in the portal are described as well as the study of the analytics that shows the need to access information without the language barrier. A professional approach is described for demonstrating the benefit for farmers and teachers to use such thematic and multilingual portal. Then the importance of new content is mentioned to ensure the update of the information as well as the sustainability of such tools.

Keywords Multilingual content • Organic farming • Agroecology • CLIR • Agricultural learning repositories

---

D. Le Hénaff (✉)
DV-IST, INRA, Route de St-Cyr, 78026 Versailles Cedex, France
e-mail: lehenaff@versailles.inra.fr

Z. Cebeci
Division of Biometry and Genetics, Faculty of Agriculture,
Cukurova University, 01330 Adana, Turkey
e-mail: zcebeci@cukurova.edu.tr

H. Ozier-Lafontaine and M. Lesueur-Jannoyer (eds.), *Sustainable Agriculture Reviews 14: Agroecology and Global Change*, Sustainable Agriculture Reviews 14,
DOI 10.1007/978-3-319-06016-3_10,

Introduction

> Africa is in the midst of a technological revolution, and nothing illustrates that fact better than the proliferation of mobile phones. Consider this: more Africans have access to mobile phones than to clean drinking water. (Hutton 2011)

This growth in mobile phone use has followed the spread of internet access in both the developing world and isolated European and Mediterranean countries. Access to knowledge is the next strategic issue; "Making the right decisions at the farm level in terms of input use efficiency, human health and resource protection is becoming an increasingly knowledge-intensive task" (Tilman 2002).

Although internet access to information resources is becoming less problematic even in isolated areas, the issue of language barrier is particularly critical in benefiting intercultural information and communicating between farmer communities. The European Commission is aware of this issue and has funded the Organic.Lingua project in 2011, under the 7th Framework Programme, to remove the linguistic barriers identified in the Organic.Edunet portal. Organic.Edunet is a web portal which enables access to educational information which originally concerned Organic Agriculture but during the past 2 years has extended to Agroecology. The target users are farmers, practitioners, industries and NGOs, as well as students and teachers. These potential users of the Organic.Edunet portal can benefit from the 18,920 pedagogical resources available and find answers to their current needs (e.g.: switching to a new crop, the adaptation of specific plants to dry climatic conditions, the effectiveness of organic fertilizers on a specific crop). These resources are available in many different

Photo 1 A plot of fodder and sugar beets. Focus on Colosse, a very powerful beet, adaptable to mechanization

languages, but many differences subsist. In particular, no resources are available in Portuguese, Chinese, Arabic or Italian. The agricultural industry is very important in these countries, and they have a considerable need for pedagogical resources.

Starting with a study of the analytics of the portal, this chapter will demonstrate the need for farmers to access experimental results, user feedback on soil management practices and fertility, how to adapt the plants to climate change and a dry climate, while adopting an ecological approach without any language barrier.

And this information must be accessible via different types of media: reports, technical datasheets, dedicated websites, videos, etc.

Automated multilingual services have been introduced in order to further support the uptake of this service by its target audience and facilitate the portal's multilingual features. It aims at enabling users to access resources in 16 different languages for scientific and society-oriented purposes. These multilingual components will be described technically and under a user-related approach.

Then a particular professional case of use is mentioned, enabling a clearer understanding of the expected benefits.

Finally, agroecology is a field where practices and regulatory frameworks, see rapid change, so such portals need to expand continuously the resources available. This may be the next issue in order for the users to maximize the benefits of using such thematic portals (Photo 1).

The Benefit of Multilinguality to Organic.Edunet

The Organic.Edunet Portal

The Organic.Edunet portal was set up in January 2010 and to date has received 194,167 visits (161,581 unique visitors) from 202 countries (as shown on the map shaded from light blue to dark blue) (Fig. 1).

The top 14 of the countries where the portal is mostly used can be seen in Fig. 2.

These numbers are impressive for such specific and topic-oriented portal. Indeed, Organic.Edunet has several advantages over traditional search engines. Its focus on a specific area means that it is easier for users to locate resources that are more relevant to their topic of interest.

Already in early 2011, the large number of visits and the results of analytical studies (Palavitsinis et al. 2011) have thus confirmed the interest aroused by such a portal that enabled access to many sources from European institutions and scientific networks

Looking deeper at the most searches in the portal, we can see from Table 1 that:

(i) English is not the only language used for searching
(ii) the mean of the searches are both agriculture-related and learning-targeted. The two queries stated in Greek mean "growing parsley" and "cruciferous vegetables".

This statement has demonstrated the need for people, farmers, and teachers to access pedagogical resources in agroecology using a cross-lingual information

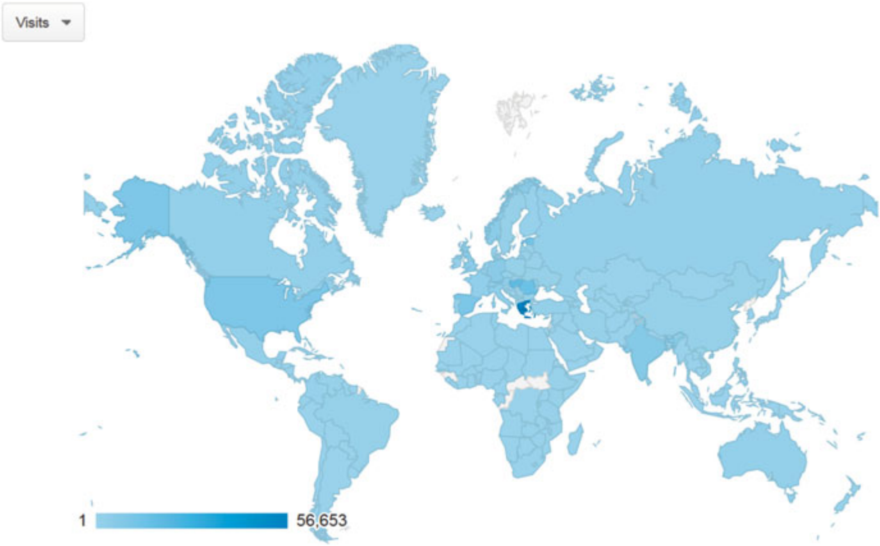


Fig. 1 Overlay map of 194,167 visits from 202 countries

Fig. 2 Top 14 countries where the portal is mostly used

1.	Greece	56,653
2.	Hungary	18,377
3.	Romania	14,336
4.	Estonia	12,295
5.	Spain	10,034
6.	United States	9,544
7.	India	6,237
8.	Germany	5,124
9.	Norway	4,579
10.	United Kingdom	4,542
11.	Austria	3,457
12.	Italy	2,943
13.	France	2,700
14.	Moldova	2,141

Table 1 List of the most popular queries on the portal

Search term	Total unique searches
School	162
αλλιέργεια μαϊντανού	144
Scenario description	139
Handbook scenario implementation school level	102
Handbook scenario implementation university level	102
School garden	97
Σταυρανθή λαχανι ά	76
αταπολέμηση εντόμων	70
αλλιέργεια μπάμιας	63
Tomate	60
Climate change	58
Patata	53
Organic garden (EA)	47
Control de plagas	42
Leche	41
αλλιέργεια φράουλας	41
αλλιέργεια πατάτας	38
Control plagas	37
Lechuga	37
αλλιεργητι ές τεχνι ές	34
αλλιέργεια σ όρ ου	32
πατάτα	31
βιολογι ή αλλιέργεια	29
αλλιέργεια αρα ά	29
αλλιέργεια μπρό ολου	29

retrieval. This was then the purpose of Organic.Lingua, a European Project, funded under the ICT-PSP of the European Commission that involves technical and metadata experts (University of Alcala-Spain, AgroKnow-Greece), content providers (INRA-France, Cukurova University-Turkey, Miksike-Estonia, IITS-Spain), innovative companies working in the fields of knowledge and multilinguality (Xerox-France, CELI-Italy, Know Center-Austria, Kessler Foundation-Italy) and communication support (Birmingham City University-UK).

Transforming Organic.Edunet into a Truly Multilingual Portal

The Cross-Lingual Information Retrieval (CLIR)

As stated by Gäde the most essential component of a truly multilingual information system is the multilingual search function (Gäde 2011). Language should not constitute a barrier to resource access on the internet, and especially for people who are not fluent in English. Within the Organic.Lingua project, a CLIR has been introduced in a re-engineered Organic.Edunet portal. This new search engine works following this process: a query (e.g. "*pomodori e agricoltura biologica*") is analyzed to determine the language. The result of this analysis is not a single answer but a list of languages by level of confidence as shows the (Fig. 3)

In this case of query, Italian is detected with the highest level of confidence. Then each term in the query is morphologically analyzed to determine which word is a noun in order to link it to a broader concept. Then, the morphological analysis has transformed *pomodori* into its lemma *pomodoro. Pomodoro* and *agricoltura* have been found in the embedded dictionary as nouns and *biologica* as an adjective. Knowing the syntax is of importance to rebuild the translated queries. The named Entities Recognition component has also found that *pomodoro* is part of food. This could provide additional features to the user at the portal interface level. Finally, the multilingual dictionary provides the translation of the words in up to 22 languages. Twenty-two queries are built up and sent to the search engine index to retrieve the related content though the portal.

This CLIR benefit is in retrieving resources that are not in the language of the search query. It avoids loosing relevant resources even if it brings content that is not understandable by the user.

In order to be able to analyse the list of results, a multilingual portal provides additional tools.

The Machine Translation Component

A list of resources is provided to the user who then needs a machine translation to be able to select the most appropriate resource for his case of interest.

Language should not constitute a barrier to resource access on the internet; several free, online services are now available to translate content, such as: http://translate.google.com, http://www.bing.com/translator, http://www.reverso.net. But they are not integrated in the portal. Google Translate and Bing provide API (*Application Programming Interface)* to translate text in a distant application but not for free or with limitations. In the case of Organic.Edunet, similar tool called Machine Translation has been plugged, enabling the user to see the title, description and keywords of the resources translated in his mother tongue.

These translations are automatic and many differences between machine translation tools exist. Most of the machine translations use multi-disciplinary dictionaries so texts using concepts in a specific area are difficult to be automatically translated. A French expert was asked in September 2013 to evaluate the translation of five resource's descriptions available in the Organic.Edunet portal using five Machine Translations. The better evaluation went to the most popular web tools as shown in the (Table 2)

However the number of records evaluated is very low and can't be taken as a full evaluation of the tools.

```
<GuessedLanguages>
  <LanguageGuesses language="it" guessConfidence="0.7718774"/>
  <LanguageGuesses language="la" guessConfidence="0.35878858"/>
  <LanguageGuesses language="ro" guessConfidence="0.3165972"/>
  <LanguageGuesses language="pt" guessConfidence="0.31619164"/>
  <LanguageGuesses language="es" guessConfidence="0.29504928"/>
  <LanguageGuesses language="en" guessConfidence="0.2885373"/>
  <LanguageGuesses language="fr" guessConfidence="0.28643128"/>
  <LanguageGuesses language="pl" guessConfidence="0.25965717"/>
  <LanguageGuesses language="nl" guessConfidence="0.25400233"/>
  <LanguageGuesses language="da" guessConfidence="0.25210613"/>
  <LanguageGuesses language="no" guessConfidence="0.25024268"/>
  <LanguageGuesses language="sv" guessConfidence="0.23891717"/>
  <LanguageGuesses language="de" guessConfidence="0.23830271"/>
  <LanguageGuesses language="et" guessConfidence="0.22747383"/>
  <LanguageGuesses language="fi" guessConfidence="0.20702967"/>
  <LanguageGuesses language="lv" guessConfidence="0.20579875"/>
  <LanguageGuesses language="hi" guessConfidence="0.17260355"/>
  <LanguageGuesses language="hu" guessConfidence="0.17040288"/>
  <LanguageGuesses language="tr" guessConfidence="0.15687594"/>
  <LanguageGuesses language="ar" guessConfidence="0.06210375"/>
  <LanguageGuesses language="el" guessConfidence="0.05537778"/>
  <LanguageGuesses language="ru" guessConfidence="0.0"/>
```


Fig. 3 List of language identification by level of confidence

Table 2 Automatic translation evaluation

Notation scale translation into French: 1 (hard to understand) to 5 (very easy to understand)	Organic.Edunet machine translation	Google free web tool	Bing free web tool	itranslate4.eu free web tool
http://organic-edunet.eu/#/resource/10624	3	4	4	4
http://organic-edunet.eu/#/resource/4705	3	4	2	2
http://organic-edunet.eu/#/resource/4706	4	4	4	4
http://organic-edunet.eu/#/resource/6041	4	4	5	1
http://organic-edunet.eu/#/resource/5412	5	5	4	1
http://organic-edunet.eu/#/resource/4720	2	4	4	3
http://organic-edunet.eu/#/resource/25620	2	2	4	4
Total	23	27	27	19

The Users Collaboration

In order to improve the translation proposed to the users of the portal, the Organic. Lingua project consortium decided to enable users to improve translations of resource's metadata using a smart bookmarklet saved in the browser personal bar. Some specific words of the domain could miss from the dictionaries of the Machine Translation tools. Human improvement in such specific domain of agriculture offers a reel benefit for this kind of portal.

Experts can also bring additional benefit by enriching the resources from the back end. Indeed, it is also possible for anyone in the field of Agroecology to suggest new resources to the portal and to describe these resources using keywords from domain ontologies. A user-friendly tool was made available to address this purpose.

Multilingual Issue in Farming and Teaching

Two Practitioner's Use Cases

If a Greek farmer (or any non-English speaking individual) initiates a search in non multilingual portal in order to shift his current soybean crop for another legume under an agroecological approach, he would not be able to obtain any results using the Greek keywords: σόγιας, αλλαγή, γρο-οι ολογίας (soybean, change, agroecology). The aim of multilingual portal in the agroecological field is to remove the linguistic barriers to accessing resources. In Organic.Edunet, for example, our Greek farmer could access a 4-page article (Martini et al. 2008) that evaluated the potential of switching from externally-sourced soybean (a high-risk GMO feed source) to other legumes produced on-farm, such as sweet lupin, protein pea and field bean, which constitute good alternative protein sources for use in the feed of organic dairy cattle (Photo 2).

As most of the farmers know, intercropping of cereals and legumes is a growing technique to support biodiversity in agroecological systems. Each of intercropped plants must have adequate space to maximize cooperation and minimize competition because they are grown together. When a Turkish farmer intends to apply intercropping he may access the appropriate resources on internet to found out more specific information. Searching the Turkish keywords: karışık ekim, baklagil, buğdaygil (intercropping, legumes, cereals) he would not be able to find any useful resources in Turkish his interest. However, in a multilingual portal, this farmer would find content in English, French, Latvian and other languages because the query and his keywords would have been translated in many other languages than Turkish.

The picture in Fig. 4 shows a query in Turkish that retrieved an interesting resource in English called "How to optimise symbiotic nitrogen fixation in organic crop rotations" presented in Turkish.

Photo 2 A plot with several varieties of cabbage in Picardie, France

Fig. 4 A resource's description auto-translated from English to Turkish

Photo 3 How to create productive and sustainable systems? A field for different varieties, in Spring in Picardie, France

An Innovative Way of Searching for Non Search Experts

Organic.Edunet provides a multilingual navigational search mechanism using its hierarchical tree structure based on both ontologies: the Organic.Edunet owns ontology and the well known Agrovoc[1] in the Agricultural field. This offers to the users a navigational search solution that presents a knowledge-base representation of the concepts (Cano et al. 2009). Contrary to traditional text-based queries, the navigational search mechanism enables the user to browse concepts and to refine very easily using a user-friendly interface.

For example when a Turkish teacher needs to access resources about intercropping, he can easily navigate through the concept's tree: Yöntem (Method) → Tarımsal Yöntem (Agricultural Method) → Karışık Ekim (Intercropping).

If the teacher looks for a specific media (presentations or images), it is possible to refine the search using facets. This became a common feature on portals and could be very useful. Indeed, an image doesn't need translation itself if the portal already provided translation of the main metadata: title, description and keywords (Photo 3).

[1]Agrovoc is a thesaurus created and maintain by the FAO. It is available as an ontology for external applications.

Table 3 Distribution of the resources by their language

Language (top 16)	No of resources	Language (top 10)	No of resources
English	11,100	English	8,557
French	1,750	Deutsch	1,031
German	920	Greek	319
Turkish	800	Estonian	302
Various Hindi	770	Hungarian	268
Estonian	445	Romanian	115
Kannada (Indian dialect)	440	Spanish	97
Greek	400	Norwegian	41
Spanish	310	Russian	27
Hungarian	280	Hindi	1
Romanian	110	Language missing	No of resources
Latvian	58	French	–
Norwegian	50	Italian	–
Russian	40	Turkish	–
Portuguese	20	Arabic	–
Italian	10	Bulgarian	–
Language missing	No of resources	Portuguese	–
Chinese	–	Slovenian	–
Arabic	–	Chinese	–
October 2013		**February 2012**	

Ensuring the Sustainability of the Such Portal

This section analyses at first the availability of the content by means of the profile of Organic.Edunet users. The interface of the portal is available in several translated versions.

Most visitors consult the Greek, Hungarian, Romanian, Estonian and English versions. In these languages, Organic.Edunet offers resources as listed in the (Table 3). By contrast, there have been very few visitors to date from Italy and Turkey.

Two conclusions can be drawn from this observation. Firstly, based on user experience (Stoitsis et al. 2012), it is crucial to support the introduction of new languages, not just in terms of interface but also with respect to content. Indeed, many visitors are Portuguese or Polish speakers and these languages are not yet available on Organic.Edunet.

In October 2013, Organic.Edunet had enabled access to 18,920 resources distributed as shown (Table 3)

Compared to February 2012, the number of resources has significantly increased. New content, especially in Portuguese and Hungarian are expected to be available very soon in order to meet the users' needs. In the field of Agroecology, this is of importance to provide up-to-date information, especially on innovative methods, products for pest management and legal aspects.

For this purpose, a widget was created, enabling the users of the portal to suggest new resources or improve the automatic translation. A Spanish agronomist, a loyal user of the portal, found on the web a paper titled “Agroecosistemas: opciones y conflictos en el suministro de servicios clave” which means “Agroecosystems: Conflicts in the provision of key services and options” by Antonio Gómez Sal in Revista Ambienta published in a Spanish magazine on environmental studies (Sal 2012). He appreciated the paper and wanted to share this information within a community of practice. Suggesting this resource on Organic.Edunet, using this widget makes the process very easy. The widget extracts the title, language, description and keywords from the webpage (if completed by the owner of the website). At this stage, the Spanish agronomist can confirm the suggested metadata directly or complete them after a short review. But aware of the linguistic barriers in accessing this resource, he can ask for the automatic translating feature to enrich the record with additional translated metadata.

Conclusion

The barriers in accessing educational resources in Agroecology are multiple. Relevant resources are drowned in the mass of results in a search tool like Google or Bing. Having a thematic portal that focuses on educational resources in Agroecology could better meet the users’ needs. This chapter demonstrated the added value of such thematic portal for practitioners or teachers that would benefit from such pedagogical resources. The Organic.Edunet’s portal was described as a use case. It also provides an interesting feedback on how the linguistic issue, in finding out resources without any linguistic restrictions, was addressed.

This chapter started with some analytics of the Organic.Edunet portal’s diversity of users. The targeted audience of such specific portal is mostly farmers, practitioners and teachers. These people do not know the best practices in searching information nor be fluent enough in English to build up queries in English.

In the context of Organic.Lingua, the Organic.Edunet portal has been re-engineered to provide Cross-Lingual Information Retrieval and automatic machine translation of resource’s metadata on demand. These components were described as well as their benefit.

Agroecology is a changing field where practices and legal aspects are changing quickly. Technics, protocols, regulation information are regularly revised. They have to be introduced in Organic.Edunet to offer up-to-date information and make the portal more attractive for the users.

Acknowledgements The work presented in this chapter has been funded with support by the European Commission and more specifically the project CIP-ICT-PSP- 270999 “Organic.Lingua: Demonstrating the potential of a multilingual Web portal for Sustainable Agricultural & Environmental Education” of the ICT Policy Support Programme (ICT PSP).

References

Cano R, Abián A, Mena E (2009) Navigation as a new form of search for agricultural learning resources in semantic repositories. In: Sartori F, Sicilia MF, Manouselis N (eds) Metadata and semantic research. Communications in computer and information science, vol. 46, pp 322–327

Gäde M (2011) User behavior and evaluation of multilingual information access in digital libraries. Bull IEEE Tech Comm Digit Libr 7(1):9 p. Available online: http://www.ieee-tcdl.org/Bulletin/v7n1/papers/gaede.pdf

Hutton J (2011) Mobile phones dominate in South Africa. Nielsen Blog. URL: http://blog.nielsen.com. Accessible: http://blog.nielsen.com/nielsenwire/global/mobile-phones-dominate-in-south-africa

Martini A, et al. (2008) Production of grain legume crops alternative to soya bean and their use in organic dairy production. Short paper at: Cultivating the future based on science: 2nd conference of the International Society of Organic Agriculture Research ISOFAR, Modena, Italy, 18–20 June 2008. Available on: http://orgprints.org/11957/

Palavitsinis N, Protonotarios V, Manouselis N (2011) Applying analytics for a learning portal: the Organic.Edunet case study. In: Proc. of the 1st international conference learning analytics and knowledge (LAK 11), Banff, Alberta, Canada, March 2011

Sal AG (2012) "Agroecosistemas: opciones y conflictos en el suministro de servicios clave", Revista Ambienta, nº 98, marzo 2012. Ecosistemas. Available at: http://www.revistaambienta.es/WebAmbienta/marm/Dinamicas/secciones/articulos/gomezsal.htm

Stoitsis G, Manouselis N, Sanchez-Alonso S (2012) Data set requirements for multilingual learning analytics. Int J Technol Enhanc Learn 4(½):47–66. doi:10.1504/IJTEL.2012.048316; 10.1504/IJTEL.2012.048316#_self

Tilman D, Cassman KG, Matson PA, Naylor R, Polasky S (2002) Agricultural sustainability and intensive production practices. Nature 418:671–677. doi:10.1038/nature01014

Soil Quality and Plant Nutrition

Hassan R. El-Ramady, T.A. Alshaal, M. Amer, É. Domokos-Szabolcsy, N. Elhawat, J. Prokisch, and M. Fári

> ***We** will know only what we are **taught**;*
> *We will be **taught** only what others deem is important to **know**;*
> *And we will **learn** to value that which is important.*
>
> ***– Native American proverb***

Abstract Soils are dynamic ecosystems that support a diversity of life. Therefore, the concept of soil quality or health, like that of human health, is not difficult to understand or recognize when the system is viewed as a whole. The challenge is to manage soils such that they are able to perform the various uses they are put to without degradation of the soils themselves or the environment. While, this is simple in concept, there are definite complexities that make the idea of soil health difficult to quantify. Which soil functions should be considered, which soil properties are most important to measure, and how to best measure those properties are some of the tough questions that need to be considered when attempting to quantify soil health. The great challenge is to manage

H.R. El-Ramady (✉)
Soil and Water Sciences Department, Faculty of Agriculture, Kafrelsheikh University, 33516 Kafr El-Sheikh, Egypt

Plant Biotechnology Department, Debrecen University, Böszörményi Útca. 138, 4032 Debrecen, Hungary

Institute of Bio- and Environmental Energetics, Debrecen University, Böszörményi Útca. 138, 4032 Debrecen, Hungary
e-mail: ramady2000@gmail.com

T.A. Alshaal
Soil and Water Sciences Department, Faculty of Agriculture, Kafrelsheikh University, 33516 Kafr El-Sheikh, Egypt

Plant Biotechnology Department, Debrecen University, Böszörményi Útca. 138, 4032 Debrecen, Hungary
e-mail: alshaaltarek@gmail.com

H. Ozier-Lafontaine and M. Lesueur-Jannoyer (eds.), *Sustainable Agriculture Reviews 14: Agroecology and Global Change*, Sustainable Agriculture Reviews 14, DOI 10.1007/978-3-319-06016-3_11,

soils in a sustainable fashion so that they will provide for human needs in the future. However, the measurement of soil processes and of the soil properties linked to these also depend on the use and location of the soil. When evaluating soil quality, it is therefore common to explore a range of soil physical, chemical, and biological properties. The single most important property determining the soil quality is the soil organic system because of the profound influence it has on soil physical, chemical, and biological properties. Therefore, many steps already taken to improve soil quality are dealing with improving soil organic matter status and hence, the vitality of the soil organic system. Some of the common ways to improve soil quality include: reduced tillage, use of green manure, application of animal manures, crop rotations, strip cropping, use of cover crops, application of sludge or biosolids, and other additions of organic materials and nutrients. These management techniques enhance the activity of both the micro- and macro-biological soil organic system, whose activities also improve properties such as soil aggregation, infiltration, and water holding capacity, decrease bulk density, penetration resistance and soil erosion, and increase cation exchange capacity. Management for soil quality can also lead to reduced need for agrochemicals and tillage, reduced fuel consumption by farm equipment, and increased sequestration of CO_2 in the soil, all of which benefit the environment. Modern agricultural science has the ability to correct many of the poor practices of the past and to maintain healthier soils that should sustain the uses they are put to.

Therefore, this review will be focused on the integrated nutrient management to enhance plant nutrition, restore degraded soils, identify site-specific parameters as indicators of soil quality, and describe the impact of soil quality improvements on increasing agronomic production and advancing global food security. Integrated nutrient management and its effect on different soil quality indicators will be also addressed.

Keywords Integrated nutrient management • Soil quality • Chemical indicators • Physical indicators • Biological indicators • Plant nutrition

M. Amer
Soil, Water and Environment Institute, Agricultural Research Center, Giza, Egypt
e-mail: megahedamer14@yahoo.com

É. Domokos-Szabolcsy • M. Fári
Plant Biotechnology Department, Debrecen University,
Böszörményi Útca. 138, 4032 Debrecen, Hungary
e-mail: domokosszabolcsy@gmail.com; fari@agr.unideb.hu

N. Elhawat
Plant Biotechnology Department, Debrecen University,
Böszörményi Útca. 138, 4032 Debrecen, Hungary

Department of Biological and Environmental Sciences, Faculty of Home Economics,
Al-Azhar University, Cairo, Egypt

J. Prokisch
Institute of Bio- and Environmental Energetics, Debrecen University,
Böszörményi Útca. 138, 4032 Debrecen, Hungary
e-mail: jprokisch@agr.unideb.hu

Introduction

The beneficial effect of adding mineral elements e.g., plant ash or lime to soils to improve plant growth has been known in agriculture for more than 2,000 years. Nevertheless, even 150 years ago it was still a matter of scientific controversy as to whether mineral elements function as nutrients for plant growth. It was mainly to the credit of Justus von Liebig (1803–1873) that the scattered information concerning the importance of certain elements for plant growth was compiled and summarized and that the mineral nutrition of plants was established as a scientific discipline. These achievements led to a rapid increase in the use of mineral fertilizers. By the end of the nineteenth century, especially in Europe, large amounts of potash, super phosphate and, later, inorganic N were used in agriculture and horticulture to improve crop growth and production (Kirkby 2012).

For over 150 years, scientists have studied plant nutrition with goals of understanding the acquisition, accumulation, transport, and functions of chemical elements in plants. From these studies, much information has been obtained about the growth and composition of plants in response to soil borne elements and to fertilization of crops in the soil or in soil-less media, as in hydroponic culture of plants. A compilation of elements known as plant nutrients and beneficial elements has also been developed from this work. Plant nutrients are chemical elements that are essential for plant growth. For an element to be essential, it must be required for a plant to complete its life cycle, it must be required by all plants, and no other nutrient can replace this requirement fully. If an element does not meet all of these requirements, for example, being required by some plants or only enhancing the growth of plants, the element may be a *beneficial element*. Much interest in plant nutrition lies in the development and use of diagnostic techniques for assessment of the status of plants with respect to plant nutrients and beneficial elements (Barker and Pilbeam 2007).

In 1939, two University of California plant physiologists, A. I. **Arnon** and P. R. **Stout**, published criteria for plant nutrient element essentiality – criteria that are still acknowledged today. These authors concluded that, for an element to be considered essential, three criteria must be met:

1. A given plant must be unable to complete its lifecycle in the absence of the element.
2. The function of the element must not be replaceable by another element.
3. The element must be directly involved in plant metabolism – for example, as a component of an essential plant constituent such as an enzyme – or it must be required for a distinct metabolic step such as an enzyme reaction.

Between 1922 and 1954, Mn, Cu, Zn, Mo, B, and Cl were determined to be essential. The 16 essential elements and beneficial mineral elements, their discoverers, and the discoverers of their essentiality are listed in Tables 3 and 4. Plant physiologists today continue to apply the three requirements set forth by Arnon and Stout over 60 years ago in attempts to determine whether additional elements are essential plants. Recent plant nutrition studies suggest that two additional elements, nickel (Ni) and silicon (Si), should be added to the list, although many plant nutritionists have yet to be convinced that Ni and Si meet all the requirements for essentiality set by Arnon and Stout (Jones 2003).

Table 1 Selected properties of micronutrients and beneficial mineral elements

Element	Atomic number	Atomic mass	Atomic radius[a] (pm)	Density (20 °C, g cm^{-3})	Valence[b]	Melting point (°C)
Al, aluminum	13	26.98	143	2.69	**+3**	660
As, arsenic	33	74.92	139	5.78	−3, **+3**, +5	817
B, boron	5	10.81	117	2.34	**+3**	2,079
Br, bromine	35	79.9	122	7.59	**−1**	−7.2
Cl, chlorine	17	35.42	97	3.21	−1	−100.9
Co, cobalt	27	58.93	167	8.9	**+2**, +3, +4	1,495
Cu, copper	29	63.54	157	8.96	**+1**, +2	1,083
F, fluorine	9	18.99	57	1.69	**−1**	−219.6
Fe, iron	26	55.8	172	7.87	+2, **+3**, +4, +6	1,535
I, iodine	53	126.9	132	4.93	**−1**	113.9
Li, lithium	3	6.94	205	0.53	+1	180.5
Mn, manganese	25	54.9	179	7.44	**+2**	1,244
Mo, molybdenum	42	95.9	201	10.2	+2, +3, +4, +5, **+6**	2,617
Na, sodium	11	22.99	180	0.79	+1	97.8
Ni, nickel	28	58.69	162	8.90	**+2**, +1, +3, +4	1,454
Rb, rubidium	37	85.47	298	1.52	+1	38.9
Se, selenium	34	78.96	122	4.28	**−2, +2**, +4, +6	217
Si, silicon	14	28.08	117	2.33	+2, −4, **+4**	1,410
Sr, strontium	38	87.63	245	2.46	+2	704
Ti, titanium	22	47.87	200	4.5	+2, 3, **+4**	3,287
V, vanadium	23	50.94	192	6.1	+2, +3, +4, **+5**	1,890
Zn, zinc	30	65.38	153	7.13	**+2**	419.6

Compiled from Enghag (2004), Kabata-Pendias and Mukherjee (2007) and Kabata-Pendias (2011)
[a]Approximately average values for the main oxidation states
[b]Valences value in bold are for the main oxidation states. PM = picometers = 10^{-12} m

According to this previous and strict definition, an element which alleviates the toxic effects of another element e.g., Si for Mn toxicity, or one which simply replaces another element e.g., Na for K may not be described as essential for plant growth (Kirkby 2012).

Plant tissue is primarily composed of carbon, hydrogen, and oxygen. These elements are derived from the fixation of atmospheric CO_2 and from the uptake of soil H_2O, and are generally available in ample quantities. However, virtually all naturally occurring elements are also found in plants, and more than 10 are essential for growth. Mineral nutrients are generally classified into macronutrients, required by plants at relatively large concentrations i.e., N, P, K, S, Ca and Mg and micronutrients, which are required in much lower quantities e.g., Cl, Fe, B, Mn, Zn, Cu, Mo and Ni. Still other elements are beneficial to plants but probably not essential for growth such as Na, Si, Co and Se. Micronutrients are predominantly bound in enzymes, where they often have important functional roles at the active sites, whereas macronutrients are constituents of organic macromolecules e.g., N, P, and S in proteins and nucleic acids or act as osmotica such as K (Tables 1, 2, 3, 4, 5, and 6; Shehata and El-Ramady 2012; Niklaus 2007).

Table 2 Selected properties of rare earth elements (Adapted from Kabata-Pendias and Mukherjee 2007)

Element	Atomic number	Atomic mass	Ionic radius[a] (pm)	Density (g cm^{-3})	Valence[b]	Melting point (°C)
Sc, scandium	21	44.96	88.5–102	2.9	**+3**	1,541
Y, yttrium	39	88.91	104–121.5	4.4	**+3**	1,522
La, lanthanum	57	138.9	117	6.15	+3	918
Ce, cerium	58	140.2	115	6.77	+3, +4	798
Pr, praseodymium	59	140.9	113	6.77	**+3, +4**	931
Nd, neodymium	60	144.2	143	7.00	+2, +3, +5	1,021
Sm, samarium	62	150.4	135	7.52	+3, +2	1,074
Eu, europium	63	151.9	131	5.24	**+3, +2**	8,022
Gd, gadolinium	64	157.3	108	5.90	**+3**, +2, +1	1,313
Tb, terbium	65	158.9	106	8.23	**+3**, +4	1,356
Dy, dysprosium	66	162.5	121	8.55	+2, +3, +4	1,412
Ho, holium	67	164.9	104	8.79	+3	1,474
Er, erbium	68	167.3	103	9.06	+3	1,529
Tm, thulium	69	168.9	117	9.32	**+3**, +2	1,545
Yb, ytterbium	70	173.0	116	6.97	**+3**, +2	819
Lu, lutetium	71	174.9	100	9.84	+3	1,663

Note: Density at 20 °C

[a]Given is one, the lowest value

[b]Valences value in bold are for the main oxidation states. PM = picometers = 10^{-12} m

Table 3 Characterization of macronutrients from the uptake by plants, abundance in earth crust, movement in both soil and plants to the principal form for plant uptake (From Shehata and El-Ramady 2012)

	WMP × 10^3 (2012)	Abundance in Earth's crust (%)	Concentration[a] (mg l^{-1})	Uptake by plants	Movement in soil	Mobility in plant	Principal forms for uptake
N	137,000 (NH_4)	20 ppm	100–200	Passive and active (NO_3^-)	Mass flow (NO_3^-) diffusion (NH_4^+)	Mobile	NO_3^- and NH_4^+ ions
P	210,000	0.10	30–50	Active ($H_2PO_4^-$)	Diffusion	Mobile	HPO_4^{2-}, $H_2PO_4^-$ PO_4^{-3}
K	34,000	1.90	10–200	Active, K^+	Diffusion	Mobile	K^+ cations
Ca	No data	3.64	20–300	Passive (Ca^{+2})	Mass flow	Immobile	Ca^{+2} cations
Mg	750	1.93	30–50	Passive (Mg^{+2})	Mass flow	Moderately immobile	Mg^{+2} cations
S	70,000	0.06–0.1	70–150	Active (SO_4^{-2})	Mass flow (SO_4^{-2})	Moderately mobile	SO_4^{-2} anions

(continued)

Table 3 (continued)

	Usual soil content	Critical level in plants (dry wt.)	Toxic level	Major antagonistic elements	Major synergistic elements	Most important sources
N	0.03–0.3 % N	3.0 % N, 0.1 % NO_3-N in leaf petioles	>5.0 %	B, Cu and K	B, Cu, Fe and Mo	Organic matter and N_2 from the atmosphere
P	0.01–0.1 % P	0.25 % total P, 500 ppm P in leaf petioles	>1.0 % in leaves	Al, B, Cd, Cr, Cu, F, Fe, Pb, Mn, Mo, Ni, Sc, Si, and Zn	Al, B, Cu, F, Fe, Mn, and Zn	Ca-, Al-, Fe-phosphates
K	0.2–3.0 % K	2.0 % dw	>5.0 % dw	Al, B, Cd, Cr, F, Mn, Mo, and Rb	Mn and Fe	Micas, Illite, and potassium feldspar
Ca	0.2–1.5 % Ca	1.0 %	>5.0 % dw	Al, B, Cd, Cu, Fe, Mn, and Zn	Cu, Mn, and Zn	Feldspar, augite, hornblende, $CaCO_3$ and $CaSO_4$
Mg	0.1–1.0 % Mg	0.25 %	>1.5 % dw	Al, Be, Cr, Co, Cu, Fe, Mn, and Zn	Al and Zn	Augite, hornblende, biotite, olivine, and $MgCO_3$
S	0.01–0.1 % S	0.3 %	No data	As, Fe, Pb, Mo, and Se	F and Fe	Iron sulfide and sulfate

WMP = World mine production by USGS (2013) and data in **metric tons** of usable ore
For nitrogen: as world ammonia production from plants; for phosphorus: as phosphate rock
For potash: as metric tons of K_2O equivalent
[a]Concentration in nutrient solution

Table 4 Discovery and origin and selected properties of micronutrients and beneficial mineral elements (From Shehata and El-Ramady 2012)

	Discovery (year)	Name origin	R. No.	Earth (ppm)	Ocean (ppm)	E N	Most important minerals
Al	H. C. Oersted (1825)	From Latin word *alumen*	3	8.2×10^4 or 8.2 %	0.002	1.61	Corundum Al_2O_3 Boehmite AlO(OH) Gibbsite or hydrargillite $Al(OH)_3$
B	Gay-Lussac and Thénard (1808)	Arabic word *buraq* or Persian *burah* (name of borax)	37	10	4.44	2.04	Borax, tincal $Na_2B_4O_7\times10H_2O$ Colemanite $Ca_2B_6O_{11}\times5H_2O$ Kernite $Na_2B_4O_7\times4H_2O$ Ulexite $NaCaB_5O_9\times8H_2O$

(continued)

Table 4 (continued)

	Discovery (year)	Name origin	R. No.	Earth (ppm)	Ocean (ppm)	E N	Most important minerals
Br	Antoine J. Balard (1826)	From Gr. Word *brômos* (stench)	50	2.4	67.3	2.96	Raw materials: in evaporated salt lakes and in the water of the Dead Sea
Cl	C. W. Scheele (1774)	From the Greek word *khlôros* (green)	19	145	1.94×10^4	3.16	Halite, rock salt NaCl Sylvite, sylvine KCl Sylvinite NaCl (KCl)
Co	Georg Brandt (1735)	German word *kobalt* or *kobold*, evil spirit	30	25	2×10^{-5}	1.88	Skutterudite $(Ni, Co)As_3$ Cobaltite (CoAsS) Linnaeite $(Co, Ni)_3S_4$
Cu	Known 5000 BC	Latin *Cuprum*	26	60	2.5×10^{-4}	1.90	Chalcopyrite $CuFeS_2$ Malachite $Cu_2(OH)_2(CO_3)$ Cuprite Cu_2O
F	Joseph H. Moissan (1886)	From the Latin word *fluo* (flow)	13	585	1.3	3.98	Fluorite, fluorspar CaF_2 Fluorapatite $Ca_5(PO4)_3F$ Cryolite Na_3AlF_6
Fe	Known ancient times	From the Latin word *ferrum* (iron)	4	5.63×10^4	0.002	1.83	Hematite Fe_2O_3 Magnetite Fe_3O_4 Siderite $FeCO_3$
I	Courtois (1811)	From Gr. word *iôdes* (violet)	63	0.45	0.06	2.66	Iodine from Chilean nitrate ores or sea organisms (brown seaweed)
Mn	J. Gahn (1774)	From *Latin word mangnes*, magnet	12	950	2×10^{-4}	1.55	Pyrolusite MnO_2 manganite MnO(OH)
Mo	P. Hjelm (1781)	From Gr. word *molubdos* (lead)	58–59	1.2	0.01	2.16	Molybdenite (MoS_2) Molibdite (MoO_3)
Na	Davy (1807)	From Latin word *natrium*, sodium	6	2.36×10^4	1.08×10^4	0.93	Albite, sodium feldspar $NaAlSi_3O_8$ Halite, rock salt NaCl
Ni	Alex F. Cronstedt (1751)	From Ger. word *kupfernickel* (false copper)	23	84	5.6×10^{-4}	1.91	Pentlandite $(Ni,Fe)_9S_8$ Gersdorffite NiAsS Garnierite $(Ni,Mg)_6(OH)_8Si_4O_{10}$
Rb	Bunsen (1861)	From Latin word *rubidus* (red)	22	90	0.12	0.82	Follows lithium in lepidolite
Se	Berzelius (1817)	From Gr. word *Selênê* (Moon)	69	0.05	2×10^{-4}	2.55	Berzelianite, silver-white mineral Cu_2Se
Si	J. J. Berzelius (1824)	From the Latin word *silex* (flint)	2	28×10^4 or 28 %	2.2	1.90	Quartz, SiO_2 Kaolinite $Al_2(OH)_4Si_2O_5$ Serpentine $Mg_3(OH)_4Si_2O_5$

(continued)

Table 4 (continued)

	Discovery (year)	Name origin	R. No.	Earth (ppm)	Ocean (ppm)	E N	Most important minerals
V	Del Rio (1801)	Goddess Vanadis (Scandinavian)	20	120	0.0025	1.63	Vanadinite ($Pb_5(VO_4)_3Cl$) Patronite (VS_4)
Zn	Marggraf (1746)	German word *zin* (meaning tin)	24	70	0.0049	1.65	Sphalerite, zinc blende (Zn, Fe)S Smithsonite $ZnCO_3$

R. No. = Ranking in order of abundance in earth crust, EN = Electronegativity (Pauling), Earth = Mean content in earth crust in ppm or g ton^{-1}, Ocean = Mean content in oceans in ppm g ton^{-1} and data from Enghag (2004), **Name Origin** from http://www.chemicalelements.com/index.html

Table 5 The common minerals and fertilizers of macronutrients (From Shehata and El-Ramady 2012)

	Common minerals	Common fertilizers or carriers		
	Mineral (formula)	Source	(%)	Formula
N	The atmosphere with 78 % nitrogen by volume	Ammonium nitrate	34	NH_4NO_3 (Solid)
		Ammonium sulfate	21	$(NH_4)_2SO_4$ (Solid)
	Sodium nitrate $NaNO_3$ (Chile saltpeter) is the most important raw materials	Anhydrous ammonia	82	NH_3 (Gas)
		Urea	46	$CO(NH_2)_2$ (Solid)
		Sulfur-coated urea	40	$CO(NH_2)_2$-S (Solid)
		Urea-formaldehyde	38	$CO(NH_2)_2$-CH_2O (Solid)
P	Variscite ($AlPO_4$ $2H_2O$)	ADHP	21	$NH_4H_2PO_4$ (11 % N)
	Strengite ($FePO_4$ $2H_2O$)	DAHP	21	$(NH_4)_2HPO_4$ (81 % N)
	DCPD ($CaHPO_4$ $2H_2O$)	Single super phosphate	16–22	$Ca(H_2PO_4)_2$ (11.5 % S)
	DCP ($CaHPO_4$)	Triple super phosphate	44–53	$Ca(H_2PO_4)_2$ (1.5 % S)
	Hydroxyapatite ($Ca_5(PO_4)_3OH$)	Phosphoric acid	34	H_3PO_4
	Fluoroapatite ($Ca_5(PO_4)_3F$)	Rock phosphate	25–40	$[Ca_3(PO_4)_2]_3$. CaF_x. $(CaCO_3)_x$ $[Ca(OH)_2]_x$
K	Orthoclase ($KAlSi_3O_8$)	Potassium chlorite	60–62	KCl
	Muscovite ($Kal_3Si_3O_{10}(OH)_2$)	Potassium sulfate	50–52	K_2SO_4 (17 % S)
	Biotite ($K(Mg, Fe)_3$ $AlSi_3O_{10}$ $(OH)_2$)	Potassium nitrate	44	KNO_3 (13 % N)
		K- orthophosphates	30–60	K_3PO_4 (30–50 % K_2O)
Ca	Anorthite ($CaAl_2Si_2O_3$)	Single super phosphate	20	$Ca(H_2PO_4)_2 + CaSO_4$ $2H_2O$
	Calcite (CaCO3)	Triple super phosphate	14	$Ca(H_2PO_4)_2$
	Gypsum ($CaSO_4$ $2H_2O$)	Gypsum	23	$CaSO_4$ $2H_2O$
	Dolomite ($[Ca\ Mg(CO_3)_2]$)	Calcium nitrate	19	$Ca(NO_3)_2$

(continued)

Table 5 (continued)

	Common minerals	Common fertilizers or carriers		
	Mineral (formula)	Source	(%)	Formula
Mg	Epsomite ($MgSO_4$ $7H_2O$)	Magnesia	55	MgO
	Bloedite ($Na_2Mg(SO_4)_34H_2O$)	Magnesium nitrate	16	$Mg(NO_3)_2$
	Biotite ($K(Mg, Fe)_3$ $AlSi_3O_{10}(OH)_2$)	Magnesium sulfate	10	$MgSO_4 \cdot H_2O$
	Magnesite ($MgCO_3$)	K- magnesium sulfate	11	$K_2SO_4 \cdot MgSO_4$
S	Gypsum ($CaSO_4$ $2H_2O$)	Ammonium sulfate	24.2	$(NH_4)_2SO_4$ (21 % N)
	Epsomite ($MgSO_4$ $7H_2O$)	Ferrous sulfate	18.8	$FeSO_4$ H_2O (32.8 % Fe)
	Mirabilite (Na_2SO_4 $10H_2O$)	Sulfur-coated urea	10–20	$CO(NH_2)_2 + S$ (37 % N)
	Pyrite (FeS_2)	Zinc sulfate	17.8	$ZnSO_4$ H_2O (36.4 % Zn)
	Chalcopyrite ($CuFeS_2$)	Gypsum	19	$CaSO_4$ $2H_2O$
	Galena (PbS)	Ammonium thiosulfate	26	$(NH_4)_2S_2O_3$

DCPD dicalcium phosphate dehydrate, *DCP* Dicalcium phosphate, *ADHP* Ammonium dihydrogen phosphate, *DAHP* Diammonium hydrogen phosphate

Table 6 Characterization of micronutrients from the uptake by plants, abundance in earth crust, movement in both soil and plants to the principal form for plant uptake (From Shehata and El-Ramady 2012)

	World mine production (2012)	Abundance in the Earth's crust (ppm)	Conc. in nutrient solution (mg l^{-1})	Uptake by plants	Movement in soil	Mobility in plant	Principal forms for uptake
B	4,600	10	0.3	Passive	Mass flow and diffusion	Immobile	Borate $(BO_3)^{-3}$ and H_3BO_3
Cl	No data	145–640	50–1,000	Active	Mass flow	Mobile	Cl^-
Cu	17,100	25–75	0.01–0.1	Active	Mass flow	Immobile	Cupric cation (Cu^{2+})
Fe	3,000,000	**5 %**	2–12	Active	Mass flow ans diffusion	Immobile	Ferrous (Fe^{2+}) and ferric (Fe^{3+})
Mn	16,000	716–1,400	0.5–2.0	Active	Diffusion and root interception	Immobile	Manganous (Mn^{2+}) cation
Mo	250,000	1.1	0.05	Active	Mass flow and diffusion	Immobile	Molybdate (MoO_4^{2-}) anion
Zn	13,000	52–80	0.05	Active	Mass flow and root interception	Immobile	Zinc (Zn^{2+}) cation

(continued)

Table 6 (continued)

	Usual soil content (mg kg^{-1})	Critical level in plants (ppm dw)	Toxic level (ppm dw)	Major antagonistic elements	Major synergistic elements	Most important sources
B	5–100	25	>100	Ca, P, K, and N	P and N	
Cl	300	20	>0.5 %	NO_3^-, SO_4^{-2}	–	
Cu	20	5	>50	Ca, Mg, P, and N	Ca, P, and N	Tourmaline accessory in silicates and salts
Fe	0.5–4.0 %	50	>400	Ca, Mg, P, and S	P, N, and S	Halite, sylvite (KCl) and carnallite (potassium magnesium chloride hexahydrate)
Mn	200–400	25	>400	Ca, Mg, P, and K	Ca and P	Copper sulfide, sulfate, and carbonate
Mo	0.5–5.0	0.1	Not known	P, K, and S	N and P	Augite, hornblende, biotite, olivine, iron oxide, and hydroxide
Zn	63	15	>300	Ca, Mg, and P	Ca, Mg, and P	Manganite, pyrolusite; accessory in silicates
						Accessory in silicates; Fe and Al oxides and hydroxides
						Zinc phosphate, carbonate and hydroxide; accessory in silicates

	Common minerals	Common fertilizers		
	Mineral (formula)	Source	(%)	Formula
B	Ulexite ($NaCa\ B_5O_9\ 8H_2O$)	Boric acid	17	H_3BO_3
	Borax ($Na_2B_4O_7\ 10\ H_2O$)	Borax	11	$Na_2B_4O_7 \cdot 10H_2O$
	Colemanite ($Ca_2B_6O_{11}.5H_2O$)	Sodium borate[a]	20	$Na_2B_4O_7$
	Kernite ($Na_2\ B_4O_6.\ 3H_2O$)	Sodium pentaborate	18	$Na_2B_{10}O_{16}.10H_2O$
		Na- tetraborate pentahydrate	14	$Na_2B_4O_7.5H_2O$
		Boron oxide	31	B_2O_3
Cl	Halite (NaCl)	Ammonium chloride	66	NH_4Cl
	Carnallite ($KMg\ (H_2O)_6\ Cl_2$)	Calcium chloride	65	$CaCl_2$
	Chloro-apatite ($Ca_5\ (PO_4)_3$)	Magnesium chloride	74	$MgCl_2$
	Cerargyrite (AgCl)	Potassium chloride	47	KCl
		Manganese chloride	56	$MnCl_2$

(continued)

Table 6 (continued)

	Common minerals	Common fertilizers		
	Mineral (formula)	Source	(%)	Formula
Cu	Chalcopyrite ($CuFeS_2$)	Copper sulfate pentahydrate	25	$CuSO_4.\ 5H_2O$
	Bornite (Cu_2FeS_4)	Copper sulfate monohydrate	35	$CuSO_4.\ H_2O$
	Chalocite (Cu_2S)	Cupric oxide	75	CuO
	Convellite (CuS)	Cuprous oxide	89	Cu_2O
	Cuprite (Cu_2O)	Copper acetate	32	$Cu(C_2H_3O_2)_2.\ H_2O$
	Malachite ($Cu_2CO_3(OH)_2$)	Copper ammonium phosphate	32	$Cu(NH_4)PO_4.\ H_2O$
	Azurite ($Cu_2(CO_3)_2(OH)_2$)	Copper chloride	17	$CuCl_2$
Fe	Hematite (α-Fe_2O_3)	Ferrous sulfate	19	$FeSO_4 \cdot 7H_2O$
	Maghemite (γ-Fe_2O_3)	Ferric sulfate	23	$Fe_2(SO_4)_3 \cdot 4H_2O$
	Magnetite (Fe_2O_3)	Ferrous oxide	77	FeO
	Geothite (α-FeOOH)	Ferric oxide	69	Fe_2O_3
	Lepidocrocite (γ-FeOOH)	Ferrous ammonium sulfate	14	$(NH_4)_2SO_4FeSO_4 \cdot 6H_2O$
	Ferrihydite ($Fe_2O_3.nH_2O$)	Iron ammonium polyphosphate	22	$Fe(NH_4)HP_2O_7$
	Ilmenite ($FeTiO_3$)	Ferrous ammonium phosphate	29	$Fe(NH_4)PO_4 \cdot H_2O$
Mn	Manganite (γ-MnOOH)	Manganese sulfate	27	$MnSO_4.\ 3H_2O$
	Hausmanite (Mn_3O_4)	Manganese oxide	69	MnO
	Pyrolusite (β-MnO_2)	Manganese oxide	63	MnO_2
	Lithisphorite [(Al, Li) $MnO_2(OH)_2$]	Manganese carbonate	31	$MnCO_3$
	Birnessite ($Na_xCa_yMn_7O_{14}$ $2.8H_2O$)	Manganese chloride	17	$MnCl_2$
		Manganese EDTA chelate	12	MnEDTA
Mo	Molybdenite (MoS_2)	Sodium Molybdate	39	$Na_2MoO_4.2H_2O$
	Molibdite (MoO_3)	Ammonium molybdate	54	$(NH_4)_6Mo_7O_{24}.2H_2O$
	Wulfenite ($PbMoO_4$)	Molybde trioxidenum	66	MoO_3
	Powellite ($CaMoO_4$)	Molybdenum sulfide	60	MoS_2
Zn	Sphalerite (ZnS)	Zinc sulfate (monohydrate)	36	$ZnSO_4 \cdot H_2O$
	Smithsonite ($ZnCO_3$)	Zinc sulfate (heptahydrate)	23	$ZnSO_4 \cdot 7H_2O$
	Hemimorphite ($Zn_4Si_2O_7(OH)_2.\ H_2O$)	Zinc oxide	78	ZnO
	Zinc bloom ($Zn_5(OH)_6(CO_3)_2$)	Zinc carbonate	52	$ZnCO_3$
	Zincite (ZnO)	Zinc sulfide	67	ZnS
	Willemite (Zn_2SiO_4)	Zinc phosphate	51	$Zn_3(PO_4)_2$
		Zinc EDTA chelates	14	$Na_2ZnEDTA$
		Zinc HEDTA chelate	9	NaZnHEDTA

For B: as boric oxide (B_2O_3)
World mine production by USGS (2013) and data in **× 10^3 *metric tons*** of usable ore
[a]Anhydrous

Table 7 Classification of plant nutrients according to biochemical behavior and physiological function (Adapted from Mengel et al. 2001)

Nutrient	Uptake	Biochemical functions
Group 1		
C, H, O, N, S	as CO_2, HCO_3^-, H_2O, O_2, NO_3^-, NH_4^+, N_2, SO_4^{2-}, SO_2 ions from the soil solution, gases from the atmosphere	Major constituents of organic material Essential elements of atomic groups involved in enzymatic processes Assimilation by oxidation-reduction reactions
Group 2		
P, B, Si	as phosphates, boric acid or borate, silicic acid from the soil solution	Esterification with alcohol groups Phosphate esters involved in energy transfer reactions
Group 3		
K, Na, Ca, Mg, Mn, Cl	as ions from the soil solution	Non-specific functions establishing osmotic potential. More specific functions for optimal confirmation of enzymes (enzyme activation) Bridging of reaction partners Balancing anions Controlling membrane permeability and electrochemical potentials
Group 4		
Fe, Cu, Zn, Mo	as ions or chelates from the soil solution	In chelated form in prosthetic groups of enzymes Enable electron transport by valency change

Elements may be classified – in addition to their relative concentrations within the plant – according to biochemical behavior and physiological function. Mengel et al. (2001) proposed a scheme for all plant nutrients including C, H and O as well as some non-essential elements (Si and Na) are considered. This scheme includes four groups can be distinguished as follows (Table 7):

I. **The first group**: it includes the major constituents of organic plant material: C, H, O, N and S. These elements are constituents of amino acids, proteins, enzymes and nucleic acids, the building blocks of life. The assimilation of all these nutrients by plants is closely linked with oxidation-reduction reactions.
II. **The second group**: P, B and Si constitute a second group of elements with close similarities in biochemical behavior. All three are taken up from the soil solution as inorganic anions or acids and occur in this form in plant cells or are bound by hydroxyl groups of sugars to form phosphate, borate and silicate esters.
III. **The third group**: it is made up of K, Na, Ca, Mg, Mn and Cl, all of which are taken up from the soil solution in the form of their ions. In plant cells, they are also present in ionic form where they have non-specific functions, e.g. in establishing electro-potentials.
IV. **The forth group**: this group includes the cations which associated with diffusible or indiffusible anions, e.g. Ca with oxalate or with the carboxylic groups of pectins in cell walls. Magnesium can also be bound very strongly by coordinate

and covalent bonds (chelation) as occurs in the chlorophyll molecule. The ability of Mg, Ca and Mn to form chelates means that these elements closely resemble those of the fourth group, Fe, Cu, Zn and Mo, which are predominantly present in plants in chelated form. An important function of these latter elements is to facilitate electron transport by valency change (Kirkby 2012).

The concepts of soil quality, soil health, and soil quality/health assessment are highly contentious within the soil science community, because many believe those terms have generalized and oversimplified the collective knowledge and wisdom developed through several centuries of intensive, indepth, global studies of soil resources. A common theme is that soil quality/health assessments are impossible and meaningless because of the complexity of soil resources. They suggest research and education should be focused on developing quality soil management practices rather than on soil quality or soil health. Proponents of soil quality argue that although soil scientists have long recognized the many unique and important properties and processes provided by fragile soil resources, outside the agricultural community, soils remain largely an under-valued resource (Karlen et al. 2003). The assessments are viewed as tools intended to alert users, in a manner analogous to a "consumer price index," that soil resource problems have or may be occurring (Karlen et al. 2008).

We contend that both groups really want the same outcomes – an improved public awareness of the importance of soil resources and a better understanding of how short-term economic decisions impact long-term properties and processes. Both camps embraced a 2004 special section in *Science* (11 June 2004) recognizing soil as "*The Final Frontier*" in order to highlight the importance of this resource and to draw attention to our incomplete knowledge of soil properties, processes and functions. The articles illustrated how processes occurring in the top few centimeters of Earth's surface are the basis of all life on dry land, but concluded that the opacity of soil has severely limited our understanding of how it functions (Sugden et al. 2004). Being among the proponents for soil quality/health assessment, it is impossible to fully comprehend and represent our counterparts' viewpoints. Our goal for this paper is to focus and clarify our perception of soil quality/health and the need for periodic assessment. Hopefully this will help address their concerns and incorporate suggestions for improvement into an assessment framework that will ultimately lead to quality soil management and improved decisions regarding fragile soil resources throughout the world (Karlen et al. 2008).

Current efforts to define soil quality/health and develop multi-factor assessment protocols can be traced to publications from the 1970s (Alexander 1971). This coincided with increased emphasis on "*Sustainable Agriculture*" during the mid- to late 1980s (National Research Council (NRC) 1989) that brought public attention to the increasing degradation of soil resources and the implications for environmental health. In Canada, the Canadian Soil Quality Evaluation Program was one of the first national efforts focused specifically on soil quality assessment. As discussion of and interest in the concepts of soil quality and soil health spread worldwide (Karlen et al. 2001), many questions were raised regarding the sustainability of current soil and crop management decisions. Several ideas for assessment evolved following publication of quantitative formula for assessing soil quality (Larson and Pierce 1991) and efforts to relate changes in various indicators to soil management practices. Interest in soil quality among natural resource conservationists, scientists, farmers and policymakers increased (Karlen et al. 2008).

Environmental biology may be characterized by interactions between geological and anthropogenic sources and life. Geological sources provide biological systems with major, minor, and trace elements. Elements present in soils are influenced by a variety of geological processes. If environmental conditions permit the elements to be available to plants, some will be taken up while others will be rejected. What is taken up becomes available to grazing animals and humans. Anthropogenic sources provide both essential and nonessential elements. In some cases, elements do not have to be biologically available to present health problems. Some elements or compounds may impact the epithelial cells in the respiratory system merely by mechanical irritation and cause damage. Often, human activities may lead to the movement of elements from places where they reside outside of biological systems to places where their inherent chemical nature is realized (Lindh 2005).

It is well documented that in addition to oxygen, carbon dioxide and water, plants require at least 14 mineral elements for adequate nutrition (Mengel et al. 2001). Deficiency in any one of these mineral elements reduces plant growth and crop yields. Plants generally acquire their mineral elements from the soil solution. Six mineral elements, nitrogen, phosphorus, potassium, calcium, magnesium and sulphur, are required in large amounts, whilst chlorine, boron, iron, manganese, copper, zinc, nickel and molybdenum are required in smaller amounts (Table 8). In geographical areas of low phytoavailability, essential mineral elements are supplied to crops as fertilizers to achieve greater yields. In addition, fertilizers containing essential mineral elements for human nutrition are occasionally supplied to crops to increase their concentrations in edible portions for the benefit of human health (White and Brown 2010).

It is thought that, geology may appear far removed from human health. However, rocks and minerals comprise the fundamental building blocks of the planet and contain the majority of naturally occurring chemical elements. Many elements are essential to plant, animal, and human health in small doses. Most of these elements are taken into the human body via food, water, and air. Rocks, through weathering processes, break down to form the soils on which crops and animals are raised. Drinking water travels through rocks and soils as part of the hydrological cycle and much of the dust and some of the gases contained in the atmosphere are of geological origin. Hence, through the food chain and through the inhalation of atmospheric dusts and gases, human health is directly linked to geology (Selinus et al. 2005).

It is clear that, for both commercial and environmental reasons, fertilizers should be used with caution, and that crop production for future food security will require sustainable fertilizer management, which might include more sophisticated decision support tools, improved agronomic practices and crops or cropping systems that require less fertilizer input. High concentrations of mineral elements in the soil solution can inhibit plant growth and reduce crop yields, as shown in Table 8

Table 8 The main chemical forms in which mineral elements are acquired from the soil solution by roots, and the critical leaf concentrations for their sufficiency and toxicity in non tolerant crop plants

Element or nutrient	Form acquired	Essentiality: Plant and animal	Critical leaf concentrations: Sufficiency	Critical leaf concentrations: Toxicity
Macronutrients (% DM)				
Nitrogen, **N**	NH_4^+, NO_3^-	Ess and Ess	1.50–4.00	>5.0
Potassium, **K**	K^+	Ess and Ess	0.50–4.00	>5.0
Phosphorus, **P**	$H_2PO_4^-$	Ess and Ess	0.20–0.50	>1.0
Calcium, **Ca**	Ca^{2+}	Ess and Ess	0.05–1.00	>10.0
Magnesium, **Mg**	Mg^{2+}	Ess and Ess	0.15–0.35	>1.5
Sulphur, **S**	SO_4^{2-}	Ess and Ess	0.10–0.50	0.5–0.7
Micronutrients (mg g^{-1} DM)				
Chlorine, **Cl**	Cl^-	Ess and Ess	0.1–6.0	4.0–7.0
Boron, **B**	$B(OH)_3$	Ess and Sug	$5.0–100 \times 10^{-3}$	0.1–1.0
Iron, **Fe**	Fe^{2+}, Fe^{3+}, Fe-chelates	Ess and Ess	$50–150 \times 10^{-3}$	>0.5
Manganese, **Mn**	Mn^{2+}, Mn-chelates	Ess and Ess	$10–20 \times 10^{-3}$	0.2–5.3
Copper, **Cu**	Cu^+, Cu^{2+}, Cu-chelates	Ess and Ess	$1.0–5 \times 10^{-3}$	$15–30 \times 10^{-3}$
Zinc, **Zn**	Zn^{2+}, Zn-chelates	Ess and Ess	$15–30 \times 10^{-3}$	$100–300 \times 10^{-3}$
Nickel, **Ni**	Ni^{2+}, Ni-chelates	Ess and Sug	0.1×10^{-3}	$20–30 \times 10^{-3}$
Molybdenum, **Mo**	MoO_4^{2-}	Ess and Ess	$0.1–1.0 \times 10^{-3}$	1.0
Beneficial and other trace elements (mg kg^{-1} DM)				
Selenium, **Se**	SO_4^{2-}, SO_3^{2-}	Bena and Ess	0.1–2.0[b]	5.0–30
Cobalt, **Co**	Co^{2+}	Ben and Ess	0.02–1.0	10–20
Silicon, **Si**	$Si(OH)_4$	Ben and Sug	<0.5 % most species	[c]
Sodium, **Na**	Na^+	Ben and Ess	0.05–2.0[d]	$2–5 \times 10^3$
Iodine, **I**	I^-	Ben and Ess	–	1.0–20
Fluorine, **F**	F^-	Ben and Sug	5.0–30	50–300
Vanadium, **V**	VO_3^-	Ben and Sug	2.0–1.5	1.0–10
Aluminium, **Al**	Al^{3+}	Ben and –	–[e]	40–200
Lithium, **Li**	Li^+	– and Sug	3.0	10–200
Lead, **Pb**	Pb^2+	– and Sug	5.0–10.0	10–300
Arsenic, **As**	H_2AsO^{-4}, H_3AsO_3	– and Sug	1.0–1.7	5.0–20
Chromium, **Cr**	Cr^{3+},CrO_4^{2-},$Cr_2O_7^{2-}$	– and Sug	0.1–5.0	5.0–30

Source: Pilon-Smits et al. (2009), White and Brown (2010), Kabata-Pendias (2011) and White et al. (2012)

The critical concentration for sufficiency is defined as the concentration in a diagnostic tissue that allows a crop to achieve 90 % of its maximum yield. The critical concentration for toxicity is defined as the concentration in a diagnostic tissue above which yield is decreased by more than 10 % (White et al. 2012)

Abbreviations: *Ess* essential, *Sug* suggested, *Ben* beneficial

[a]Beneficial, according to Kabata-Pendias (2011). According to Pilon-Smits et al. (2009):

[b]≤0.01 % non -Se accumulators, 0.01–0.1 % Se accumulators and ≥0.1 % Se hyperaccumulators

[c]10–15 % horsetails, commelinid monocots

[d]<0.05 % non-halophytes and >0.25% in halophytes

[e]<0.1 % non-accumulators and ≥0.1 % Al accumulators

(Mengel et al. 2001). In particular, toxic concentrations of Mn, Al, B, Na, Cl and Fe occur frequently on agricultural soils. Toxicities of Mn and Al occur on acid mineral soils, toxicities of B and Na occur on sodic (Na-rich) soils, and toxicities of Na and Cl occur on saline soils, throughout the world. Na, B and Cl toxicities and imbalances of Ca, Mg and K also occur in irrigated agriculture. In addition, Mn and Fe toxicities can occur on waterlogged or flooded soils and specific geological formations can result in toxicities of particular mineral elements, such as Ni, Co and Cr toxicities on certain serpentine soils and Se toxicity on seleniferous soils (White and Brown 2010).

Unfortunately, anthropogenic activities have led to toxic concentrations of Zn, Cu, Cd, Hg and Pb in particular environments. Often, traditional agronomic countermeasures allowing crop production on such soils are expensive and only partially or temporarily successful. Plant breeders are therefore developing crop genotypes that tolerate these soils. As is the case with wild plants, physiological mechanisms that allow crop plants to grow on soils containing high concentrations of mineral elements are based on their exclusion from the plant and/or tolerance of these elements through their sequestration as non-toxic compounds and/or in non-vital cellular compartments (Marschner 2002).

In general, plants uptake many elements through their roots and more than 50 elements have been found in various plants. However, not all are considered to be essential elements. The essential nutrients required by green plants are exclusively inorganic, and an essential element may be defined as one that is required for the normal life cycle of a green plant and whose role cannot be assumed by another element. Twenty elements are thought to be essential to the growth of most plants, and they are usually classified as macronutrients and micronutrients. Figure 1 shows that different nutrients are very important for plant growth and also for crop productivity, even micro- and macro-nutrients and also beneficial mineral elements.

Therefore, it could be concluded that, the definition of soil quality encompasses physical, chemical and biological characteristics, and it is related to fertility and soil health. Many indicators can be used to describe soil quality, but it is important to take into account sensitivity, required time, and related properties, than can be explained. This review will focus on the relation between plant nutrition and soil quality. This will include integrated nutrient management, and its relation to soil quality, managing soil quality and productivity, impact of soil health on the environment and finally different soil quality indicators as affected by different cultivated crops. The different soil quality indicators also will be highlighted.

Soil Quality Definition

The interest in soil quality can be traced back to the ancient Roman civilization and before that. Trough the time, the use of agricultural residues, application of organic matter, rotation, and tillage practices has been fundamental in maintaining soil fertility. One important discovery, at the end of the nineteenth century, was the nitrogen fixing microorganisms, associated with roots that opened the door to a better understanding

Fig. 1 These photos explain that plants can uptake many elements through their roots and more than 50 elements have been found in various plants. However, not all are considered to be essential nutrients. The essential nutrients required by green plants are exclusively inorganic, and an essential element may be defined as one that is required for the normal life cycle of a green plant and whose role cannot be assumed by another element (Photos by H. El-Ramady and M. Fári)

of rhizosphere and the development of soil ecology as related to soil fertility. Traditional soil management in agriculture is based on temperate crop rotations with grass crops for livestock production, improving soil structure and increasing fertility, with an important role of animals and natural fertilizers. After the Second World War, this traditional system was reduced, increasingly separating livestock from arable land, which lead to the elimination of grass and animal manure application in many arable crop systems. Soil management was neglected, leading to growing concerns about the physical condition of the soil, soil erosion and leaching of nutrients. These concerns triggered definitions of national policies in Canada, United States and England aiming at land conservation and recovery of soil's ability to meet its multiple functions, concepts that finally met in "soil quality" (Martinez-Salgado et al. 2010).

It has been of interest to humankind ever since the dawn of civilization and settled agriculture. Some ancient civilizations e.g. those in the valleys of the Nile, Indus and Yangtze thrived for millennia because soil quality was maintained by the alluvial processes of the specific rivers that supported these cultures. However, many ancient cultures perished because they could not maintain or enhance the quality of their soil resources. Decline in soil quality by accelerated erosion and the attendant degradation toppled many ancient civilizations by washing/blowing away the very foundation on which they developed (Lowdermilk 1939). Whereas, the concern of soil quality has challenged humankind for at least 10,000 years, the definition and the basic concepts remain a work in progress and keep evolving with every generation. A soil scientist of Moorish Spain, Ibn-Al-Awam, wrote several volumes during the twelfth century on agricultural issues. The book '*Kitab al-Felhah*' or 'Book of Agriculture' was translated into Spanish in 1802. The book was brought to public attention in 1802 in the 'Encyclopedia of Islam' (1760–1777). In the book, the author writes: '*The first step in science of agriculture is the recognition of soils and of how to distinguish that which is of good quality and that which is of inferior quality.' The best of all soils, according to the author, are the alluvium of river valleys 'because of the mud with which they are mixed, for the running water brings sediments removed from the surface of the soil along with dead leaves and manure*' (Banqueri 1802; Lal 2004).

Although the concept of soil quality has been embraced since ancient times and attempts to quantify it date back to the early 1940s (Kellogg 1943), agreement on assessing and interpreting soil quality remains elusive (Karlen et al. 2003). Nevertheless, there is broad consensus on the critical importance of soil quality to the integrity of terrestrial ecosystems and their ability to recover from disturbances such as drought, climate change, pollution, and agricultural impacts (Fernandez et al. 2006). A major limitation of traditional approaches to quantifying the relationship between soil quality and productivity is the confounding effect of landscape quality factors such as topography, hydrology, and climatic parameters (Zvomuya et al. 2008).

When evaluating an agricultural management system for sustainability, the central question is: Which production system will not exhaust the resource base, will optimize soil conditions, and will reduce food production vulnerability while at the same time maintaining or enhancing productivity? Soil quality can be seen as a conceptual translation of the sustainability concept toward soil. It could be summarized some different soil quality definitions in Table 9.

Table 9 Development of the definition of soil quality and some of the most important cited soil quality definitions during the last 25 years

Soil quality definition	Reference
The sustained capability of a soil to accept, store and recycle water, nutrients and energy	Anderson and Gregorich (1984)
The capacity of soils to function within the ecosystem boundaries and to interact positively with the environment external to that ecosystem	Larson and Pierce (1991)
The capacity of a soil to function, within ecosystem and land use boundaries, to sustain biological productivity, maintain environmental quality, and promote plant and animal health	Doran and Parkin (1994)
The degree of fitness of a soil for a specific use	Gregorich et al. (1994)
Ability of soil to perform or function according to its potential, and changes over time due to human use and management or to unusual events	Mausbach and Tugel (1995)
The capacity of a specific kind of soil to function, within natural managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation	Karlen et al. (1997)
Quality of soil, as distinct from health, is largely defined by the ability of soil to perform various intrinsic and extrinsic functions. Quality is represented by a suite of physical, chemical, and biological properties that together: (i) provide a medium for plant growth and biological activity; (ii) regulate and partition water flow and storage in the environment; and (iii) serve as an environmental buffer in the formation and destruction of environmentally hazardous compounds	Doran and Safley (1997)
Encompassing an indefinite (open) set of tangible or dispositional attributes of the soil. These attributes may be substituted for or supplemented by other attributes without needing to change the term. Therefore, it is a vessel to contain what is assigned to it. The attributes assigned to the term will differ among soil and the various demands, because the term is influences by value judgements	Patzel et al. (2000)
Soil quality can be defined as the fitness of a specific kind of soil, to function within its capacity and within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation	Arshad and Martin (2002)
The capacity of soil to perform specific functions of interest to humans	Lal (2004)
Soil quality is defined by the interactions of a particular soil's measurable chemical, physical, and microbiological properties	Baldwin (2009)

It could be analyzed this definition as follows: the first part, "*the capacity of a soil to function*": There are a number of "functions" carried out by the soil. For example, soil is a medium for the growth of plants and animals, a place where gases are exchanged, where water and energy moves, and where pollution can be neutralized. How well the soil can perform these tasks relates to its "capacity to function". The second part of the soil health definition says "*within ecosystem and land use boundaries*". Soils function differently within different ecosystems and land uses. Therefore, the capacity of the soil to function is not the same everywhere. It is dependant upon the surrounding ecosystem and the use the soil is put to. Examples of different potential land uses include urban, agricultural cropland, pasture, or native systems such as prairie, forest, or wetlands. "Normal" soil function in an urban setting would be different than "normal" function in an agricultural setting, and both would be different than "normal" function in a wetland, for example. The third part of the definition states "*to sustain biological productivity*". The soil is a major ecological setting within which organisms thrive. More species probably exist below the soil surface than above it. How well a soil is performing its function as a "household" for soil organisms, and therefore sustaining biological productivity, is a major component of soil health. Next, the definition says "*maintain environmental quality*". Soils serve as a natural filter. As long as they are not overwhelmed with excessive amounts of pollutants, they can remove many harmful pollutants from soil water before it reaches the ground water or moves into rivers and streams, and can remove carbon dioxide from the atmosphere as a part of the soil–plant system. Through their pollution filtering effects, healthy soils help to maintain environmental quality. Finally, the soil health definition states "*and promotes plant and animal health*". Healthy plants require soils with an appropriate balance of nutrients in which to grow, healthy herbivores require plants with an appropriate balance of nutrients on which to graze, and healthy carnivores require herbivores with an appropriate balance of nutrients they can eat. Ultimately, the health of all land organisms is tied to the soil. Therefore, healthy soils are required for healthy plants and animals all the way up the food chain, including healthy humans (Brevik 2009).

As mentioned before, soil quality is not new topic. Prior to the mid-1980s, controlling soil erosion and minimizing its effect on crop productivity were major foci for North American soil management research. Gradually attention broadened to include sustainable agriculture, environmental health and prevention of further soil resource degradation. An important outcome of this expansion was the Canadian Soil Quality Evaluation Program and its assessment of soil health (Acton and Gregorich 1995). They were among the first to propose a quantitative formula for assessing soil quality and relating the changes to soil management practices. As a result, soil quality was recognized and interpreted as a more sensitive and dynamic way to measure soil condition, response to management changes and resilience to stresses imposed by natural forces or human uses.

In **1994, Dr Larry Wilding**, president of the Soil Science Society of America appointed a 14-person committee to define the soil quality concept, examine its rationale and justification, and identify the soil and plant attributes that would be useful for describing and evaluating it. The Committee presented its first report in the June 1995 issue of *Agronomy News*, stating that the simplest definition for soil quality is 'the capacity (of soil) to function'. An expanded version by Karlen et al. (1997) defined soil quality as 'the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation' (Karlen et al. 2004).

A comparative soil quality evaluation is one in which the performance of the system is determined in relation to alternatives. The biotic and abiotic soil system attributes of alternative systems are compared at some time. A decision about the relative sustainability of each system is made based on the difference in magnitude of the measured parameters (Larson and Pierce 1994). A comparative assessment is useful for determining differences in soil attributes among management practices that have been in place for a certain period (Wienhold et al. 2004). In a dynamic assessment approach, the dynamics of the system form a meter for its sustainability (Larson and Pierce 1994). A dynamic assessment is necessary for determining the direction and magnitude of change a management practice is having (Wienhold et al. 2004), especially when compared to the common, existing farmer practices and it must be understood that this assessment normally must involve an adequate time frame (Verhulst et al. 2010).

Because soil quality cannot be measured comprehensively with a single indicator, soil quality assessments often focus on determining a "*minimum data set*" (MDS) of soil characteristics with the greatest influence on soil quality. A huge variety of MDS has been proposed, corresponding to differing selection and combination of these properties depending on the location, scale and objectives of different studies. In the MDSs proposed in the literature, soil organic matter (SOM), texture and density are almost unanimously present (Masto et al. 2008) among numerous other physical and chemical properties. The biological properties of soil can be taken into account directly (Bohanec et al. 2007; Kaschuk et al. 2010) or indirectly by assuming a correlation between the density of soil microflora and the SOM content in mineral soils (Garrigues et al. 2012). Moron (2005) proposed that the indicators used to quantify soil quality must be sensitive to detect changes, easy to measure and interpret, and accessible to many users. In this way, they will constitute an effective tool to show changes in soil important properties. There is a need to establish critical values in order to determine what soils and what functions of those soils are being damaged or recovered.

The biochemical properties of soil have been used widely to evaluate soil quality, both individually and combined in simple indexes and in more complex ones, which stresses the fact that the scientific community recognizes their potential value. Generally, biochemical properties related to the biocycles of the elements such as C, N, P and S are used to diagnose soil quality. These properties include both general biochemical parameters i.e., microbial biomass C, dehydrogenase activity and N mineralization potential, and specific biochemical parameters i.e., the activity of hydrolytic enzymes, such as phosphatase, urease and β-glucosidase. Biochemical properties can be used both individually, as simple indices, or in combination using complex equations derived from mathematical combinations or the application of statistical programs (Gil-Sotres et al. 2005).

Therefore, it could be concluded that, efforts to define and quantify soil quality are not new, but establishing consensus about a set of standardized indicators remains difficult. Also, the view of land managers is usually not taken into account when evaluating various sets of indicators. Several soil quality definitions have been proposed. One of the most widely used is that of Doran and Parkin (1994): "*the capacity of a soil to function, within ecosystem and land use boundaries, to sustain productivity, maintain environmental quality, and promote plant and animal health*". Soil quality is a combination of soil physical, chemical and biological properties that are able to readily change in response to variations in soil conditions. As environments differ as well as the soil functions of interest, there is no methodology to characterize soil quality based on a universal set of indicators.

Agricultural Management Practices and Soil Quality

Agricultural activities as part of the natural resource management (NRM) practice impact soil and water quality at the watershed or catchment level (Twomlow et al. 2008). The negative effects on soil quality that lead to soil degradation can be broadly classified in two categories. One negative effect is caused by soil loss by water and wind erosion (den Biggelaar et al. 2004), and the second negative effect takes place due to deterioration in physical, chemical and biological properties of the soil (Poch and Martinez-Casanovas 2006). The causes of physical, chemical and biological deterioration include loss of organic matter, waterlogging, salinization and alkalization of the soil, and the contamination of water resources. It has been observed that the intensification of production systems without adequate investment to sustain the system, results in the loss of fertility (Pathak et al. 2005). The effects of loss of soil fertility are manifested as reduced yields due to reduced soil quality (Lal 2004). However, it is not necessary that agricultural practices always have a negative impact on soil quality and productivity. It is possible through quality soil and water and nutrient management practices to improve or maintain soil quality and sustain productivity at the same time. The changes in soil quality are monitored using a range of physical (soil erosion, depth, aggregation and aggregate stability, bulk density, infiltration, total and air-filled porosity, compaction, hydraulic conductivity), chemical (pH, organic C, total N, electrical conductivity, cations and acidity, available macro- and micronutrients) and biological (microorganisms, microbial biomass and activity, respiration, mineralizable N, microbial biomass C and N, earthworm and termite biomass) characteristics (Sahrawat et al. 2010).

The underlying principle of improved or quality management for sustaining productivity and soil and water quality under rainfed conditions in the semi-arid tropics (SAT) is based on exploiting the synergy between soil and water conservation practices and integrated nutrient management (INM) practice (supply of nutrients through mineral and organic sources) at the watershed level (Bationo et al. 2008). Agricultural production being an integrated interactive effect of soil-water-fertilizer-climate continuum, a judicious and scientific management of this complex system is crucial for enhancing crop productivity on a sustained basis. Among the various inputs, water and fertilizer (nutrients) are considered as the two key inputs making maximum contribution to crop productivity and soil quality. Efficient management of these two costly inputs together with synergistic interaction with other appropriate production factors is most critical for any crop cultivar to achieve its genetic yield potential. Soil management through different agricultural practices like tillage can further optimize their use efficiencies. Technologies developed on the principles of eco-friendly and efficient balanced fertilization and based on optimization of nutrient supplies from all the available sources, inorganic and organic, for predetermined yield targets of the cropping sequences through an efficient combination of soil, water, organic matter, tillage and nutrient management, will provide a prescription for sustainable agricultural development. Since sustainability of agricultural production system has become an issue of national and international concern, one of the options is to assess the soil quality as impacted by the various soil and crop management practices. Hence, the present investigation was undertaken to quantify the interactive effects of tillage, water and nutrient practices on soil quality and crop productivity in rice-wheat and maize-wheat cropping systems (Fig. 2; Singh 2010).

It could be asked that, what makes a healthy soil. Is soil merely a solid medium that holds nutrients for plant growth? Increasing concern for the sustainability of our natural resources has led to the development of a more complex concept of soil health. Karlen et al. (1997) proposed the following as vital soil functions: (1) sustaining biological activity, diversity, and productivity; (2) regulating and partitioning water and solute flow; (3) filtering, buffering, degrading, immobilizing, and detoxifying organic and inorganic materials, including agricultural, industrial and municipal by-products and atmospheric deposition; (4) storing and cycling nutrients and other elements within the Earth's biosphere; and (5) providing support of socioeconomic structures and protection for archeological treasures associated with human habitation. The term "soil quality" has been coined to describe the combination of chemical, physical, and biological characteristics that enables soils to perform a wide range of functions (Evanylo and McGuinn 2009).

It is well known that, soil health is presented as an integrative property that reflects the capacity of soil to respond to agricultural intervention, so that it continues to support both the agricultural production and the provision of other ecosystem services. The major challenge within sustainable soil management is to conserve ecosystem service delivery while optimizing agricultural yields. It is proposed that soil health is dependent on the maintenance of four major functions: carbon transformations; nutrient cycles; soil structure maintenance; and the regulation of pests and diseases. Each of these functions is manifested as an aggregate of a variety of biological processes provided by a diversity of interacting soil organisms under the influence of the abiotic soil environment. Analysis of current models of the soil community under the impact of agricultural interventions (particularly those entailing substitution of biological processes with fossil fuel-derived energy or inputs) confirms the highly integrative pattern of interactions within each of these functions and leads to the conclusion that measurement of individual groups of organisms, processes or soil properties does not suffice to indicate the state of the soil health. A further conclusion is that quantifying the flow of energy and carbon between functions is an essential but non-trivial task for the assessment and management of soil health (Kibblewhite et al. 2008).

Maintaining soil quality for various diverse uses is a complex problem, but it is agreed that the use of soil quality indicators with threshold values (Dexter and Zoebisch 2006) can help in developing management practices that sustain productivity and maintain environmental quality (Pathak et al. 2005). Recent research on soil quality in relation to agricultural practices suggests that the degradation of top

Fig. 2 Soil management through different agricultural practices can further optimize their use efficiencies. Technologies developed on the principles of eco-friendly and efficient balanced fertilization and based on optimization of nutrient supplies from all the available sources, inorganic and organic, for predetermined yield targets of the cropping sequences through an efficient combination of soil, water, organic matter, tillage and nutrient management, will provide a prescription for sustainable agricultural development (Photos by H. El-Ramady and M. Fári)

soils is usually reversible, while degradation of sub-soils is rather more difficult to reverse or in some instances may even be irreversible (Dexter and Zoebisch 2006). Importantly, the complementarities between conservation and productivity objectives make watershed or catchment development an attractive option and an entry point for implementing agricultural and rural development activities in the semi-arid areas of India (Wani et al. 2005). Attempts have also been made to develop a land quality index specifically for dryland crops such as sorghum in the semi-arid tropical regions of India (Mandal et al. 2001). Such focused research is important and needs encouragement as this fosters the development of a sustainable system with proper choice of crop and natural resource management practices in an integrated way (Sahrawat et al. 2010).

The degradation of soil and water resources, especially in the developed countries has clearly brought home the message that these natural resources are finite and that the mismanagement of soil resource can have adverse effects on environmental quality including surface and groundwater quality and global warming (Lal 2007). Indeed, the environmental concerns have focused attention on the development of NRM practices that conserve soil and water resources, sustain productivity and maintain environmental quality. The adverse effects of agricultural practices as a part of NRM on soil quality occur when farming systems are intensified, without due consideration to the conservation of soil and water resources, through non-judicious use of agricultural chemicals, especially pesticides and mineral fertilizers (Sahrawat et al. 2005). The adverse effects on the soil quality also take place when land in the sensitive ecosystems such as semi-arid and arid regions with porous soils are used for intensified production systems disregarding soil and water conserving practices in NRM (Sahrawat et al. 2010; Lilburne et al. 2004).

Good soil quality is essential not only for increased productivity, but also for the agroecosystem to provide its services and benefits derived from the regulation of ecosystem processes. Soil also plays a key role in providing agroecosystem supporting services such as nutrient cycling and primary productivity (Wani et al. 2005). These agroecosystem benefits cannot be derived from a degraded land resource base. Thus, maintaining the soil quality is of paramount importance and critical for the soil to perform its production and environment-related functions on a sustainable basis (Twomlow et al. 2008).

For sustained productivity, the maintenance of soil fertility on a long-term basis is a prerequisite. For sustained soil fertility, it is essential that organic matter and nutrients removed in harvest or produce plus those lost through physical, chemical and biological processes are compensated through external addition on a regular basis such that organic matter status is maintained and nutrient balances are not negative in the longer term. Moreover, the maintenance of soil organic matter level at a threshold level, which depends on the soil type and climatic factors, is of critical importance for maintaining the physical, chemical and biological integrity of the soil, and to perform its agricultural productivity and environmental functions on a sustainable basis (Bationo et al. 2008). The changes in soil quality are monitored using a range of physical (soil erosion, depth, aggregation and aggregate stability, bulk density, infiltration, total and air-filled porosity, compaction, hydraulic conductivity), chemical (pH, organic C, total N, electrical conductivity, cations and acidity, available macro- and micronutrients) and biological (microorganisms, microbial biomass and activity, respiration, mineralizable N, microbial biomass C and N, earthworm and termite biomass) characteristics (Sahrawat et al. 2010).

Therefore, it could be concluded that, soil quality may be affected by land use type and agricultural management practices because these may cause alterations in soil physical and chemical properties and in soil biotic community determining, in turn, a reduction in land productivity. It has been reported that soil land use, arable versus pasture, influenced biological soil quality more than soil type.

Meaning of Soil Quality and Soil Health

Although the terms "soil quality" and "soil health" have been used synonymously (Doran 2002), their definitions must be differentiated. *Soil quality* is related to possible functions and uses of soil, but also on the location and scale of study. In contrast, soil health represents a holistic approach for understanding the soil system, independent of soil use and soil users. *Soil health* considers the soil as a finite, nonrenewable and dynamic resource. Although originally based on the idea of soil as a living entity, soil health has evolved to become the primary indicator of sustainable land management (Garrigues et al. 2012).

The terms *soil quality* and *soil health* are often used interchangeably to describe the soil's ability to support crop growth without becoming degraded or otherwise harming the environment. Farmers prefer the term *soil health* because it reflects a judgment of the soil as either a robust or ailing resource. The term also portrays the idea of soil as a living, dynamic entity that functions in a *holistic* way – it depends on the condition or state of its interacting parts – rather than as an inanimate entity with a value that depends on its innate characteristics and intended use (Romig et al. 1995). Soil quality, therefore, should be distinguished from a soil's *inherent* properties, which cannot be managed or adjusted by farmers. Inherent properties are determined by factors such as climate, topography, vegetation, parent material, and time. From a productivity standpoint, each soil has an innate capacity to function, and some soils will be inherently more productive than others. In organic farming, a high quality soil is one that provides an environment for optimum root growth, thereby enhancing crop health and productivity. Optimum root growth, however, will also be influenced by the plant species and its genetic potential, environmental conditions imposed by weather, and cultural practices used in the farming system (Baldwin 2009).

Soil quality is related to soil functions and soil health concepts views soil as a finite and dynamic living resource (Doran and Zeiss 2000). Plant health is clearly a component of soil health but necessarily not of soil quality (Karlen et al. 1997). Though the use of soil health has emerged in recent years, variation in ability of soils to suppress plant diseases is known since many decades (Janvier et al. 2007). Thus there is a considerable degree of overlap in the meaning of soil quality and soil health (Doran 2002), though soil health perceptions tend to focus more on biotic components of soil

(Anderson 2003). Soil degradation or deterioration in soil health or quality implies loss of the vital functions of soil: (i) providing physical support, water and essential nutrients required for growth of terrestrial plants; (ii) regulation of the flow of water in the environment and (iii) elimination of the harmful effects of contaminants by means of physical, chemical and biological processes, i.e., environmental buffer or filter (Bastida et al. 2006). The quality and health of soil determine agricultural sustainability and environmental quality, which jointly determine plant, animal and human health (Doran 2002). Minor variations in articulation and expression of soil functions and there are evident in the available literature (Laishram et al. 2012).

On the other hand, there are two ways in which the concept of soil health (or the closely related concept of soil quality) has been considered, which can be termed either 'reductionist' or 'integrated'. The former is based on estimation of soil condition using a set of independent indicators of specific soil properties – physical, chemical and biological. This approach has been much discussed and well reviewed (e.g. Doran et al. 1994; Doran and Jones 1996). This reductionist approach has much in common with conventional quality assessments in other fields, such as materials science. The alternative, integrated, approach makes the assumption that the health of a soil is more than simply the sum of the contributions from a set of specific components. It recognizes the possibility that there are emergent properties resulting from the interaction between different processes and properties. These aspects do not seem to have been explored to the same extent in recent literature. The definition of soil health is derived from a context

which we accept as an essential feature of sustainable agriculture, namely that agricultural production should not prejudice other ecosystem services that humans require from agricultural landscapes (Kibblewhite et al. 2008).

Therefore, the terms soil quality and soil health are often used interchangeably to describe the soil's ability to support crop growth without becoming degraded or otherwise harming the environment. Although the terms soil quality and soil health have been used synonymously, their definitions must be differentiated. Soil quality is related to possible functions and uses of soil, but also on the location and scale of study. In contrast, soil health represents a holistic approach for understanding the soil system, independent of soil use and soil users. Soil health considers the soil as a finite, nonrenewable and dynamic resource. Although originally based on the idea of soil as a living entity, soil health has evolved to become the primary indicator of sustainable land management.

Evaluation of Agricultural Soil Quality

It could be defined a healthy agricultural soil as follows: it is one that is capable of supporting the production of food and fibre, to a level and with a quality sufficient to meet human requirements, together with continued delivery of other ecosystem services that are essential for maintenance of the quality of life for humans and the conservation of biodiversity (Kibblewhite et al. 2008).

Agricultural soil quality evaluation is essential for economic success and environmental stability in rapidly developing regions. At present, a wide variety of methods are used to evaluate soil quality using vastly different indicators. Globally, accepted method of soil quality evaluation would assist agriculture managers, scientists, and policy makers to better understand the soil quality conditions of various agricultural systems. A better working knowledge of a soil's quality is important to improve sustainable land use management (McGrath and Zhang 2003), provide early warning signs of adverse trends, identify problem areas, and provide a valuable base against which subsequent and future measurements can be evaluated. This knowledge can only come from reliable, accurate soil quality evaluation. Comprehensive evaluation of agricultural soil quality, which refers to the condition and capacity of farmland including its soil, weather, and biological properties, for purposes of production, conservation, and environmental management (Pieri et al. 1995), is essential to making wise decisions that will improve crop production and environmental sustainability. Soil quality evaluation is still a developing, but promising field of agriculture science. With improved technical tools, information, and methodology for evaluating soil quality comes the ability to integrate significant, site-specific remediation strategies into agriculture operations (Ditzler and Tugel 2002). Though agricultural soil quality evaluation has progressed in recent years due, in large part, to the emphasis on global environmental change, improving soil quality evaluation is imperative for the development of sustainable agriculture and may also be used to judge the sustainability of soil management and land use systems (Smith et al. 1994; Wang and Gong 1998). Specifically, suitable evaluation methods and appropriate indicators of soil quality are among the most important considerations due to their significant influence on soil quality results (Qi et al. 2009).

Many soil quality evaluation methods have been developed since the USDA Soil Conservation Service released its land capability classification system in 1961 (Klingebiel and Montgomery 1961), such as a soil quality card design and test kit (Ditzler and Tugel 2002), soil quality index methods (Doran et al. 1994), multiple variable indicator kriging methods (Nazzareno and Michele 2004), and the dynamic variation of soil quality models (Larson and Pierce 1994). Among these, soil quality indices are perhaps the most commonly used methods today (Andrews et al. 2002), because they are easy to use and quantitatively flexibility. Soil quality indices are especially relevant to soil management practices because they use site-specific indicators of soil conditions that integrate anthropogenic effects over time and over multiple types of effects (Arshad and Martin 2002). Unfortunately, one of the most limiting aspects of soil quality evaluation today is the lack of a universally acceptable method for developing soil quality indices. There exists a tautological development of new indices, which appears to be endemic, self-propagating and little justified (Zhang et al. 2004), and researchers should place greater emphasis on evaluating the suitability of existing indices prior to developing new ones. A number of recent papers have evaluated soil quality, but usually a self defined indicator method and equation is introduced for which the indices were developed. To our knowledge, no comparison has been made among indices based on different indicator methods and models. A universally accepted index should include clear methods for indicator selection, scoring, and weighting, as well as a universal model that would aid in comparison of soils of different regions and in scientific communication. The development of a universal soil quality index should follow a logical path: (i) establish a representative indicator method, (ii) assign weights for selected indicators, and (iii) validate the index using a model. Indices formulated on ecological principles and properly validated will better communicate the complexity of quality integrity (Qi et al. 2009).

Therefore, it could be concluded that, using soil quality indices to evaluate agricultural soil quality can provide similar results even when different indicator methods and models have been used in the study area. It could be evaluated the soil quality using the Integrated Quality Index (IQI) and Nemero Quality Index (NQI) in combination with three indicator selection methods: Total Data Set (TDS), Minimum Data Set (MDS), and Delphi Data Set (DDS). In order for one method to become the standard for research and to facilitate discussion and cooperation, a standard should be rapid, reliable, and economically feasible. For this reason, the MDS indicator method is the most suitable of the three methods, because it adequately represents the TDS method and is more accurate than the DDS method. It could be suggested that, using the IQI index with the MDS indicator method as a starting point towards an international standard for future research. Care should be taken in determining which indicators are included in the MDS method.

Factors Controlling Soil Quality

Soil quality criteria and corresponding standards vary with soil function, which complicates the use of a common definition of soil quality. Thus, soil quality is best defined in relation to the function ascribed to the soil and interpreted using soil quality indicators based on quantitative measures selected according to that function, e.g., sustaining biological productivity, maintaining environmental quality, and promoting plant and animal health (Nortcliff 2002). A function particularly relevant to agricultural ecosystems is biological productivity, as measured by crop yield. The capacity of soil to sustain productivity is a function of intrinsic soil properties (soil quality) and extrinsic factors (landscape quality factors, e.g., precipitation, temperature, topography, and hydrology). Monitoring productivity and long-term sustainability of agricultural ecosystems relies on selecting a suite of intrinsic soil properties or soil quality indicators (Larson and Pierce 1994) that are measurable surrogates of physical, chemical, and biological soil attributes that determine how well a soil performs. These indicators can be classified as either inherent or dynamic (Wienhold et al. 2004). Inherent soil quality indicators are those attributes related to a soil's natural composition and properties as influenced by the factors and processes of soil formation, while dynamic indicators relate to soil properties and processes that change on a human time scale as a result of land use and management decisions. While the relationship between productivity and extrinsic factors is well established and considerable research effort has been directed toward determining the influence of management practices (e.g., tillage, crop rotation, organic amendments) on soil quality indices (Cambardella et al. 2004), less is known about the pattern of the relationship between soil quality and productivity (Zvomuya et al. 2008).

The ecosystem services provided by soil are driven by soil biological processes, but our concept of soil health embraces not only the soil biota and the myriad of biotic interactions that occur, but also the soil as a habitat (Young and Ritz 2005). The key concept here is that soil provides a living space for the biota, which is defined by the architecture of the pore networks. Indeed, it is the porous nature of soils that governs so much of their function since the physical framework defines the spatial and temporal dynamics of gases, liquids, solutes, particulates and organisms within the matrix, and without such dynamics there would be no function. The walls of soil pore networks provide surfaces for colonization, and their labyrinthine nature defines how, and to large extent where, organisms can move through the total soil volume (Kibblewhite et al. 2008).

Kibblewhite et al. (2008) summarized the factors controlling soil quality as follows:

(1) **Soil type:**

Particular soil types form in response to the nature of parent material, topography and environmental factors, such as climate and natural vegetation. Past land management by humans can alter natural soils considerably, for example by loss of surface horizons due to erosion, alteration of soil water regime via artificial drainage, salinization due to poor irrigation practices, loss of natural soil organic matter caused by arable production or contamination. Thus, land-use and management are the controlling factors for soil health. A set of fixed characteristics such as texture, stone content, etc. combine with climate to set an envelope of possible soil habitat conditions, especially those relating to the soil water regime. Variable factors such as pH, bulk density and soil organic matter content, which are influenced by land-use and management, then determine the prevailing condition of the habitat within the range for a particular soil. These fixed and variable abiotic factors interact with biotic ones to determine the overall condition of the soil system and its associated health. Primary biological factors will include the presence or absence of specific assemblages and types of organisms, the availability of carbon substrate and nutrients, and the concentrations of toxic materials.

(2) **Organisms and functions:**

The relationships between community structure and function are inevitably complex and a prevalent theme in contemporary soil ecology (Bardgett et al. 2005). They are underwritten by the three principles of repertoire (i.e. the 'toolkit' of available functions), interaction and redundancy (Ritz 2005). Relationships between diversity and function have been postulated to follow a number of forms (Swift et al. 1996), but rigorous experimental demonstration of these issues is relatively scarce, not least owing to the difficulty in manipulating soil biodiversity as the sole factor. There is some experimental evidence that there may be threshold levels of soil biodiversity below which functions decline (Setälä and McLean 2004). However, in many instances, this is at experimentally prescribed unrealistically low levels of diversity that rarely prevail in nature. Many studies demonstrate high levels of functional redundancy in soil communities (Setälä et al. 2005). It could be argued that high biodiversity within trophic groups is advantageous since the group is likely to function more efficiently under a variety of environmental circumstances, due to an inherently wider potential. More diverse systems may be more resilient to perturbation since if a proportion of components are removed or compromised in some way, others that prevail will be able to compensate.

(3) **Carbon and energy:**

The energy that drives soil systems is derived from reduced carbon that is ultimately derived from net primary productivity. Carbon is the common currency of the soil system, and its transfer with associated energy flows is the main integrating factor. This suggests that the quantities and quality of different organic matter pools may be indicative of the state of the soil system, while the flows and allocations of carbon between assemblages of organisms may provide information about their relationships to ecosystem functions.

(4) **Nutrients:**

Nutrients are a controlling input to the soil system and the processes within it. Their levels and transformations are critical to soil health. After carbon, the cycling of nitrogen and phosphorus to, from and within the soil system most affects its dynamics and the delivery of ecosystem services, including agricultural production. Manipulation of nutrient supplies to increase productive outputs from the soil system by the addition of fertilizers has been one of the keystones of agriculture for centuries. Nonetheless, knowledge is limited about the impacts of nutrient additions on the condition of different assemblages of soil organisms and thence on their functions. Generally, while it is considered that the availability of carbon substrate is normally the primary limiting factor on microbial activity in soils, this is not necessarily the case, and there is accumulating evidence that soil microbes may frequently be N limited (Schimel et al. 2005). Where demand for nitrogen is higher than its supply, the functional capacity of the soil system will be strongly influenced by N availability. When the soil system is disturbed, for example by tillage, losses via leaching or to the atmosphere are increased because mixing of the soil leads to more rapid decomposition of organic matter and the conversion rate of organic nitrogen to mineral forms may exceed the biological demand, particularly where balancing of available nitrogen to plant requirements is poorly managed. Agricultural strategies based on additions of animal manures and the use of mineral fertilizers counter losses of nitrogen, phosphorus and other nutrients with the aim of restoring and sustaining soil health. In well-managed systems employing high levels of manufactured, processed or mechanized inputs, where these strategies are implemented effectively, productivity is maintained, but it may be compromised in subsistence agriculture where nutrient additions are inadequate or absent. In industrial agriculture, on the other hand, additions of nutrients beyond that which can be used by the soil–plant system lead to their damaging leakage from the soil system into other environmental compartments via leaching and gaseous emissions. In this case the soil system is polluted and unhealthy (Kibblewhite et al. 2008).

Therefore, it could be concluded that, the capacity of soil to sustain productivity is a function of intrinsic soil properties or soil quality and extrinsic factors including landscape quality factors, e.g., precipitation, temperature, topography, and hydrology. factors controlling soil quality include soil type, organisms and functions, carbon and energy and nutrients.

Assessment of Soil Quality

With soil as a multifunctional resource, soil quality assessment must be approached considering both the ecosystem characteristics and primary purpose for which the evaluation is being made. The ultimate purpose of assessing soil quality is not to achieve high aggregate stability, biological activity, or some other soil property. The purpose is to protect and improve long-term agricultural productivity, water quality, and habitats of all organisms including people. By assessing soil quality, a land manager will be able to determine if a set of management practices is sustainable. For example, agricultural management systems located on the most suitable lands, according to their agro-ecological potentialities and limitations, are the best way to achieve sustainability.

It is well known that a good or healthy soil has the following properties:

- feels soft and crumbles easily
- drains well and warms up quickly in the spring
- does not crust after planting
- soaks up heavy rains with little runoff
- stores moisture for drought periods
- has few clods and no hardpan
- resists erosion and nutrient loss
- supports high populations of soil organisms
- has a rich, earthy smell
- does not require increasing inputs for high yields
- produces healthy, high-quality crops (Sullivan 2001)

Assessment of soil health across agricultural systems, soil types and climatic zones presents major scientific and policy challenges. Given the multicomponent nature of soil systems, the breadth of goods, services and functions that they are called upon to provide, and their spatial variability, a complex debate is to be expected about appropriate methods for soil assessment. Clearly, no single indicator will encompass all aspects of soil health, nor would it be feasible (or necessary) to measure all possible indicators. Emergent proposals for soil assessment are linked to the establishment of legal frameworks for the protection of soil at national (Defra 2004) and international levels. For example, the European Commission is implementing a Thematic Strategy for Soil Protection in Europe which identifies erosion, declining organic matter, contamination, compaction, salinization, loss in biodiversity, soil sealing, landslides and flooding as the main threats to soil. The soil system is an open one and its health is affected by external environmental and anthropogenic pressures. The reaction of the soil system to these pressures can be described in terms of resistance and resilience (Orwin and Wardle 2004). Resistance is denoted by the magnitude of the change in state for a given level of perturbation. It further indicates a change in conversion ratio, for example a reduction in the respiration rate arising from compaction. Resilience describes the capacity of the system to return to its original state following perturbation and reflects the 'self-healing' capacity of the soil system, a concept that maps onto that of self-organization. Indeed, resilience may be a way of measuring the capacity for self-organization in soils. Some formally demonstrated examples of soil resilience are where the soil structure rejuvenates following compaction (Griffiths et al. 2005), microbial biomass reverts to antecedent concentrations following a drying cycle (Orwin and Wardle 2004) or decomposition potential is restored following a temperature perturbation (Griffiths et al. 2004). If the perturbation is within the capacity, the soil system can recover to its original condition, but if not, a permanent loss of soil health is expected. For example, in the latter study, while the grassland soil under study was resilient to a heat perturbation, this was not the case where the soils were subjected to copper (Griffiths et al. 2004).

There are, however, practical difficulties which make assessment of soil system health by measurement of performance curves and reactions to external pressures rather problematic. First, there is difficulty in rigorously defining at least some of the ecosystem services other than food-and-fibre production. Second, soil systems are multifunctional and able to deliver a variety of combinations and levels of services, so that full evaluation of the system performance would require very extensive testing. Third, soil systems are open systems and their performance is variable and interactive with environmental factors, such as air temperature and precipitation, which are not easily controlled. Fourth, soil system performance does not respond instantaneously to altered conditions, and its assessment has to be made over significant time periods. In truth, field assessment of whole soil system performance requires long-term, complex and detailed experimentation which can pragmatically only be conducted at a restricted number of sites. While an alternative within-laboratory assessment may provide useful information that helps to understand better how the system operates under well-controlled experimental conditions, it cannot provide an assessment which is indicative of whole system performance in the field (Kibblewhite et al. 2008).

It could be identified critical processes in the soil system as transformations of carbon, cycling of nutrients, maintenance of the structure and fabric of the soil, and biological regulation of soil populations. There are existing techniques for assessing the performance of specific processes linked to these functions, such as respiration rates following organic matter addition, organic nitrogen mineralization rates during incubation, etc. While providing useful information about specific processes, these reflect the current activity within soil rather than any intrinsic capacity to support ecosystem services. An indication of the health of the soil system as a whole requires a more integrative approach. Individual processes are not related solely in a linear fashion, but within a network of interactions leading to a nonlinear system with associated feed-forward and feedback loops. It could be proposed that assessment of soil system health may be achieved using diagnostic tests, for example, abiotic ones that are indicative of the state of the habitat, i.e. physical and chemical conditions such as bulk density, aggregate stability, pH, cation exchange capacity, etc., and the levels of key energy and nutrient reservoirs such as ratios of organic matter fractions and nutrient balances; as well as biotic measures, such as those which are discussed below, which describe the community composition and populations of key functional groups of organisms such as earthworms, N fixers, pest-control populations, etc. (Kibblewhite et al. 2008).

Although there are many similarities between all soil systems, differences in soil forming factors over space and time have led to distinct soil populations with characteristic properties. Any scientific assessment of soil health has to be made with due regard to these different populations. Soils that are intrinsically very fertile, for example because they are deep, well drained and have a favourable texture and background nutrient content, may be in good or bad health, and in the latter case may only be able to support delivery of ecosystem services at levels below that of a less fertile soil that is in excellent (healthy) condition. A more instrumental approach is needed at the individual field level to support operational decision making about nutrient additions, pesticide applications, cultivation timing, etc. Nonetheless, assessment of soil health by analysis of changes, trends and ranges using diagnostic tests for soil habitat condition and biological community structure offers a powerful means for evaluating the impacts of climate, land use change and altered agronomic practices on the valuable natural capital represented by soil (Kibblewhite et al. 2008).

Proposals to assess soil quality emerged initially in the USA. An early proponent of the concept was Alexander (1971) who first suggested developing soil quality criteria. It could be followed the historical review of soil quality assessment as follows (adapted from Bone et al. 2010):

Event or citation	Details
Alexander (1971)	Soil quality has developed from the suggestion of Alexander (1971) that soil quality criteria should be developed, where proposals to assess soil quality emerged initially in the USA
Warkentin and Fletcher (1977)	Later in the 1970s, it was suggested that soil quality should be evaluated in relation to land function
Anderson and Gregorich (1984)	The interaction with holistic environmental quality, water and air quality was discussed in the mid-1980s
Bone et al. (2010)	There was much discussion of the subject in the 1990s including suggestion of minimum datasets for assessment, discussion about the differences between soil health and soil quality, and a differentiation between the intrinsic properties of a soil and soils productivity as a result of management practices (Larson and Pierce 1991; Pierce and Lal 1992; Mausbach and Tugel 1995; Romig 1995; Karlen et al. 1997; Seybold et al. 1998; Doran and Zeiss 2000)
Bone et al. (2010)	Pierce and Larson (1993) and Doran and Parkin (1994) developed the definition further by including key soil functions, the fitness for use and the dynamic state of soils in the definition of soil quality, which clearly inspired later definitions (Karlen et al. 1997; USDA-NRCS 2008), and soil protection policy (Blum et al. 2004; de Souza 2009)

Therefore, it could be summarized that, assessment of soil health across agricultural systems, soil types and climatic zones presents major scientific and policy challenges. It could be said that, no single indicator will encompass all aspects of soil health, nor would it be feasible or necessary to measure all possible indicators. Emergent proposals for soil assessment are linked to the establishment of legal frameworks for the protection of soil at national and international levels. There are existing techniques for assessing the performance of specific processes linked to these functions, such as respiration rates following organic matter addition, organic nitrogen mineralization rates during incubation, etc. While providing useful information about specific processes, these reflect the current activity within soil rather than any intrinsic capacity to support ecosystem services.

Changes in Physical, Chemical and Biological Soil Properties

In India, a long-term experiment (1975–1998) was conducted at farm in Patancheru to evaluate the impact of improved (broad-bed and furrow land treatment, cropping during rainy and post-rainy seasons with the implementation of soil and water conservation practices and integrated nutrient management) and traditional (cultivated rainy season fallow, post-rainy season cropping on flat land configuration) management practices on physical characteristics and productivity of Vertisols (Sahrawat et al. 2010). The results showed that after 23 years of imposition of the treatments, clay content decreased and gravel content increased in the surface (0–10 cm) soil layer under traditional compared to improved management. Other physical characteristics such as bulk density, total and air-filled porosity, penetration resistance and cumulative infiltration were also more favorably poised under improved than under traditional management practices. The decrease in the quality of soil physical parameters (texture and other physical properties) of Vertisols under traditional management might have been, at least in part, due to greater soil loss by erosion (El-Swaify et al. 1985). Soil loss by erosion results in not only in the loss of finer soil fraction, but also leads to loss of organic matter and other dissolved plant nutrients (Karanam et al. 2008). Moreover, the loss of soil chemical fertility and organic matter becomes a source of offsite pollution due to contamination by sediments and chemicals (Sahrawat et al. 2005). In India, soils in the semi-arid tropics (SAT) regions have relatively low contents of organic matter compared to their counterparts in the temperate or humid tropical regions. Moreover, the traditional farming practices followed by farmers in the dryland systems of the SAT regions do not help to maintain sufficient organic matter levels (Sahrawat et al. 2006). Soil organic matter contents directly or indirectly impacts the productivity and soil quality. Wani et al. (2003) reported the results of a long-term experiment conducted in Vertisol watersheds to determine changes in soil organic C and total N status. It was found that organic C and total N contents were significantly higher in the soil profile (0–120 cm depth) under improved management than under traditional management practices. In addition to changes in organic matter quantity and quality, potentially mineralizable soil N, soil properties such as microbial population and biomass, earthworm biomass and activity, and soil respiration serve as sensitive indicators of the impact of agricultural practices. Potentially mineralizable N in soil represents the active fraction of organic matter that contributes to the and crop management practices that enhance inputs of organic matter (use of crop rotations with legumes, and cover crops) to soil, reduced tillage and through the use of beneficial soil microorganisms (Sahrawat et al. 2010).

It is well established that, soil biological and biochemical properties have been proposed as sensitive indicators of soil degradation. Nevertheless, their potential to predict the deterioration of major soil functions related to physical stability, and water and nutrient storage and fluxes has not been validated under experimental conditions. Soil fertility is closely tied to soil physical and biological properties and their temporal development has been recognised as a decisive factor for sustainable soil use. Therefore, monitoring physical and biological soil properties became a legal duty within the amendment of the Environmental Protection Laws. Long-term monitoring observes soil physical and biological properties over space and time, helps to early detect and predict changes in soil quality, provides the legislature and implementing bodies with crucial information to support decision-making and allows them to take precautionary soil-protection measures. In addition, long-term monitoring makes a contribution to assess ecological sustainability within maintenance of natural resources.

Therefore, it could be concluded that, there are a lot of physical, chemical and biological indicators or properties should be monitored. The physical properties include soil colour and texture, bulk density, and water holding capacity, whereas the chemical indicators include soil pH, soil organic matter, nutrient dynamics, and so on. On the other hand, the biological properties include microbial biomass-C and -N, soil enzyme activities and so on. The sensitivity of these biological and biochemical variables should be monitored to follow changes in physical, chemical and biological soil properties.

Soil Quality and Soil Fertility

In soil science, during the last 20 years, a very important problem was in attention of researchers, state administrations and diverse ecological organizations: that of soil quality. Soil fertility denominates the phenomenon *fertility of the soil* which can be measured by different specific parameters. Quality is a philosophical category; it is identical with the existence of things and processes; it includes the ensemble of determinations which confers to the objects and processes a certain individuality in relation with the coexisting objects and processes and a certain stability in the running time. But, besides the quantitative determination, all processes and phenomena are also characterized by a quantitative determination, through: number of its component parts, size, development rhythm, volume, etc. In brief, quality includes different categories of phenomena; the quality may be appreciated (good, bad, etc.), but the phenomena may be quantified by parameters (Ştefanic and Gheorghiţă 2006).

The words fertility and quality of a soil are two distinct philosophical categories. The fertility is the fundamental feature of an agricultural soil, having all characteristics of a body impregnated with life. Its level can be quantified by certain parameters, corresponding to certain physiological and enzymic processes and certain specific substance accumulations. Biological quality of soil cannot be quantified or described by parameters, it can be appreciated as good, bad, useful, useless, etc. To use the notion of biological soil quality instead of that of fertility is a semantic mistake, which generates confusion in the human thinking. When some scientific or technical publications insert, among the parameters, those of crop yields, for soil fertility or soil quality level determination, they make other mistakes: firstly, by the confusion fertility – quality, and second, by ignoring the role of crop management practices which are capable to ensure high yields or low yields on the same soil fertility. The level of soil fertility must be quantified only on a base of soil intrinsic features (Ştefanic and Gheorghiţă 2006).

Therefore, it could be concluded that, the strong relationship between soil quality and soil fertility could be addressed within the following items: historical background for biological conception of soil fertility, towards agricultural management for sustainable soil quality, and finally soil quality and its fertility management.

Historical Background for Biological Conception of Soil Fertility

It is well documented that soil fertility has always been a primary focus and defining character in the tradition of sustainable organic agricultural systems. From a holistic view, soil fertility is a function of the biology of the whole farm, a view that sets it apart from conventional agriculture, whereby soil fertility is primarily seen as managing mineral nutrients field by field. Soil biology, discovering the evolution laws from the sterile rock to fertile soil, intervened vigorously in agriculture practice, recommending crop management practices which do not contravene to these laws. Thus, since 1924, Steiner initiated the doctrine of Biodynamic Agriculture, that his continuer Pfeiffer (1938) experimented in Europe, South Africa, Korea and USA, and Howard (1941) initiated the doctrine of Organic Agriculture in England and USA. After the second World War, agricultural practices, based on soil biological laws, were diversified, being framed in different trends of Biological Agriculture. Offensive of Ecological Organizations against any manner, of nature and human habitat degradation, was also reflected in soil cultivation, generating the doctrine and practices of Ecological Agriculture that includes, all other Biologic Agriculture types. Under the pressure of a new orientation of agrarian politics, in the biological science domain, the old theme of the definition and estimation of agricultural soil fertility was revised (Ştefanic and Gheorghiţă 2006).

It could be followed the historical background for biological conception of soil fertility as follows (adapted from Ştefanic and Gheorghiţă 2006):

Event or citation	Details
Vaillant (1901)	Wrote the higher the humus content is, the more fertile is the soil and this fertility seems to be due, especially, to a large number of dinitrogen fixing organisms living here
Remy (1902)	Pointed out that some tests in differentiate between soils used the decomposition rate of nitrogen organic compounds in soil, making evident the conception that soil fertility can be estimated by biological criteria
Winogradsky (after 1890)	Discovering variation of the number and activity of soil microflora, emitted the idea that the soil is a living organism
Christensen (1910–1915)	Was the first researcher who suggested that the power of a soil for disintegrating cellulose can serve as index of soil fertility
Waksman (1932)	Described the best the correlation of the vital and chemical processes in soil. He did not succeed to distinguish between the concept of soil fertility and that of soil productivity
Pavlovschi and Groza (1949)	Stated that if so far the feature of a living organism was not recognized to the soil, nobody contests that the arable soil is an organized biological medium
Steiner (1924) and Pfeiffer (1938)	Elaborated the theory and practice of Biodynamic agriculture, in Götheanum Institute – Dornach (Switzerland) and substantiated the conception that the soil behave like a living organism, ecologically integrated
Howard (1941)	The first definition of the soil fertility was given by, the founder, in England, of Organic farming: Soil fertility is the condition of a soil rich in humus, in which the growth processes are getting on fast and efficiently, without interruption…… there must be permanently an equilibrium between the growth processes and those of decomposition The key of fertile soil and a thriving agriculture is the humus
Maliszewska (1969)	Compared the biologic activities of various soils and suggested that respiration, proteolytic and cellulolytic activities are the most suitable parameters which correlate with soil fertility
Batistic and Mayaudon (1977)	Investigated the soil respiration and its enzymic activity under the influence of different treatments with N, P, K fertilizers and/or liquid dejections from cattle and concluded that the outstanding increase of respiration and enzymic activities of the soil, was only produced in organically fertilized treatments, that showed an increase of biological fertility of soil
Ştefanic (1994)	Fertility is the fundamental feature of the soil, that results from the vital activity of micropopulation, of plant roots, of accumulated enzymes and chemical processes, generators of biomass, humus, mineral salts and active biologic substances. The fertility level is related with the potential level of bioaccumulation and mineralization processes, these depending on the program and conditions of the ecological subsystem evolution and on anthropic influences
Ştefanic and Gheorghiţă (2006)	Soil fertility is the feature of the terrestrial loose crust to host complex processes (biotical, enzymical, chemical and physical) which store biomass, humus and minerals

Therefore, it could be concluded that, Ştefanic and Gheorghiţă (2006) gave a synthetic definition of soil fertility, easier, understood and used by farmers for realizing a sustainable, ecological agriculture. According to this definition, the agrotechnical measures applied to soil must improve and maintain the soil fertility and phytotechnical measures must ensure the plant growth, without damaging the vitality and cultural condition of a soil.

Towards Agricultural Management for Sustainable Soil Quality

It is well documented that, soil quality concepts are commonly used to evaluate sustainable land management in agroecosystems. Developing sustainable land management systems is complicated by the need to consider their utility to humans, their efficiency of resource use, and their ability to maintain a balance with the environment that is favorable both to humans and most other species. In particular, humanity is challenged to develop agricultural management systems that balance the needs for production of food and fiber with those for maintenance of the environment. It could be concluded that, a sustainable agriculture is to sustains the people and preserves the land. Soil quality is conceptualized as the major linkage between the strategies for agricultural conservation management practices and achievement of the major goals of sustainable agriculture. In short, the assessment of soil quality, and direction of change with time, is the primary indicator of sustainable land management (Karlen et al. 1997). Strategies for sustainable management, such as those shown in Table 10, maximize the benefits of natural cycles, reduce dependence on non-renewable resources, and help producers identify long-term goals for sustainability that also meet short-term needs for production. However, successful development and implementation of standards for assessment of soil health and sustainability can only be accomplished in partnership with agricultural producers, who are the primary stewards of the land. Economic survival and viability are the primary goals of land managers, and while most appreciate the need for environmental conservation, the simple fact remains that "it's hard to be green when you're in the red" (Doran and Zeiss 2000).

Sustainable soil management can maintain and even improve soil quality through the use of soil-specific practices, adapted to local soil, terrain, and climatic conditions, by using decision or planning support tools. The agro-ecological paradigm for a new agriculture defended in this study needs to be considered under two central perspectives: site specificity and time dimension. However, several general principles can apply in most situations across international boundaries. These basic principles on sustainable agricultural practices focus on the positive effects on the soil quality: (i) increased organic matter, (ii) decreased erosion, (iii) better water infiltration, (iv) more water-holding capacity, (v) less subsoil compaction, and

Table 10 Strategies for sustainable agricultural management and proposed indicators of crop performance and soil and environmental health (Adapted from Doran and Zeiss 2000)

Sustainability strategy	Indicators for producers
Conserve soil organic matter through	
Maintaining soil C & N levels by reducing tillage Recycling plant and animal manures	Direction/change in organic matter levels with time (visual or remote sensing by color or chemical analysis) Specific OM potential for climate, soil, and vegetation
And/or increasing plant diversity, where C inputs ≥ C outputs	Soil water storage
Minimize soil erosion through	
Conservation tillage	Visual (gullies, rills, dust, etc.)
Increased protective cover (residue, stable aggregates, cover crops, green fallow)	Surface soil properties (topsoil depth, organic matter content/texture, water infiltration, runoff, ponding, cover %)
Balance production and environment through	
Conservation and integrated management systems (optimizing tillage, residue, water, and chemical use)	Crop characteristics (visual or remote sensing of yield, color, nutrient status, plant vigor, and rooting characteristics)
Synchronizing available N and P levels with crop needs during year	Soil physical condition/compaction
	Soil and water nitrate levels
	Amount and toxicity of pesticides used
Better use of renewable resources through	
Relying less on fossil fuels and petrochemicals	Input/output ratios of costs, energy, and renewable/non-renewable resources
More on renewable resources and biodiversity (crop rotations, legumes, manures, IPM, etc.)	Leaching losses/soil acidification
	Crop characteristics (as listed above)
	Soil and water nitrate levels

(vi) less leaching of agro-chemicals to groundwater. To achieve these objectives, the following sustainable soil use and management strategies will be developed: (i) arable land identification, (ii) crop diversification, (iii) biomass restoration, (iv) appropriate tillage intensity, and (v) soil input rationalization (De la Rosa and Sobral 2008).

One way to integrate information from soil indicators into the management decision process is to develop a soil quality index (Mohanty et al. 2007). When soil management focuses on sustainability rather than simply on crop yield, a soil quality index can be viewed as a primary indicator of sustainable land management (Doran 2002). The most commonly used approach to develop an integrated soil quality index was suggested by Karlen and Stott (1994). They selected soil functions associated with soil quality, such as accommodating water entry, accommodating water transfer and absorption, resisting surface degradation, and supporting plant growth, to evaluate the effects of different types of soil management on soil quality (Lima et al. 2013).

When management goals focus on sustainability rather than simply crop yield, a soil quality index (SQI) can be viewed as one component within a nested agroecosystem sustainability hierarchy (Fig. 3). The SQI is one factor that contributes to the

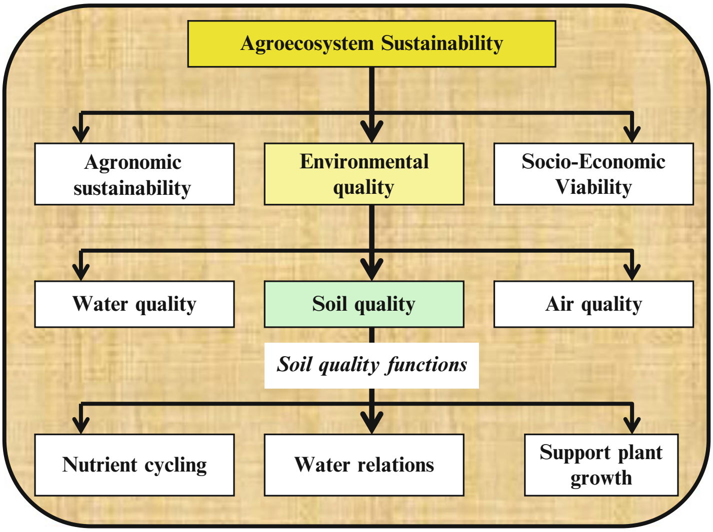


Fig. 3 Nested hierarchy of agroecosystem sustainability showing the relationship of soil quality to the larger agroecosystem (Adapted from Andrews et al. 2002)

evaluation of higher level sustainable management goals (both individual and societal). Once the system's management goals are identified, soil quality indexing involves three main steps: (1) choosing appropriate indicators for a minimum data set (MDS); (2) transforming indicator scores; and (3) combining the indicator scores into the index. The concept of the minimum data set of soil quality indicators that reflect sustainable management goals is widely accepted but has relied primarily on expert opinion (EO) to select MDS components (Andrews et al. 2002).

It could be concluded that soil is the site of a vital range of ecosystem functions which provide humans with a range of essential services. In natural ecosystems, these functions and services are driven by the energy generated by carbon transformations carried out by the soil biological community acting in a highly interactive and integrated fashion. Conventionally, the practice of agriculture may be seen as providing only a single service, namely arable or livestock food production. Primary and secondary production depends on soil-based ecosystem functions such as nutrient cycling, maintenance of soil structure and biotic population regulation. Society may also require that other services, such as the supply of good quality water, protection of human health and reduction of greenhouse gas emissions, be maintained at acceptable levels. This demand is already being strongly voiced in many developed economies. A major target of sustainable agriculture must be to ensure that the full range of ecosystem services is conserved for future generations: agricultural soils must thus retain a multifunctional capacity. We use soil health as a term to describe the capacity of soil to deliver a range of different ecosystem functions and services (Kibblewhite et al. 2008).

Agricultural interventions, such as the use of pesticides, powered tillage and the use of inorganic sources of nutrients, impact upon the biological communities of soil, damage their habitats and disrupt their functions to varying extents. The link between disturbance, targeted biota and effect on function is far from linear owing to the high level of interaction between organisms and functions. The main integrating feature in the soil community is energy flow. The majority of the soil organisms depend directly or indirectly via one or more trophic levels on the processes of organic matter decomposition for their source of energy and carbon. Any disruption of this energy generating system may thus result in changes in the flow of energy and carbon to the different functions. Assessment of the relative energy allocation to different functions remains to be computed but may prove difficult owing to the second integrating feature of the soil health system, that of the probability of participation in more than one function by the same organisms. Sustainable management of soil health requires the setting of criteria for acceptable levels of soil-based ecosystem functions and in particular the balance between the food production functions and others supporting soil conservation, water flow and quality, crop, livestock and human health control, and greenhouse gas emissions. The established principles for establishing and maintaining soil fertility are familiar (Kibblewhite et al. 2008).

Sustainable management of soil will nonetheless always be related to particular circumstances. The priorities in industrial agriculture, to reduce and refine the input management system, are clearly different from those of subsistence farmers where the key to sustainable management is to increase inputs. In Africa generally, and more sporadically through much of the tropical regions, production is inadequate, resources limited and food sufficiency and agricultural profitability are lacking. The key issue here is to find management practices that will ‘lift’ the systems and can be implemented within the limited resource base (including cash) that is available, and are also sustainable in the long term. In sharp contrast is the case of industrial agriculture where productivity and returns are high (although the latter is often distorted by subsidies) and where the realization of unacceptable impacts on the environment and human health has led to the search for more sustainable practices that nonetheless do not compromise productivity or profitability. In both cases, a healthy soil is central to the sustainable solution (Kibblewhite et al. 2008).

Sustainable solutions with regard to soil health will depend on the willingness of society to pay for its maintenance, which in its turn depends on the value accorded to the various functions and services it supports. To date, it appears that both the measurement and economic evaluation of soil-based ecosystem functions have not been made. Industrial societies, through the agency of governmental policies, have increasingly shown themselves willing to pay the costs for establishing limits to polluting effects (e.g. on nitrate levels in groundwater) or in encouraging actions to enhance ecosystem functions (e.g. for carbon sequestration). Few would now disagree with the assertion that a practice which results in substantial accumulations of heavy metals, pesticides or nitrates is undesirable, and be prepared to pay for it to be avoided or alleviated, even when the effects of these accumulations on human health or agricultural production are unclear. Legislation has placed limits on such effects in many countries. The same widespread consensus in relation to soil degradation by erosion, organic matter loss and physical damage is emerging only now. Despite the great variety of biophysical and socioeconomic circumstances that need to be accommodated, a working hypothesis for sustainable agriculture may be advanced that 'agriculture can be productively and profitably practised without impairment of soil health'. A more cautious assertion that recognizes the reality behind such a target is that 'some degree of trade-off between the optimization of one ecosystem function (in this case food or fibre production) and others (e.g. water quality, carbon sequestration) is acceptable and indeed inevitable in any managed landscape'. Irrespective of which of these approaches becomes dominant, the emergence of a globally acceptable concept of sustainable agriculture will require the convergence of the excess-resource and inadequate-resource trajectories of change on a diversity of practices rather than any single homogenized approach such as has characterized agricultural development over the past 50 years (Kibblewhite et al. 2008).

Therefore, it could be concluded that, soil is the site of a vital range of ecosystem functions which provide humans with a range of essential services. The practice of agriculture may be seen as providing only a single service, namely arable or livestock food production. A major target of sustainable agriculture must be to ensure that the full range of ecosystem services is conserved for future generations: agricultural soils must thus retain a multifunctional capacity. Sustainable solutions with regard to soil health will depend on the willingness of society to pay for its maintenance, which in its turn depends on the value accorded to the various functions and services it supports. To date, it appears that both the measurement and economic evaluation of soil-based ecosystem functions have not been made.

Soil Quality and Its Fertility Management

Soil fertility or soil quality is first a scientific problem and then a practical one, depending on the perception of researchers, agronomists or farmers. All think of the same phenomenon, but not all define it in the same manner. Depending on the definition, we have a correct or false method for quantifying the value of an agricultural soil. In this paper, we have tackled the confusion between the notions: soil fertility and soil quality. This confusion is not new, but today, when state authorities are alarmed about the degradation of soils, the technical measures for estimating the level of fertility, for controlling the crops and for avoidance of the degradation of soils, the semantic content of the notions: soil fertility and soil quality must be solved. In our opinion, the soil fertility is the correct expression, and in this conception, we have given a new definition and a methodology, verified in different soil types in Romania, for quantifying the level of fertility.

Classical soil fertility rating is a function of the crop response to added nutrients and fertilizers recommendations are primarily based on expected financial returns from the crop from applied nutrients rather than an integrated consideration of the costs and benefits of the outcomes of fertilizer addition, e.g., of environmental cost associated with leaching and volatilization of added fertilizers (Oenema et al. 2003). Janssen (1999) gave the concepts of target soil fertility, which also referred as ideal soil fertility by Janssen and de Willigen (2006a) and target soil fertility. Janssen and de Willigen (2006b) presented Ideal Soil Fertility-Saturated Soil Fertility framework integrating the concepts of plant physiology, agronomy and soil chemistry, that explicitly takes sustainable soil fertility, environmental protection and balanced plant nutrition as starting points unlike most existing fertilizer recommendations based on the economics of fertilizer use (Janssen and de Willigen 2006a).

Soil is an important component of terrestrial ecosystems because it preserves nutrient reserves, supports many biological processes such as activities linked to nutrient cycles and filters, keeps and transforms pollutants reducing their toxic effect. To preserve this resource and its functions, it is necessary first of all to know the conditions and the processes occurring in it, for example, through the determination of soil quality. Soil quality may be affected by land use type and agricultural management practices because these may cause alterations in soil physical and chemical properties and in soil biotic community (Caravaca et al. 2002) determining, in turn, a reduction in land productivity (Sanchez-Maranon et al. 2002). It has been reported that soil land use (arable versus pasture) influenced biological soil quality more than soil type (Marzaioli et al. 2010).

Plants, as a whole, grow in soil, particularly those cultivated by man. Ever since man has started growing crops it has been well known that soils have different levels of fertility. Factors underlying the phenomenon of soil "fertility" or the capability of soils to produce good crop growth have therefore been of interest for a very long time. The discovery that plants receive most of their chemical constituents from the soil revealed that one of the components of soil fertility is the content of plant nutrients present within a soil. Plant growth and crop production depend, to a large extent, on soil nutrient supply capacity (SNSC). However, the primary importance of nutrients that plants need from the soil does not rest on the total content, but rather the content of soluble and easily accessible nutrients, termed available nutrients, although the total and the available nutrients may relate closely. These nutrients can be taken up by plants directly or released and taken up during the plant's growth period, determine the SNSC, and are thereby regarded as the basis of soil fertility. One major reason why different soils have different productivity levels is mainly attributed to their capacity to supply such available nutrients. Soils deficient in available nutrients without fertilization produce low crop yields because the uptake of nutrients by the crop is limited by the amount and the rate of available nutrients released from the soil. This is usually less than the rate required by the crop for maximum dry matter reduction. In contrast, when soils are sufficient in nutrient supply, substantial rates of fertilization without consideration of the SNSC and crop production potential can cause many problems such as low use efficiency, crop yield decline, and underground water contamination (Li and Wang 2010).

Low crop production stemmed from low soil fertility, which rendered plants unable to use available water under nutrient stress conditions, resulting in low water use efficiency and difficulties for sustainable agriculture. If soil fertility is improved, agricultural production is expected to increase. Therefore, this review will be highlighted on the integrated nutrient management and its relationship with plant nutrition, indicators of soil quality, and describe the impact of soil quality improvements on increasing crop production and advancing global food security.

Soil health is important for the sustainable development of terrestrial ecosystem. Soil quality is a combination of soil physical, chemical and biological properties that are able to readily change in response to variations in soil conditions (Brejda et al. 2000). According to Liebig et al. (2001) these properties are grouped into a Minimum Data Set (MDS), i.e. a collection of selected indicators able to measure soil state and function from plot to regional scale (Karlen et al. 1997). A wide amount of indicators of different nature makes interpretation of results difficult, so it is essential to elaborate numerical indices that represent synthetic tools able to integrate information about soil quality functions deriving from single parameters. A lot of different methods have been suggested to calculate indices from indicators collected into a Minimum Data Set (Wienhold et al. 2004; Zornoza et al. 2008). Generally, the definition of a soil quality index starts by choosing a Minimum Data Set; as different indicators are expressed by different numerical scales, scoring functions were used to normalize data (linear and nonlinear scoring). The integration of a dimensional indicators (obtained by normalization) into quality indices is possible through many procedures based on additive, multiplicative or weighed mean techniques (Andrews et al. 2002; Marzaioli et al. 2010).

Soil fertility is a measure of the ability of soil to sustain satisfactory crop growth in the long-term, and can be determined by physical, chemical and biological processes intrinsically linked to soil organic matter content and quality. Given that a decrease in soil fertility is a major constraint to productivity, investing in practices leading to soil fertility enhancement is likely to generate large returns (Syers 1997). In recent years, increased concerns for healthy food production and environmental quality, and increased emphasis on sustaining the productive capacity of soils, have raised interest in the maintenance and improvement of soil organic matter through appropriate land use and management practices (Puget and Lal 2005). Crop residues are an important source of organic matter that can be returned to soil for nutrient recycling, and to improve soil physical, chemical and biological properties (Kumar and Goh 2000). Globally, the total crop residue production is estimated at 3.8 billion tons per year, of which 74 % are from cereals, 8 % from legumes, 3 % from oil crops, 10 % from sugar crops and 5 % from tubers (Lal 2005). Besides C, crop residues contain all mineral nutrients, the content of which varies among crop species depending on the fertility of the soil. These residues should be returned to the soil, and should be spread uniformly over an entire field to prevent impoverishment of nutrients and organic C in the soil (Brennan et al. 2004). However, it is difficult to predict how much of the nutrients in the residue will become available to crops during a given time because of the complex processes governing residue decomposition and nutrient release. In addition, the nature of crop residues and their management can significantly affect the amount of nutrients available for subsequent crops as well as the content and quality of soil organic matter (Yadvinder-Singh et al. 2005).

Effective management of crop residues in the field should conserve soil and its resources with minimal adverse effects on the environment (Puget and Lal 2005; Yadvinder-Singh et al. 2005). After harvesting crops, crop residues can be (i) left on the soil surface, (ii) swathed and concentrated in windrows, (iii) incorporated into soil, and/or (iv) burnt prior to tillage or seedbed preparation. Crop residues that are partially or wholly removed from field can be used as mulches, composts, industrial raw material, household fuel, biofuel for off-setting fossil fuel emissions or fodder for animals (thereby returning residues to the field as animal wastes) (Lal 2005). Tillage options range from (1) no-till, (2) chisel, disk, or sweep till (minimum tillage), to (3) several passes by mouldboard plough or disc plough (conventional tillage) (Bhupinderpal-Singh and Rengel 2007).

The words fertility and quality of a soil are two distinct philosophical categories. The fertility is the fundamental feature of an agricultural soil, having all characteristics of a body impregnated with life. Its level can be quantified by certain parameters, corresponding to certain physiologic and enzymic processes and certain specific substance accumulations. Quality, and in this case, biological quality of soil is a human representation, combining a number of general characteristics among the others, the fertility. The quality (biologic) of a soil cannot be quantified or described by parameters, it can be appreciated as good, bad, useful, useless, etc. To use the notion of soil (biologic) quality instead of that of fertility is a semantic mistake, which generates confusion in the human thinking. When some scientific or technical publications insert, among the parameters, those of crop yields, for soil fertility or soil quality level determination, they make other mistakes: firstly, by the confusion fertility – quality, and second, by ignoring the role of crop management practices which are capable to ensure high yields or low yields on the same soil fertility. The level of soil fertility must be quantified only on a base of soil intrinsic features. Soil fertility or soil quality is first a scientific problem and then a practical one, depending on the perception of researchers, agronomists or farmers. All think of the same phenomenon, but not all define it in the same manner. Depending on the definition, we have a correct or false method for quantifying the value of an agricultural soil. Therefore, it could be tackled the confusion between the notions soil fertility and soil quality. This confusion is not new, but today, when state authorities are alarmed about the degradation of soils, the technical measures for estimating the level of fertility, for controlling the crops and for avoidance of the degradation of soils, the semantic content of the notions soil fertility and soil quality must be solved (Ştefanic and Gheorghiţă 2006).

Therefore, it could be concluded that, the role of different crop residue management practices as well as the quantity and quality of crop residues in governing the chemical, physical, and biological parameters of soil quality are closely linked to each other with respect to overall soil fertility. A better understanding of these aspects of soil fertility will help maximise the beneficial effects of crop residues on agricultural soils, such as minimising soil degradation, increasing soil fertility through build-up of soil organic matter, thereby sustaining plant productivity, and minimise the negative effects, such as immobilisation of nutrients, leaching and run-off losses of nutrients, erosion, and impeding of sowing operations, thereby contributing directly to the sustainability of crop-production systems. Soil fertility reflects the physical, chemical and biological state of soil. It can be defined in relation to the plants that grow naturally or are introduced into soil. Knowledge of the origin of soil helps to predict the level of soil fertility prior to land management. Soil disturbance alters the physical, chemical and biological components of soil fertility either directly or indirectly.

Integrated Nutrient Management and Soil Quality

It is well known that integrated nutrient management (INM) or integrated plant nutrient management (IPNM) is an approach that involves the management of both organic and inorganic plant nutrients for optimal production of cultivated crops, forage, and tree species, while conserving the natural resource base essential for long-term sustainability. The basic concept underlying IPNS/INM is the maintenance or adjustment of soil fertility/productivity and of optimal plant nutrient supply for sustaining the desired level of crop productivity (FAO 1995). The objective is to accomplish this through optimization of the benefits from all possible sources of plant nutrients, including locally available ones, in an integrated manner while ensuring environmental quality. This provides a system of crop nutrition in which plant nutrient needs are met through a pre-planned integrated use of: mineral fertilizers; organic manures/fertilizers e.g., green manures, recyclable wastes, crop residues, and FYM; and biofertilizers. The appropriate combination of different sources of nutrients varies according to the system of land use and the ecological, social and economic conditions at the local level (Fig. 4; Roy et al. 2006).

Effective INM involves four interrelated strategies:

1. ***Conservation and efficient use of native soil nutrients***

Conservation practices help to reduce loss of nutrients from agroecosystems due to surface water flows and from erosion of soil by wind and water. Vegetative barriers minimize off-farm transport of dissolved nutrients, dust, and sediments, and deep-rooted plants act as nutrient safety nets, intercepting leached nutrients from the root zone and returning them to the soil surface via litter fall, mulch, or as green manure. In general, conserving existing nutrient resources is easier and cheaper than replenishing and rehabilitating degraded resources.

2. ***Recycling of organic nutrient flows***

Returning crop residues and/or animal manure to cropland is important for system sustainability. Composting crop residues and animal manures enhances the utilization efficiency of easily lost nutrients such as nitrogen. Converting linear flows (lost from the system) of organic nutrients to cyclical flows (returned to the system) can reduce the need for external nutrient inputs. There are related potential price benefits in organic product markets. Livestock are important for processing crop residues, adding value to farm outputs, improving labor efficiency, and providing manure.

Fig. 4 Integrated nutrient management can be achieved using an approach involves the management of both organic and inorganic plant nutrients for optimal production of cultivated crops, forage, and tree species. Photos explain that the appropriate combination of different sources of nutrients varies according to the system of land use and the ecological, social and economic conditions at the local level. It should be followed the proper agricultural soil quality management (Photos by H. El-Ramady)

3. ***Enhancing biological nitrogen fixation and soil biological activity***

Nitrogen-fixing crop, forage, and tree/shrub species scavenge nitrogen from the soil and/or fix nitrogen from the atmosphere when soil levels are below plant requirements. Most nitrogen-fixing plant species also form symbiotic relationships with mycorrhizal fungi that improve soil aggregation; nutrient and water use efficiencies, and protect the plant roots from a variety of pathogens. This is one example of an INM practice that also contributes to IPM. Integration of nitrogen-fixing species into cropping systems diversifies inputs/outputs and reduces risk on both economic and ecological fronts.

4. ***Addition of plant nutrients***

The nutrient content of highly weathered soils is very low. In most cases, the export of nutrients in harvested products results in one or more plant nutrients becoming limiting. In the humid tropics, calcium and phosphorus are often limiting for crop growth and productivity. Appropriate amounts of lime and nutrients are essential to optimize plant root growth, enhance the efficiency of added nutrients, and avoid soil degradation. Although inorganic fertilizers such as limestone and rock phosphate are consistent with organic agriculture, inorganic fertilizers are often the most efficient means of adding soil nutrients. In many places (such as Africa) they are essential for improving productivity to levels that will then enable adoption of wider INM practices (World Bank 2004).

Fertilizers are in some regions applied in doses and with methods that are far from efficient, and in other areas the lack of fertilizers is still the main constraint to have a higher productivity. Integrated Plant Nutrient Management aims to use nutrients in a more rational way (yield-targeted, site-and soil specific); understanding the interrelation of different nutrients; use combinations of mineral and organic fertilizers; provide nutrients on a cropping-system/rotation basis; and use on-farm and off-farm waste through recycling. Nutrient cycling is an important component of Conservation Agriculture, in which minimum soil disturbance, intercropping, crop rotations and a permanent soil cover minimize the need for chemical fertilizers. Healthy crops are also less susceptible to pests, thus contributing to crop protection. A better application of nutrients will reduce runoff, and by this benefits the overall ecosystem, including marine areas (FAO 2012).

According to FAO, the term integrated plant nutrient management (IPNM) is interpreted in the much broader more holistic sense of "*land husbandry*". It thus embraces soil, nutrient, water, crop, and vegetation management practices, tailored to a particular cropping and farming system, undertaken with the aim of improving and sustaining soil fertility and land productivity and reducing environmental degradation. Integrated Plant Nutrient Management aims to optimize the condition of the soil, with regard to its physical, chemical, biological and hydrological properties, for the purpose of enhancing farm productivity, whilst minimizing land degradation. There is now greater awareness that IPNM can, not only provide tangible benefits in terms of higher yields, but simultaneously and almost imperceptibly conserve the soil resource itself. The field level management practices considered under the heading of IPNM would include the use of farmyard manures, natural and mineral fertilizers, soil amendments, crop residues and farm wastes, agroforestry and tillage practices, green manures, cover crops, legumes, intercropping, crop rotations, fallows, irrigation, drainage, plus a variety of other agronomic, vegetative and structural measures designed to conserve both water and soil. The underlying principles on how best to manage soils, nutrients, water, crops and vegetation to improve and sustain soil fertility and land productivity and their processes are derived from the essential soil functions necessary for plant growth. The following are fundamental to the approach outlined in these guidelines (FAO 2012):

- Loss of soil productivity is much more important than the loss of soil itself, thus land degradation should be prevented before it arises, instead of attempting to cure it afterwards – i.e., the focus for IPNM should be on sustaining the productive potential of the soil resource.
- Soil and plant nutrient management cannot be dealt with in isolation but should be promoted as an integral part of a productive farming system.
- Under rainfed dryland farming conditions soil moisture availability is the primary limiting factor on crop yields, not soil nutrients as such, hence IPNM requires the adoption of improved rainwater management practices (conservation tillage, tied ridging, etc.), so as to increase the effectiveness of the seasonal rainfall.
- With declining soil organic matter levels following cultivation, the adoption of improved organic matter management practices are a prerequisite for restoring and maintaining soil productivity (improved soil nutrient levels, soil moisture retention, soil structure and resistance to erosion).

The need to adopt a wider concept of nutrient use beyond but not excluding fertilizers results from several changing circumstances and developments. These are:

- The need for a more rational use of plant nutrients for optimizing crop nutrition by balanced, efficient, yield-targeted, site- and soil-specific nutrient supply.
- A shift mainly from the use of mineral fertilizers to combinations of mineral and organic fertilizers obtained on and off the farm.
- A shift from providing nutrition on the basis of individual crops to optimal use of nutrient sources on a cropping-system or crop-rotation basis.
- A shift from considering mainly direct effects of fertilization (first-year nutrient effects) to long-term direct plus residual effects. To a large extent, this is accomplished also where crop nutrition is on a cropping-system basis rather than on a single-crop basis.
- A shift from static nutrient balances to nutrient flows in nutrient cycles.
- A growing emphasis on monitoring and controlling the unwanted side effects of fertilization and possible adverse consequences for soil health, crop diseases and pollution of water and air.
- A shift from soil fertility management to total soil productivity management. This includes the amelioration of problem soils (acid, alkali, hardpan, etc.) and taking into account the resistance of crops against stresses such as drought, frost, excess salt concentration, toxicity and pollution.

- A shift from exploitation of soil fertility to its improvement, or at least maintenance.
- A shift from the neglect of on-farm and off-farm wastes to their effective utilization through recycling (Roy et al. 2006)

These realizations have led to the widening of the concept of fertilization to one of INM, where all aspects of optimal management of plant nutrient sources are integrated into the crop production system. For developing INM practices, the cropping systems rather than an individual crop, and the farming systems rather than the individual field, are the focus of attention. In contrast to organic farming, INM involves a needs-based external input approach, taking into account a holistic view of soil fertility. One of the aims of INM is to obtain high yields and good product quality – in a sustainable agriculture with practically no damaging effects on the environment. INM offers great possibilities for saving resources, protecting the environment and promoting more economical cropping (FAO 2006).

The major components of INM are the well-known and time-tested sources of plant nutrients with or without organic matter. These primarily include mineral fertilizers containing both major nutrients and micronutrients; suitable minerals such as phosphate rock, pyrites and elemental S; crop residues; green manures and green leaf manures; various organic manures of plant, animal, human and industrial origin; recyclable wastes from various sources with or without processing provided these do not contain harmful substances or pathogens above permissible limits; animal slurries and biogas plant slurry; microbial inoculants or biofertilizers; commercial organic fertilizers (Roy et al. 2006).

It could be concluded that integrated nutrient management or integrated plant nutrient management is an approach that involves the management of both organic and inorganic plant nutrients for optimal production of cultivated crops, forage, and tree species, while conserving the natural resource base essential for long-term sustainability. The addressing of mineral toxicities in soils, fertilizer management for optimal sustainability, plant nutrition for human health, soil quality considerations for integrated nutrient management, managing soil quality and productivity, and the impact of soil health on the environment will be also highlighted.

Addressing Mineral Toxicities in Soils

It is well known that, agriculture in many parts of the world is restricted by excessive concentrations of mineral elements in the soil solution. It is estimated that about 5 % of agricultural land is saline or sodic and contains toxic concentrations of Na, Cl or B (Munns and Tester 2008), that over 40 % of the world's arable land suffers from soil acidity and, therefore, Al and Mn toxicities (Von Uexküll and Mutert 1995), and that Mn and Fe toxicities affect crop production in many waterlogged or flooded soils worldwide (Marschner 2002). Traditional agronomic countermeasures can be employed to address these problems and plant breeders are developing crop genotypes that tolerate these adverse abiotic environments better, through either conventional breeding or transgenic strategies. Crop production on acid soils is primarily limited by Al toxicity. The presence of excessive Al in the rhizosphere inhibits root elongation (Mengel et al. 2001). Resistance is generally conferred by the release of organic acids, such as malate, citrate and oxalate, at the root apex that form Al-complexes and reduce the phytoavailability of toxic Al species in the root elongation zone (Ma et al. 2001). In some plant species, such as wheat and maize, the release of organic acids is constitutive, whereas in other plant species, such as soybean, sorghum and rye, it is induced by exposure to Al (Ma et al. 2001). In general, proteins that release malate from root cells into the rhizosphere belong to the Al-activated Malate Transporter (ALMT) family, whereas those that release citrate into the rhizosphere belong to the Multidrug and Toxin Extrusion (MATE) family (Delhaize et al. 2007). In common bean (Phaseolus vulgaris), Al-resistance is effected by the Al-inducible release of citrate into the rhizosphere (Rangel et al. 2010).

It is well established that, many natural and agricultural ecosystems are characterized by sub-optimal availability of mineral nutrients and ion toxicities. Mineral stresses are likely to have important, complex, and poorly understood interactions with global climate change variables. For example, most terrestrial vegetation is supported by weathered soils with some combination of low P, low Ca, Al toxicity, and Mn toxicity. Each of these stresses has complex, yet distinct, interactions with global change variables, making it very difficult to predict how plants in these environments will respond to future climate scenarios. Important, yet poorly understood, interactions include the effects of transpiration on root acquisition of soluble nutrients, particularly Ca and Si, the effects of altered root architecture on the acquisition of immobile nutrients, particularly P, the effects of altered root exudate production on Al toxicity and transition metal acquisition, and the interaction of photochemical processes with transition metal availability. The interaction of Mn toxicity with light intensity and other global change variables is discussed as an example of the complexity and potential importance of these relationships. There are conceptual models of plant response to multiple resource limitations, but are inadequate. Furthermore, substantial genetic variation exists in plant responses to mineral stress, and traits improving adaptation to one stress may incur tradeoffs for adaptation to other stresses. Root traits under quantitative genetic control are of central importance in adaptation to many mineral stresses. An integration of quantitative genetics with mechanistic and conceptual models of plant response to mineral stresses is needed if we are to understand plant response to global change in real-world soils (Lynch and St. Claira 2004).

Eticha et al. (2010) confirm that, following exposure to Al, restoration of root growth in the common bean is correlated with the release of citrate into the rhizosphere. They then reveal that, although the initial restoration of root growth is dependent upon Al-induced expression of genes encoding citrate transporters of the MATE family, in the longer term, Al-tolerance is achieved by the maintenance of citrate synthesis in the roots of resistant genotypes through post-translational regulation. The implication is that continued synthesis and release of organic acids must be achieved to confer Al resistance and the potential for crop production on acid soils. Mn toxicity also limits crop production on acid soils. Mn is required by plants for the manganese-protein in photosystem II and the manganese-containing superoxide dismutase and also acts as a cofactor for a number of enzymes that catalyse redox, decarboxylation and hydrolytic reactions (Marschner 2002). Excessive Mn^{2+} is toxic because it can displace Ca^{2+}, Mg^{2+}, Fe^{2+} and Zn^{2+} in their essential cellular functions. Consequently, Mn-induced Ca, Mg and Fe deficiencies are common symptoms of Mn toxicity. Other symptoms of Mn toxicity are caused by the generation of reactive oxygen species in the cell wall. Low Mn^{2+} concentrations must be maintained in metabolic compartments, which can be achieved through its sequestration in the vacuole and/or the cell wall (Puig and Penarrubia 2009). Large differences in Mn tolerance exist both between and within plant species (White and Brown 2010).

Therefore, it could be concluded that, mineral stress could be defined as suboptimal availability of essential nutrients or toxicity of nutrient or non-nutrient minerals, especially Al, Na, Cl, Mn, and other heavy metals. The mineral toxicity is a primary constraint to plant growth over the majority of the earth's land surface. Natural ecosystems, managed forests and rangelands, and agriculture in less developed countries are largely characterized by multiple mineral stresses. This being the case, we will not be able to understand or predict ecosystem responses to global change variables without understanding how these variables interact with mineral stresses.

Fertilizer Management for Optimal Sustainability

It is well documented that, one of the most important challenges facing humanity today is to conserve/sustain natural resources, including soil and water, for increasing food production while protecting the environment. As the world population grows, stress on natural resources increases, making it difficult to maintain food security. Long term food security requires a balance between increasing crop production, maintaining soil health and environmental sustainability. It is also well documented that, crops require a sufficient, but not excessive, supply of essential mineral elements for optimal productivity. An insufficient supply of mineral elements required in large quantities and/or mineral elements with low phytoavailability in soils often limits crop production. In many agricultural soils, there is rarely sufficient phytoavailable N, P or K to supply enough of these elements for the rapid growth of crop plants during their early growth. Hence, these elements are supplied as fertilizers in both intensive and extensive agricultural systems. In addition, in areas where mineral deficiencies occur in animals and/or humans, fertilizers are applied not only to increase crop production but also to increase concentrations of essential mineral elements in edible portions. However, there are both financial and environmental costs to the use of mineral fertilizers (Conley et al. 2009; Ju et al. 2009). Therefore, it is important to optimize the efficiency with which fertilizers are used in crop production. Increased fertilizer use efficiency can be achieved agronomically, through improved fertilizer-management practices, and/or genetically, by cultivating crops that acquire and/or utilize mineral elements more effectively (White and Hammond 2008; Fageria 2009). The latter can be addressed through conventional breeding and/or modern biotechnological approaches. Ultimately, sustainable crop production is achieved when stable levels of food production and quality are maintained without compromising economic profitability or the environment (White and Brown 2010).

Agronomic mineral use efficiency (MUE) is generally defined as crop dry matter (DM) yield per unit of mineral element available (Ma) in the soil (g DM g^{-1} Ma), which is equivalent to the product of the plant mineral content (Mp) per unit of available mineral (g Mp g^{-1} Ma), often referred to as plant mineral uptake efficiency (MUpE), and the yield per unit plant mineral content (g DM g^{-1} Mp), often referred to as the mineral utilization efficiency (MUtE). Considerable within-species genetic variation has been observed in all these measures for the mineral elements frequently supplied in fertilizers, including N, P and K (Fageria 2009; Sylvester-Bradley and Kindred 2009).

Therefore, it could be concluded that, application of imbalanced and/or excessive nutrients led to declining nutrient-use efficiency making fertilizer consumption uneconomical and producing adverse effects on atmosphere and groundwater quality causing health hazards and climate change. On other hand, nutrient mining has occurred in many soils due to lack of affordable fertilizer sources and where fewer or no organic residues are returned to the soils. There are some studies can be provided an insight into the practical understanding, and illustrated beyond any doubt, how INM strategy can result in agronomically feasible, economically viable and environmentally sound sustainable crop production systems by enhancing soil fertility and C sequestration, and reducing N losses and emission of greenhouse gases.

Plant Nutrition for Human Health

It is well documented that, humans are likely to require at least 25 mineral elements for their well-being (Stein 2010). The dietary source of most of these elements is plants. Regrettably, mineral malnutrition is prevalent in both developed and developing countries and it is estimated that up to two-thirds of the world's population might be at risk of deficiency in one or more essential mineral element (White and Broadley 2009). This is considered to be one of the most serious challenges to humankind. The mineral elements most commonly lacking in human diets are Fe, Zn, I, Se, Ca, Mg and Cu (Stein 2010). Edible plant tissues can contain low concentrations of mineral elements for a variety of reasons: some plant species have inherently low concentrations of particular mineral elements (Watanabe et al. 2007); crops might be grown in areas with low mineral phytoavailability, such as occur throughout the world for Fe, Zn and Cu in calcareous or alkaline soils (Cakmak 2008; Broadley et al. 2007), for Mg in coarse-textured, calcareous or strongly acidic soils (Wilkinson et al. 1990), for I in midcontinental regions (Risher and Keith 2009) and for Se in soils derived mostly from igneous rocks (Hartikainen 2005; Broadley et al. 2006); or edible portions could be consumed that have intrinsically low concentrations of mineral elements with restricted phloem mobility, such as fruits, seeds and tubers (Karley and White 2009; White and Broadley 2009).

To address the occurrence of mineral deficiencies in human populations, plant scientists are devising methods of applying fertilizers and/or using plant breeding strategies to increase the concentrations and/or bioavailability of mineral elements in agricultural produce (Cakmak 2008; White and Broadley 2009). These approaches are termed ‘agronomic’ and ‘genetic’ biofortification, respectively. Agronomic strategies to increase the concentrations of mineral elements in edible portions of major crops have been reviewed recently by various authors in the contexts of both sustainable economic development and global health (Cakmak 2004; Graham et al. 2007). These have included reviews of appropriate methods, infrastructural requirements and practical benefits for food production, economic sustainability and human health, of agronomic biofortification of edible crops with Fe and Zn, the successful use of inorganic Se fertilizers to increase dietary Se intakes in Finland, New Zealand and elsewhere (Ekholm et al. 2007), and the iodinization of irrigation water to increase dietary intakes of I in China (Lyons et al. 2004). Similarly, researchers are investigating genetic variation in mineral concentrations in edible portions of major crops, the interactions between genotype and environment, and the potential for breeding for increased concentrations of mineral elements in produce (White and Broadley 2009). Although the total concentrations of Fe, Zn and Cu in most soils are sufficient to support mineral-dense crops, the accumulation of these mineral elements is often limited by their phytoavailability and acquisition by plant roots (White and Brown 2010).

The mineral and trace element contents of plants are known to be affected by the cultivar of plant, soil conditions, weather conditions during the growing, use of fertilizers and the state of the plants maturity at harvest (Hattori and Chino 2001). During the past 30 years many agricultural practices have changed in different parts of the world such as Finland. The total amount of major plant nutrients has decreased 25 % and the use of phosphorous (P) in fertilizers has decreased 66 % since 1975 (National Board of Agriculture 2003). Cereal cultivars have also changed completely. Likewise, many new cultivars of peas, potatoes and other vegetables have appeared and the growing of older cultivars has either ended or clearly decreased (Kangas and Teravainen 2004). The cadmium content of cereals in Finland is known to be low by reason of the phosphate raw material used in fertilizers (Tahvonen 1995). Selenium supplementation of fertilizers has changed the Se content of all vegetable foods in Finland (Ekholm et al. 1995). Geological origin also affects minerals, since these vary in different countries. In Finland, however, food marketing includes foods from different parts of the country so that no regional differences are present in the foodstuffs sold (Ekholm 1997). Consequently, the mineral and trace element contents of plant foods may have changed since the 1970s when they were studied by Koivistoinen (1980) (Ekholm et al. 2007).

Fruits and vegetables have low energy content, while the nutrient densities are very high. Increased consumption of fruits and vegetables can help replace foods high in saturated fats, sugar and salt and thus improve the intake of most micronutrients and dietary fibre. Daily consumption of fresh fruits and vegetables (>400 g day^{-1}) is recommended to help prevent major non-communicable diseases such as cardiovascular diseases and certain cancers (WHO 2003). Therefore, updating the mineral and trace element contents of vegetable foods is important. We wanted also to know how the intakes of minerals have changed since the mid-1970s (Ekholm et al. 2007).

Therefore, it could be concluded that, scientific evidence from numerous sources has demonstrated that judicious fertilizer management can increase productivity and market value as well as the health-promoting properties of fruits and vegetables. Concentrations of carotenoids (vitamin A precursors) tend to increase with N fertilization, whereas the concentration of vitamin C decreases. Foliar K with S can enhance sweetness, texture, color, vitamin C, beta-carotene, and folic acid contents of muskmelons. In pink grapefruit, supplemental foliar K can boost beta-carotene and vitamin C concentrations. Several studies on bananas have reported positive correlations between K nutrition and fruit quality parameters such as sugars and ascorbic acid, and negative correlations with fruit acidity. Plant nutrition is one of the most components of the world's agricultural systems that could change to accomplish this mission more effectively. Paying more attention to the impacts of plant nutrition on the quality of food is an area of great opportunity for improving the health of the human family.

Integrated Plant Nutrient Management at Farm Level

It is only after they have made improvements in the biological, physical and hydrological properties of their soils that farmers can expect to get the full benefits from the supply of additional plant nutrients, in the form of inorganic fertilizer, to their crops. At the farm field level IPNM therefore calls for an integrated and synergistic approach which involves:

- Matching the land use requirements of individual agricultural enterprises with the land qualities present in the areas where they are undertaken – i.e. the biological, chemical and physical properties of the soil, and the local climatic conditions (temperature, rainfall, etc.);
- Seeking to improve yields by identifying and overcoming the most limiting factors in order of their diminishing influence on yield;
- Better plant management, especially: (i) improved crop establishment at the beginning of the rains, so as to increase protective ground cover thereby reducing splash erosion, enhancing infiltration and biological activity; and (ii) timely weeding to reduce crop yield losses from competition for nutrients and soil moisture;

- Combinations of complementary crop, livestock and land husbandry practices which maximize additions of organic materials and recycle farm wastes, so as to maintain and enhance soil organic matter levels (ideally at levels of at least 50–75 % of those under natural vegetation);
- Land management practices that ensure soil moisture conditions are favorable for the proposed land use (e.g. moisture harvesting/conservation in low rainfall areas, drainage in high rainfall areas);
- The replenishment of soil nutrients lost by leaching and/or removed in harvested products through an integrated plant nutrition management approach that optimizes the benefits from all possible on- and off-farm sources of plant nutrients (e.g. organic manures, crop residues, rhizobial N-fixation, P and other nutrient uptake through root mycorrhizal fungi infestation, transfer of nutrients released by weathering in the deeper soil layers to the surface via tree roots and leaf litter, rock phosphate, inorganic fertilizer, etc.);
- Combinations of crop, livestock and land husbandry practices that reduce rainfall impact, improve surface infiltration, and reduce the velocity of surface runoff thereby ensuring any soil loss is below the 'tolerable' level for the soil type;
- Conservation tillage, crop rotation, agroforestry and restorative fallow practices that maintain and enhance the soils physical properties through maintaining an open topsoil structure, and breaking any subsoil compacted layer (hoe/plough pan) thereby encouraging root development and rainfall infiltration (e.g. use of ox drawn chisel ploughs, double dug beds, pasture leys, interplanting of deep rooted perennial crops/trees and shrubs) (FAO 2012).

Therefore, it could be summarized that, integrated nutrient management at the farm level means improvements in the biological, physical and hydrological properties of farmers' soils can expect to get the full benefits from the supply of additional plant nutrients, in the form of inorganic fertilizer, to their crops.

Soil Quality Considerations for Integrated Nutrient Management

Agricultural production being an integrated interactive effect of soil-water-fertilizer-climate continuum, a judicious and scientific management of this complex system is crucial for enhancing crop productivity on a sustained basis. Among the various inputs, water and fertilizer or nutrients are considered as the two key inputs making maximum contribution to crop productivity. Efficient management of these two costly inputs together with synergistic interaction with other appropriate production factors is most critical for any crop cultivar to achieve its genetic yield potential. Soil management through tillage can further optimize their use efficiencies. Technologies developed on the principles of eco-friendly and efficient balanced fertilization and based on optimization of nutrient supplies from all the available sources, inorganic and organic, for predetermined yield targets of the cropping sequences through an efficient combination of soil, water, organic matter, tillage and nutrient management, will provide a prescription for sustainable agricultural development. Since sustainability of agricultural production system has become an issue of national and international concern, one of the options is to assess the soil quality as impacted by the various soils and crop management practices (Singh 2010).

Integrated use of mineral fertilizers and organic manures could improve the soil quality under both the cropping systems as evident from carbon management index. Under tropical conditions, although the optimized tillage, water and integrated nutrient management is the fertility building practice, it does not ensure the protection of carbon sequestered from the environmental oxidation as CO_2 because of the bulk of the captured carbon gets distributed into oxidation-vulnerable macro-aggregates. Integrated use of mineral fertilizers and organic manures were associated with the improvement of soil fertility status in respect of major and micronutrients (Singh 2010).

One of the most important challenges facing humanity today is to conserve/sustain natural resources, including soil and water, for increasing food production while protecting the environment. As the world population grows, stress on natural resources increases, making it difficult to maintain food security. Arid and semiarid subtropical soils of northwestern states of India, developed under harsh climate, are inherently poor in organic matter, fertility and water-holding capacity. In these soils, N, P and S deficiencies are principal yield-limiting factors for crop production. INM, which entails the maintenance/adjustment of soil fertility to an optimum level for crop productivity to obtain the maximum benefit from all possible sources of plant nutrients – organics as well as inorganics – in an integrated manner (Aulakh and Grant 2008), is an essential step to address the twin concerns of nutrient excess and nutrient depletion. INM is also important for marginal farmers who cannot afford to supply crop nutrients through costly chemical fertilizers. This paper summarizes the results of extensive research work carried out with dominant crop rotations of major field crops grown in the subtropical northwestern states of India to investigate the role of INM in harnessing economically-viable sustainable production of prominent cropping systems, enhancing nutritive quality of the produce, improving soil health, and minimizing environmental pollution. Aulakh (2010) provided from his studies an insight into the practical understanding, and illustrated beyond any doubt, how INM strategy can result in agronomically feasible, economically viable and environmentally sound sustainable crop production systems by enhancing soil fertility and C sequestration, and reducing N losses and emission of greenhouse gases. Formulation and adoption of careful strategies to propagate the long-term usefulness of INM in providing nutrients and improving the soil health, educative extension efforts about the economic and environmental benefits of INM, regulations for prohibiting the burning of crop residues, and some incentives for encouraging the crop residue incorporation as a means of disposal could lead to the adoption of such eco-friendly practices.

Therefore, it could be concluded that, one of the most important challenges facing humanity today is to conserve and/or sustain natural resources, including soil and water, for increasing food production while protecting the environment. Since sustainability of agricultural production system has become an issue of national and international concern, one of the options is to assess the soil quality as impacted by the various soil and crop management practices.

Managing Soil Quality and Productivity

Maintaining or improving soil quality is crucial if agricultural productivity and environmental safety are to be preserved for future generations (Reeves 1997). Every farming practice may influence soil quality either in a positive or negative manner (Emmerling et al. 2002). Among the different farming practices, the management of organic amendments and mineral fertilizers could have a major impact on soil fertility and quality status, influencing the quantity and quality of organic residues and nutrient inputs entering the soil and the rate at which the residues and organic matter decompose (Giacometti et al. 2013). It is well documented that tillage, fertilization, crop rotation, water management, liming and cover crops are soil management practices that can significantly affect soil quality. Tillage is used to incorporate residues, prepare a seedbed, control weeds, and incorporate lime, fertilizer and other chemicals, and by doing so will often enhance plant growth and thus improve soil quality. Negative effects associated with tillage include erosion caused by the physical downhill movement of soil i.e. tillage erosion, exposure of the soil surface to wind and water erosion, and loss of soil organic matter through oxidation. To balance these factors, no-tillage or conservation tillage practices are being developed and recommended as management strategies to improve soil quality throughout the world.

Fertilizer applications can have either positive or negative effects on soil quality. Identifying yield-limiting nutrients and using fertilizers to correct the deficiencies often increases crop yield and organic inputs above and below ground. However, repeated application of ammoniacal fertilizers and leaching of excess nitrate nitrogen can degrade soil quality through acidification. Crop rotations can be used to improve soil quality by altering the quantity and quality i.e., C:N ratio and lignin content of residue added to the soil, varying the soil space utilized for nutrient and water uptake by using crops with different rooting patterns, and providing cover to protect soil from erosion. Water management affects soil quality primarily through its effects on plant growth. In regions where precipitation is sufficient to support adapted crops, the primary soil quality concerns are to minimize runoff and leaching by achieving good infiltration and storage within the soil profile. If soil water levels are consistently high i.e. hydric soils, plants must be adapted to the saturated conditions e.g. lowland rice (*Oryza sativa* L.) or drainage must be installed. Drainage generally improves aeration and allows the production of a wider range of crops, but can degrade soil quality by enhancing soil organic matter decomposition. In regions requiring irrigation for crop production, irrigation water quality, irrigation scheduling, method of irrigation and drainage potential (for leaching of salts from the soil profile and prevention of waterlogging) are critical management concerns (Karlen et al. 2004).

Because there are many different uses of soil, there are also many different concepts of what constitutes soil quality. Probably the most familiar concept of soil quality would be as it relates to the growth of plants. Soils with appropriate properties are important to grow abundant crops of maize, wheat, rice, and other crops that form the centerpiece of much of the world's diet. A home gardener would have a very similar view of soil quality as a farmer, as the home gardener would be interested in soils with appropriate properties to grow good crops of garden staples such as carrots, lettuce, peas, beans, potatoes, and so on. In the case of both the farmer and the home gardener, good soils are often associated with dark colored soils, because dark colored soils usually have high organic matter content. Such soils are often good soils to grow crops in because they contain a good mix of physical and chemical properties that support plant growth (Brevik 2009).

Another view of soil quality involves nutrient availability. Consider, for example, soils used for two different cropping purposes. On one soil, the crop is blueberries (*Vaccinium corymbosum*). On another soil, the crop is maize (*Zea mays*). Blueberries thrive in acidic soils, while maize will struggle. This is because blueberries have a high iron requirement, and iron is readily available in acidic soils. These acidic soils are commonly lower in organic matter content and lighter in color than more basic soils that have the dark color often associated with fertility, but they may be well suited to supporting blueberries. An engineer might have a very different idea of soil health altogether than a farmer or gardener. An engineer might, for example, be looking for a soil that will do a good job as a filtering material for a septic system. Soils that are good for the growth of crops may or may not be good for septic systems, as water table levels that are beneficial for the growth of crops might be too high for good septic performance. Soils used as a foundation for buildings are an entirely different issue again, as they will be too compact for a septic system or for good crop growth (Brevik 2009).

These brief examples are hardly comprehensive, in either the depth at which they are explored here or in illustrating all the different concepts of soil health that are out there. However, they do serve to illustrate that soil health is not a one size fits all proposition, and that is the main point to this particular discussion. Soil quality means different things to different people, so there is no perfect set of properties that come together to describe a "healthy" soil. The concept of soil health is location and land use dependant. Soil productivity can be defined as the capacity of a soil, in its normal environment, to support plant growth. In agricultural systems this relates directly to crop and forage yields, and ties directly back to the portion of the soil health definition that states "the capacity of a soil to sustain biological productivity". Because one of the primary components of soil health is the provision of a soil environment that supports biological productivity, we find that soil productivity is directly linked to the concept of soil health (Brevik 2009).

The management decisions made by a producer have a profound affect on the overall quality of the agro-ecosystem, including the health and long-term productivity potential of the producers' soils. The primary management goals when managing for soil health and productivity include:

- Avoiding the undesirable buildup of salts or other toxic materials;
- Maintaining or enhancing soil depth by keeping soil erosion rates low enough that soil formation will replace soil lost to erosion;
- Improving the soil as a rooting medium;
- Using agrochemicals in quantities low enough to avoid adverse effects on the environment;
- Maintaining or enhancing soil biodiversity;
- Avoiding monoculture cropping systems;
- Minimizing soil compaction;
- Maintaining or building soil organic matter (SOM) levels;
- Enhancing rainwater infiltration and percolation, plant available soil water, and minimizing evaporative losses (Brevik 2009).

There are a number of ways to achieve these management goals. They focus primarily on maintaining or building SOM, limiting erosion, and environmentally responsible management of agrochemicals to allow long-term or sustainable high crop yields. Therefore, it could be concluded that, the management decisions made by a producer have a profound affect on the overall quality of the agro-ecosystem, including the health and long-term productivity potential of the producers' soils. It is worth to mention that, soil quality involves nutrient availability.

Impact of Soil Health on the Environment

It is well documented that, to maximize yields of food and fibre, a variety of agricultural management processes are imposed on the ecosystem, including artificial inputs such as chemical and tillage. These practices and inputs supplement or even 'substitute' for biological functions that are seen as inadequate or inefficient for achieving required levels of production. This distorts the natural balance of the ecosystem and may compromise the output of other environmental services. The loss of non-productive services may affect farmers directly but often has effects which are distant in space and time. For example, nutrient leakage from the soil–plant system may lead to degradation of surface and ground waters and pollute drinking water supplies, while fine seed bed preparation on some land may increase the risk of soil erosion and sediment transfer to streams, or lead to surface capping, rapid surface water runoff and increased flood risk. In these and other cases, the costs of remediation or lost services are not borne by the farmer but elsewhere in the economy (Environment Agency 2002). Achievement of sustainable development requires that such externalities are contained, and new legal frameworks are being constructed that attach economic value to natural functions (i.e. by recognizing them as services), particularly those that relate to the water cycle, through legislation, incentives, trading mechanisms, etc. (European Commission 2005). Thus, one essential component of sustainable agriculture is (as embedded in our definition of soil health) to balance the ecosystem functions in such a way as to secure the target of agricultural production without compromising other ecosystem functions with respect to both present and future needs (Kibblewhite et al. 2008).

All agricultural soils have been altered from their natural state by human interventions which are aimed at maximizing production functions and which, to some degree, always result in a loss of other ecosystem functions. After clearing the natural vegetation to establish agricultural fields, all the major soil properties whereby we describe its health are changed, largely negatively. After a period of continuous cultivation they reach a new, dynamic, equilibrium. This has been most substantially documented in terms of the decline in soil organic matter content over the years immediately following clearing and the initiation of cultivation (Leigh and Johnston 1994). If there are no additions of nutrients to replace those lost by release during the transition to a new equilibrium and subsequently in crop offtake, the capacity of the soil ecosystem to deliver production and other services declines, and according to our proposed definition so does the health of the soil. Furthermore, the loss of ion exchange capacity which is concomitant with a decline in soil organic matter reduces the capacity of the soil system to retain nutrients that would otherwise be leached to groundwater. The soil food web may also be substantially changed. The agricultural management practised in the years immediately subsequent to clearing may serve to either exacerbate or ameliorate the processes of change put in place during the conversion phase. The intensity of agricultural intervention varies enormously across different farming systems, and may be expected to have both quantitatively and qualitatively different impacts on the soil health system. Different soils in different climatic and topographic situations may be more or less resilient to the introduction of agriculture (Kibblewhite et al. 2008).

The effects of intensive mechanical tillage on soil food webs provide a most instructive insight into the impacts of agricultural intervention on the integrated functioning and health of the soil system. The adoption first of animal-drawn and then of fossil fuel-driven tillage was one of the most significant steps in the history of agricultural intensification, enabling huge savings in human labour and increased efficiency, through improved timing in other agricultural operations, as well as the guarantee of a well-prepared seed bed. However, over the past two decades or so, there has been a substantial reversion to reduced tillage practices in many parts of the world, particularly in North and South America (Landers et al. 2001). The main perceived benefits driving the adoption of reduced or even zero tillage regimes were improved water and soil conservation, consequent on improved soil protection from the retained crop residues as well as reduced costs in terms of fuel. A number of major and long-term studies comparing soil food webs under intensive and reduced or zero tillage conditions have been made since the mid-1980s. Wardle (1995) reviewed and analyzed more than 100 papers reporting on these studies and was able to derive a number of generalizations with respect to the impacts of tillage on the soil food web and a variety of processes mediated by the soil biota. The most obvious effect is a relationship between the size of the organism and the inhibitory effect of tillage. This is indeed not unexpected, since mechanical tillage disrupts the spatial integrity of the soil fabric, particularly at meso- and macrofaunal scales. To some extent, tillage is intended to substitute for biological ploughing and it is well known that earthworms are killed during this process. In no-till, however, the enhanced activity of the macrofaunal engineers in soil structure modification 're-substitutes' for the withdrawal of intensive tillage. The origin of changes to the water regime under no-tillage, such as reduced runoff, increased infiltration and storage, are significantly physical in origin but the results of the food web studies show that enhanced activity of the macrofaunal ecosystem engineers also plays a substantial part (Kibblewhite et al. 2008).

The most significant lesson that the widespread and detailed studies of the effects of tillage contribute to our understanding of soil health is that the single practice of ploughing has multiple, and largely negative, impacts on the soil biota, the processes they mediate and the environmental functions that they contribute. The positive side of this story is that the response of the soil biota to a removal of this disturbance is one of integrated reconfiguration, revealing the resilience of the system, and that the capacity for self-organization has not been lost. These generalizations must clearly be qualified by the differences in detail that occur under the varying circumstance of soil type, climate and management intensity. The same broad lesson emerges from consideration of the impact of pesticides and fertilizers. While there have been many studies of the ecological impacts of pesticides on above-ground ecology and soil macro- and mesofauna, rather less information is available on their impacts, or indeed those of other practices, on soil microbial ecology. All pesticides, whether applied directly or targeted at the above-ground parts of the plant or the pests themselves, are liable to end up in the soil and in contact with soil organisms. The impacts of a wide range of pesticides on specific groups of soil organisms, soil food webs and, to a more limited extent, biological processes in soil have been extensively documented (Edwards 1993). Predictably, the effects are highly variable, dependent on the type and amount of pesticide, soil environment and biotic groups studied. Generally speaking, however, the impacts are similar to those of tillage in that the impacts with the most far-reaching effects are often those at the higher trophic levels. Thus, the impact is not restricted to the target but has disruptive effects on the biological regulatory capacity of the soil community with damaging consequences for all soil functions (Edwards 2002). The same concerns thus exist with respect to the impact of pesticides on soil health as exist for their use generally, i.e. not only that indiscriminate use can have dangerous consequences for human health and impacts on environmental functions, but also that the whole basis of pesticide use can be economically inefficient if the non-target impacts are weighed against the targeted success (Kibblewhite et al. 2008).

The impacts of industrially produced fertilizer on the soil health system and ecosystem functions relate firstly to their effect on primary productivity. The effects of excessive quantities are on process rates rather than any direct toxic effects. A very important indirect impact is the fact that high fertilizer input use is commonly associated with reduction in the quantity of organic matter input. The presence of high concentrations of ammonium inhibits nitrogen fixation and stimulates nitrification. High levels of some nitrogenous fertilizers can lead to acidification in some soils and consequent effects on the soil biota. Excess nitrate may leach from the soil and contaminate sources of drinking water and/or change the nutrient balance in aquatic ecosystems. These excesses also fuel denitrification and the production of nitrous oxide. The combination of these effects has been documented extensively and has led to the conclusion that the global nitrogen cycle is significantly out of balance, and that agriculture is one of the main contributors (Wood et al. 2000). In terms of soil health at a more local level, the effect is a substrate-driven loss of internal controls and the opening up of cycle function. These direct effects of inorganic fertilizers on the nutrient cycling function are exacerbated by the reduction in organic matter inputs which often accompanies high rates of fertilizer use. Although fertilizers are highly effective in increasing crop production, integrative practices of combining them with organic inputs are commonly abandoned in the interests of efficiency, and above-ground residues are often removed or burned. Inorganic fertilizers have been shown to increase the rate of decomposition of 'low-quality' organic inputs and soil organic matter (Vanlauwe et al. 2001). This effect is usually attributed to the enhancement of microbial decomposer activity previously limited by low nutrient concentrations in the organic resources. It should be noted, however, that the results of experiments on this effect are equivocal: although a majority of results indicate the above effect, in a significant minority added inorganic nitrogen has either a neutral or even an inhibitory effect on the decomposition of low-N plant materials (Hobbie 2005). This is probably indicative of the interaction with secondary rate limiting factors, but makes the point that the addition of a single 'simple' source of nitrogen can have complex interactive effects on carbon transformations in the soil. The commonly observed overall effect of continuous inorganic fertilization with diminished input of carbon and energy is continuing decline in soil organic matter content (Kibblewhite et al. 2008).

Therefore, it is important to select a combination of techniques that work well for the given situation and setting in which they are being used. Through modern agricultural science we now have the ability to correct many of the mistaken practices undertaken by those in the past and to maintain healthier soils that should sustain the uses they are put to. Only time will tell if we are smart enough to effectively utilize the knowledge we now have. The impacts of agricultural practice on the soil health system, as a basis for deriving some principles for managing soil for sustainable soil health should be considered. It could be also noted that although each of the three substitutive practices have been considered separately, they are commonly used in concert. Comparative studies of soil food webs and functions in such multiple substitution systems and low substitution integrated agriculture confirm the improved soil health in the latter.

Soil Quality Indicators as Affected by Different Cultivated Crops

As mentioned before, the concept of soil quality appeared in the literature in the 1990s (Karlen et al. 1997). Several soil-quality definitions have been proposed, and they can probably be grouped into two broad categories depending on whether they emphasize either (1) soil functions or (2) soil use. The most important functions include water flow and retention, solute transport and retention, physical stability and support, retention and cycling of nutrients, buffering and filtering of potentially toxic materials, and maintenance of biodiversity and habitat (Andrews et al. 2004). A soil may have a high quality for one function but not for other functions. In contrast, the latter definition of soil quality can be simply defined as "fitness for use" (Letey et al. 2003). Thus, the soil- "function" definition emphasizes soil ecological services, whereas the soil-"use" definition implies specifying soil uses according to a soil's environmental or industrial context e.g., agriculture, road construction. The latter definition also implies responsibilities for those who use soil. These two definitions are interrelated and have been integrated, for example, in a sequential framework that evaluates a soil's quality for a specific purpose while considering its functions (Carter 2002). Thus, while soil quality can be considered the degree to which soil can meet a set of functions and/or uses, the members of the set may vary according to the soil context, the issues considered important, or the method used to analyze soil quality (Garrigues et al. 2012).

Soil quality is a critical component of ecosystem functioning and agricultural sustainability. Since no consensus on how to define soil quality exists, neither does consensus on how to assess and evaluate impacts on it. A healthy soil must also have strong resistance to degradation processes and able to recover following a perturbation because of inherent resilience. The term "*soil health*" is primarily used by farmers, land managers, extension agents, and other practicing professionals (Lal 2011). Soil quality can not be measured directly, so certain indicators must be used, which are measurable properties of soil and plant that provide clear information about how well the soil can function. In this study some biological and bio-chemical e. g. biotic and abiotic indicators were measured under different cover vegetations treated with bio-chemical fertilizers.

It is well established that, soil quality indicators are parameters for judging a soil's biological, physical, and chemical properties, which can be measured as quantities. While overall soil health can be measured by the soil's contribution to how well an ecosystem functions, soil quality can be measured by certain parameters or *indicators*. Examples of such indicators are soil water-holding capacity, organic carbon content, and microbial respiration. Checklists of physical, chemical, and microbial indicators are commonly assembled in a *minimum data set* (MDS). MDS indicators can be measured quantitatively at regular intervals. In other words, these indicators can be defined with specific units of measure, and the measurements can be judged against some common standards or analyzed for improvements over time. A general minimum data set of quantitative indicators is presented in Table 11. Such a data set may vary from location to location depending on how the land is used, such as for rangeland, wetland, or agricultural land. The relative importance of indicators within a data set is likely to change as land use changes. Comparisons between data sets are usually restricted to sites having similar conditions (Baldwin 2009).

Table 11 Proposed minimum data set or commonly used physical, chemical and biological indicators for screening soil quality

Selected indicator	Function and rationale for measurement
Soil organic matter	Because of its important roles for crop production, chemical functions associated with cycling and supplying essential plant nutrients especially N, P, and S; and physical functions associated with soil structure, tilth, surface crusting, runoff, and water as well as air entry, retention and transmission
Soil pH	Defines biological and chemical activity thresholds. Nutrient availability, and both toxicities and deficiencies, pesticide absorption and mobility, process models, microbial habitat, and plant root growth and development
Electrical conductivity (EC)	Defines plant and microbial activity thresholds. Defines also crop growth, soil structure, water infiltration; presently lacking in most process models
Salinity and SAR	They are generally more important in arid or semi-arid areas where excessive transpiration can result in a buildup of salts in the near surface horizons. They can also help detect the presence of seeps where water that infiltrated at higher landscape positions has flowed along impervious layers and now intersects the surface once again
Extractable N, P, and K	Describes plant-available nutrients and potential for N loss
	Indicates productivity and environmental quality
	Capacity to support plant growth, environmental quality indicator
Suspected pollutants	Plant quality, and human and animal health
Soil texture	Indicates how well water and chemicals are retained and transported
	Provides an estimate of soil erosion and variability
Soil aggregation	It reflects the arrangement of the primary sand-, silt-, and clay-sized particles into structural units defined as peds. Soil structure, erosion resistance, crop emergence an early indicator of soil management effect
Soil depth and rooting	Indicates productivity potential. Estimate rooting volume for crop production and erosion and evens out landscape and geographic variability
Infiltration rate	Describes the potential for leaching, productivity, and erosion
Soil bulk density (SBD)	Plant root penetration, porosity, adjust analysis to volumetric basis. Its potential effects on plant root development, exploration and nutrient needs
Water holding capacity (WHC)	Describes water retention, transport, and erosion
	Available water is used to calculate soil bulk density and organic matter
Microbial biomass C and N	Describes microbial catalytic potential and repository for carbon and nitrogen. Provides an early warning of management effects on organic matter
	It reflects nutrient cycling processes, management practices such as tillage intensity, crop type and crop residue management strategies
Potentially mineralizable N	Describes soil productivity and nitrogen supplying potential
	Provides an estimate of biomass. Availability of crops, leaching potential, mineralization/immobilization rates, process modeling
Soil respiration	Defines a level of microbial or biological activity, process modeling; estimate of biomass activity, early warning of management effect on organic matter. Provides also an estimate of biomass activity

Source: Compiled from Larson and Pierce (1994), Doran et al. (1996), Karlen et al. (2008), Baldwin (2009), Brevik (2009) and Laishram et al. (2012). *SAR* sodium adsorption ratio

Soil quality indicators should be selected according to the soil functions of interest (Nortcliff 2002) and threshold values have to be identified based on local conditions to generate a meaningful soil quality index. Indicator selection can be done using expert opinion, based purely on statistical procedures, or some combination of both to obtain a minimum data set (MDS). According to Roming et al. (1995), using indicators of soil quality that have meaning to farmers and to other land managers is likely the most fruitful means of linking science with practice in assessing the sustainability of land management practices (Lima et al. 2013).

Even though the properties that constitute a healthy soil are not the same in all places and all situations, there are some important soil properties that indicate soil health. These properties fall into three main categories: soil chemical, physical and biological properties. Soil chemical and physical properties have long been studied by soil scientists, and the basic tests and their procedures are well established. Many of the biological tests, on the other hand, are fairly new to soil science, so the exact procedures to be followed and the meanings of the results are less universally agreed upon in the soils community. Not all of these indicators are tested for in all cases, while under some circumstances other indicators than those listed in the table may be tested. This goes back to the idea, that soil health does not mean the same thing in all circumstances. Exactly what constitutes a healthy soil depends on the local conditions under which the soil has formed, and on the use to which the soil is being put. Because of this, there is no single group of tests for soil health, and no single set of results from these tests that indicates a soil is healthy. When evaluating soil health, all the information gathered must be pooled, evaluated as a group, and conclusions reached on a case-by-case basis (Brevik 2009).

Qualitative descriptions of soil quality are usually personal assessments of short-term changes in soil quality. The personal assessment may be a thoughtful conclusion based on recollections of how things were “way back when” compared to how they are today. When making qualitative assessments of soil quality, it is important to rely upon a set of well-defined *qualitative indicators*. Although these qualitative indicators cannot be gauged in units of measure, each one can be assessed based on the specific observations noted in Table 12 (Baldwin 2009).

It may be tempting to think that soil quality is simply an agricultural issue, but it is actually much bigger than that. Management of soils for soil health helps to combat some of the most important environmental issues of the modern era. The three biggest water pollutants in the modern world are nitrogen, phosphorus, and sediments. Erosion of the soil surface layers put all three of these pollutants into surface water bodies, nitrogen and phosphorus from SOM and fertilizers and sediments from the mineral content of the soil. Therefore, practices such as crop rotations, strip cropping, cover crops, leaving crop residues on the soil surface, conservation tillage, and vegetative buffers that are used to enhance soil health also serve to protect surface water sources from pollution.

Table 12 Qualitative soil quality indicators, where the personal descriptions used to describe changes in soil quality can be subjective or exact (Adapted from Baldwin 2009)

Indicator	Poor	Medium	Good
Earthworms	0–1 worms in shovelful of top foot of soil. No casts or holes	2–10 in shovelful. Few casts, holes, or worms	10+ in top foot of soil. Lots of casts and holes in tilled clods. Birds behind tillage
Organic matter (OM) color	Topsoil color similar to subsoil color	Surface color closer to subsoil color	Topsoil clearly defined, darker than subsoil
Roots/residue/(OM)	No visible residue or roots	Some residue, few roots	Noticeable roots and residue
Subsurface compaction	Wire breaks or bends when inserting surveyor's flag	Have to push hard, need fist to push flag in	Flag goes in easily with fingers to twice the depth of plow layer
Soil tilth, mellowness, and friability	Looks dead. Like brick or concrete, cloddy. Either blows apart or hard to pull drill through	Somewhat cloddy, balls up, rough pulling seedbed	Soil crumbles well, can slice through, like cutting butter. Spongy when you walk on it
Erosion	Large gullies over 2 in. deep joined to others, thin or no topsoil, rapid run-off the color of the soil	Few rills or gullies, gullies up to 2 in. deep. Some swift runoff, colored water	No gullies or rills. Clear or no runoff
Water holding capacity	Plant stress 2 days after a good rain	Water stress after a week	Holds water for a long period of time without puddling
Drainage, infiltration	Water lays for a long time, evaporates more than drains, always very wet ground	Water lays for short period of time, eventually drains	No ponding, no runoff, water moves through soil steadily. Soil not too wet, not too dry
Crop condition	Problem growing throughout season, poor growth, yellow or purple color	Fair growth, spots in field different, medium green color	Normal, healthy dark green color, excellent growth all season, across field
pH	Hard to correct for desired crop		Proper pH for crop
Nutrient holding capacity	Soil test values dropping with more fertilizer applied than crops use	Little or slow change	Soil tests trending up in relation to fertilizer applied and crop harvested

Likewise, healthy soils that have increased nutrient content due to increased SOM levels need lower levels of agrochemical application to grow a healthy crop, helping to reduce the potential for these chemicals to leach into ground water supplies (Brevik 2009).

Managing soils for soil health also has a positive impact on global warming through greenhouse gas emissions. Conservation tillage techniques require fewer field passes and smaller equipment, which translates into less fuel consumed and fewer greenhouse gases released as exhaust. In one study conducted in the United States it was estimated that conservation tillage uses 33.7 l ha^{-1} less fuel than conventional tillage when growing cotton. This estimate accounts for both the smaller equipment used and the decreased amount of time equipment spends in the field in a conservation tillage system. Managing for soil health can do more than reducing greenhouse gases from equipment use, however. Using the soil–plant system, it is possible to remove carbon dioxide (CO_2), the leading greenhouse gas, from the atmosphere. During photosynthesis, plants use CO_2 from the atmosphere and water to make sugars. Some of these sugars are incorporated into plant tissues, and when the plant or a portion of the plant dies, the dead tissues can be incorporated into the soil. When plant tissues that have been added to the soil decompose, CO_2 is released back into the atmosphere (Brevik 2009).

The secret to removing CO_2 from the atmosphere lies in the balance between OM added and OM lost from the soil. If SOM is being depleted, CO_2 is being released into the atmosphere more rapidly than plants remove it and soils are a net source of atmospheric CO_2. If, however, SOM is being increased plants are removing CO_2 from the atmosphere more rapidly than it is being released into the atmosphere through the decomposition of SOM. This process of increasing SOM is called carbon sequestration. Thus, one of the prime goals of managing for soil health, the goal of increasing or maintaining SOM, can aid in removing a major greenhouse gas from our atmosphere. While carbon sequestration in soils is not going to solve the global greenhouse gas problem, it is one step that can be taken to start addressing the greenhouse gas issue (Brevik 2009).

Therefore, it could be concluded that many reasons have been outlined here for improving and maintaining the health of our soils. It is important to note that there is no best approach to managing for soil health in any and all situations. It is also important to note that no single technique is going to maximize soil quality and productivity, some combination of cover crops, conservation tillage, manuring, crop rotations, etc. is going to give better results than any one technique alone. It has been well established that, organic inputs from litters and roots due to the growth of vegetation influences soil physical and chemical conditions, and the diversity, composition and production of vegetation largely determine soil microbial communities. However, soil microbes mediate the key soil processes, including the decomposition of organic matter, recycling of nutrients and homeostasis of terrestrial ecosystems. Also, the soil microbial biomass, phylogenetic diversity and different physiological activities are sensitive to changes in ecosystems, including vegetation and soil conditions and may provide early indications for assessing the status in stability, resistance and resilience of the ecosystems. These facts require good understanding on the interactions of vegetation succession, soil physical, chemical and biological status, and microbial communities in the ecosystems.

Soil Quality Indices and Indicators

It is well known that, assessing soil quality is difficult, because unlike water and air quality for which standards have been established primarily by legislation, soil quality assessments are purpose oriented and site specific. However, a quantitative assessment of soil quality could provide much needed information on the adequacy of the world's soil resource base in relation to the food and fibre needs of a growing world population. To assess soil quality, indicators (soil properties) are usually linked to soil function. Several indicators have been suggested reflecting changes over various spatial and temporal scales. Improved soil quality often is indicated by increased infiltration rate, aeration, macro-pores, aggregate size, aggregate stability and soil organic matter and by decreased bulk density, soil resistance, erosion and nutrient runoff (Sharma et al. 2005).

Soil quality indices are decision tools that effectively combine a variety of information for multi-objective decision making (Karlen and Stott 1994). A number of soil quality and fertility indices have been proposed (Andrews et al. 2002), none identifies state of soil degradation that affects its functionality. Bastida et al. (2006), building on the approach of Andrews et al. (2002), suggested microbiological degradation index. While many workers have appreciated and recommended the use of soil quality indices, reservations about their utility have also been expressed. Many a times the concepts associated with soil quality are used in close association with the concepts of sustainability, leading to a degree of confusion and inappropriate use of the term soil quality. Sojka and Upchurch (1999) suggest that the search for a single, affordable, workable soil quality index is unattainable. Selection of soil quality indicators or synthetic indices is guided by the goal of ecosystem management. If achieving sustainability is the goal of agroecosystem management, a soil quality index will constitute one component within a nested agroecosystem sustainability hierarchy. Management goals may also differ by the interests and visions of different sections of people concerned with agriculture. Once the management goals are identified, soil quality indexing involves three steps: (i) selection of soil properties/indicators constituting the minimum data set (ii) transformation of indicator scores enabling quantification of all indicators to a common measurement scale and (iii) combining the indicator scores into the index. Selection of soil properties/indicators of soil quality and their statistical/mathematical treatment to derive a composite index vary a lot. Velasquez et al. (2007) stressed the importance of identifying subindicators e.g., macrofauna, organic matter, physical quality, chemical quality and soil morphology, reflecting different aspects of soil quality (Laishram et al. 2012).

Although they are easy to apply, the use of two parameters in a soil quality index has almost the same limitations as the use of one parameter: the lack of information. Therefore, to obtain indices that provide and integrate more information on the quality of a soil, multiparametric indices have been developed for agroecosystems and for non-agricultural soils. The first multiparametric index for soil quality was probably that established by Karlen et al. (1994). These authors used the framework established by Karlen and Stott (1994), based in the utilization of normalized scoring functions for evaluating a production system's effect on soil quality in Lancaster (WI, USA). Although the systems based in Karlen and Stott (1994) have been widely developed, their major handicap resides in the fact that weighting is subjective and not depending of any mathematical or statistical method. These weights are provided attending to the importance of a soil function in fulfilling the overall goals of maintaining soil quality under specific conditions or purposes. Using Karlen and Stott's system and the same functions, Karlen et al. (1994) evaluated the effect of different applications of residues on the long term soil quality under *Zea mays* culture, showing that crop residue had a positive effect on soil quality. These authors made a brief but clear justification of selected parameters, indicating the importance and meaning of each indicator. They gave great importance to these water relations, using a variety of physical, chemical and biological parameters (Table 13; Bastida et al. 2008).

Soil quality indicators have been defined as soil processes and properties that are sensitive to changes in soil functions (Doran and Jones 1996). It is important to build a simple, sensitive, and workable indicator method for soil quality evaluation (Dumanski and Pieri 2000). Soil quality indicators should be a combination of chemical, physical, and biological properties (Aparicio and Costa 2007). Several authors have proposed sets of soil quality indicators (Larson and Pierce 1994; Doran and Parkin 1994; Karlen et al. 1998), and have evaluated soil quality based on the total data set (TDS) indicator method they selected. Also, representative indicators were suggested by many authors, such as the minimum data set (MDS), selected according to correlation between indicators and ease of measurement (Andrews et al. 2002) and the Delphi data set (DDS) (Zhang et al. 2004), selected according to the importance of the indicators to soil quality based on the opinion of experts (Herrick et al. 2002). A common feature of these indicator methods is that they are all identified and described by scientists and land managers according to their own terminology (Ditzler and Tugel 2002). Soil quality index calculation, a core issue in soil quality evaluation, is usually an indirect approach based on an integrated evaluation of quality indicators and their weights. It is a widely accepted approach because of its advantages in identifying the systematic complexity of soil productivity under natural conditions and farming practices, through the use of fuzzy mathematical methods to evaluate relationships between certain soil factors and land productivity (Sun et al. 2003).

Many quantitative models have been developed in soil quality index calculation, such as the integrated quality index (IQI) and Nemoro quality index (NQI). The IQI model, developed from the soil quality index of Doran and Parkin (1994), is the sum of corresponding weight values of all the selected indicators, which combines metrics into an index by an equation that uses a simple scoring system that weights all quality indicators equally. The NQI model, developed by Nemoro (Qin and Zhao 2000), is based on the average and the minimum indicator score, and indicator weights are not used in this model. The results are affected by the minimum indicator score and reflect the Law of the Minimum in crop production (van der Ploeg et al. 1999). The disparity between soil quality indicator methods and models leads

Table 13 Indicators used by different authors in soil quality indexes in agroecosystems from 1994 to 2007 (Adapted from Bastida et al. 2008)

Objective	Indicators used	Authors
Soil quality index: Evaluation of effects of crop residue management on soil quality under corn culture	Aggregate stability, porosity, worms, microbial biomass, respiration, ergosterol, total C, total N, bulk density, available water, pH, electrical conductivity	Karlen et al. (1994)
Relative soil quality index: Evaluation of changes in soil quality in natural and agriculture systems	Soil depth, texture, slope, organic matter, total and bioavailable N, P and K, cation exchange capacity and pH	Wang and Gong (1998)
Adaptation of indices to evaluate effect of three cultivation systems on soil quality	Aggregate stability, organic C crop residues, porosity, exchangeable K, pH	Hussain et al. (1999)
Soil quality index: Evaluation of effects of different apple production systems: conventional, organic and integrated	Aggregate stability, porosity, worms, porosity, organic C, microbial biomass C and N, cationic exchange capacity, pH and N	Glover et al. (2000)
Land quality index: Agroecosystem performance: effects of conventional and alternative agricultural systems	Seed yield, N content of seed, pH, organic C, nitrates	Liebig et al. (2001)
Soil quality index: Evaluation of tomato and cotton crop quality in conventional and organic cultivation	Organic matter, electrical conductivity, pH, water water-stable aggregates, real density and Zn	Andrews et al. (2002)
Biochemical soil fertility index: Comparison of long term effect of organic and mineral fertilisation in sugar beet	Organic C, total N, dehydrogenase activity, alkaline phosphatase activity, protease activity, amylase activity	Koper and Piotrowska (2003)
Sustainability index: Comparison of long term effect of organic amendments in systems for cultivating maize and rice	Organic C, total N, Extractable K, extractable nitrates and ammonium content, microbial biomass C and N, mineralizable N, respiration, bacterial counts, mycchorhizal infection, dehydrogenase activity	Kang et al. (2005)
Soil quality index: Selection of adequate managements in drylands comparing between conventional and minimal cultivation	Available N, K and S, microbial biomass C and saturated hydraulic conductivity	Sharma et al. (2005)
Soil quality index: Effects of swine manure compost application on soil quality under different vegetable and rice systems	Bulk density, aggregates, organic C, pH, available K and P, extractible Cu and Zn, microbial biomass, C, mineralizable N	Lee et al. (2006)

(continued)

Table 13 (continued)

Objective	Indicators used	Authors
Alteration index: Effects on the quality of agricultural soils contaminated with industrial and municipal wastes, organic fertilisation or irrigation with poor quality water under different crops: *Ficus carica*, maize, tomato, etc.	Arylsulphatase enzymatic activities, β-glucosiadase, phosphatase, urease, ivertase, dehydrogenase and phenoloxidase	Puglisi et al. (2005)
Soil alteration index: Effects on the quality of agricultural soils contaminated with industrial and municipal wastes, organic fertilisation or irrigation with poor quality water under different crops: *F. carica*, maize, tomato, etc.	PLFAs (phospholipid fatty acid)	Puglisi et al. (2006)
Soil quality index: Effects of cultivation practice (conventional and without ploughing) in rice–wheat systems, and maintaining vegetal residues on soil quality	Bulk density, aggregate stability, resistance to penetration, organic matter	Mohanty et al. (2007)
Soil quality index: Evaluation of agricultural soils fertilised with inorganic and/or farm yard manure	Bulk density, water retention, pH, electrical conductivity, bioavailable nutrients, organic matter, microbial biomass and crop yield	Masto et al. (2007)
Soil quality index: Compare the effect of land preparation methods (broad bed and furrows, green manure, ridge and furrows, reduced tillage) on soil quality	Bulk density, aggregate stability, organic C, microbial biomass C, pH, available water capacity	Erkossa et al. (2007)

to questions about whether the application of various indices would yield different results. However, opportunities for comparison among indices are rare because it is unusual to have more than one soil quality index available for any particular area (Qi et al. 2009).

As mentioned before, soil quality is estimated by observing or measuring different properties or processes, and, several of these indicators can be used to determine soil quality indices. According to different authors, like Doran and Zeiss (2000), indicators should be limited and manageable in number by different types of users, simple and easy to measure, cover the largest possible situations (soil types), including temporal variation, and be highly sensitive to environmental changes and soil management. The selection of indicators thus depends on the soil and functions being assessed. These features include, among others: support for the development of living organisms, water and nutrient flows, diversity and productivity of plants and animals, elimination or detoxification of organic and inorganic contaminants. Likewise, the selection depends on the sensitivity of these properties to soil management or changes in climate, as well as the accessibility and usefulness to producers, scientists, conservationists and policy makers (Doran and Zeiss 2000). The selection of indicators implies knowing research needs, and the power to interpret the indicator: the land use, the relationship between the indicator and the soil function that is being evaluated, the easiness and reliability of the measurement, the variation in time of the crop, application of organic matter or crop rotation in relation to sampling, the sensitivity of the soil property to be measured against changes in the ecosystem (Rezaei et al. 2006). Moreover, many soil ecosystems functions are difficult to infer directly and, consequently, soil quality must often be inferred from other easily measurable soil properties (Weil and Magdoff 2004), bearing in mind that soil quality should be directed mainly towards the detection of changes or trends that can be measured in time; however some indicators may change faster than others; thus not only the changes detected must be real but also sufficiently sensitive in short periods of time, so a quick action on the agroecosystem can be taken to correct problems before undesirable situations or irreversible losses of soil quality occur. General properties as aggregate stability, bulk density, pH, salinity, cation exchange capacity, microbial biomass, enzymatic activity, and basal respiration are used as indicators of soil quality (Martinez-Salgado et al. 2010).

It could be mentioned that, some authors suggest that a soil quality indicator is not adequate if it is not directly related to the target user. If the goal is a quality index for soil crop production, then soil organic matter, infiltration rate, soil aggregation, pH, microbial biomass, N forms, bulk density, electrical conductivity or salinity, and available nutrients, represent a group of indicators that can be used to describe most of the soil basic functions like the ability to accept, hold and release water to plants, maintain productivity, and respond to management and erosion processes (Weil and Magdoff 2004). In the same way, for a better interpretation of soil quality indicators, Segnestam (2002) expressed the need of using a baseline for comparison and to determine whether positive or negative impacts on environment have occurred. Besides, variations in time and rates of change as well as local indicators should be determined to define potential models for larger scales. For this reason the indicators associated to organic matter are considered to determine soil quality; they can be correlated with different chemical, physical and biological properties, some of them having high sensitivity, and their changes can offer stakeholders, policy or research institutions, correlated results in short time and make decisions timely for a given agroecosystem (Martinez-Salgado et al. 2010).

Soil quality indicators are useful to policy makers as they can: monitor the long-term effects of farm management practices on soil quality; assess the economic impact of alternative management practices designed to improve soil quality, such as cover crops and minimum tillage practices; examine the effectiveness of policies addressing the agricultural soil quality issue; and improve policy analysis of soil quality issues by including not only environmental values but also taking into account economic and social factors (Kleinhenz and Bierman 2002).

Physical and chemical properties have been extensively used to measure soil quality. However, these properties usually change on a time scale (decades), which are too long for management purposes. In contrast, soil properties based on biological and biochemical activities, such as soil enzymes have been shown to respond to small changes in soil conditions, thus providing information sensitive to subtle alterations of soil quality (Garcia-Ruiz et al. 2009). Soil microbial communities are influenced by many factors as soil management and cover crops (Carrera et al. 2007); kind of fertilizer and its applying way (Carrera et al. 2007); plant development stage and cultivars (Ferreira et al. 2008) as well as pesticides (Ferreira et al. 2009). Thus, microbial properties allied to the total organic C content can be used to evaluate the sustainability of agricultural production. These properties are described as biological indicators capable of detecting changes in soil quality and its biological properties (Ferreira et al. 2010).

Correspondingly categories of soil properties, which including chemical, biological, and physical, do not exactly align with the soil functions. The complex interactions between soil properties, indicators, and soil functions require that for assessment of soil quality integration of soil properties into the soil property categories is necessary. Burger and Kelting (1999) suggested that good indicators should have the following features:

- Possess an available baseline against which to compare change;
- Provide a sensitive and timely measure of a soil's ability to function;
- Be applicable over large areas but specific enough to be sensitive;
- Be capable of providing a continuous assessment;
- Be inexpensive, easy to use, collect, and calculate;
- Discriminate between natural changes and those induced by management;
- Be highly correlated to long-term response; and
- Be responsive to corrective measures (Bone et al. 2010).

Therefore, it could be summarized that, many studies have analyzed soil quality using different indicators but only a few have used the obtained results to establish a soil quality index. In addition, the few indices that exist have not been widely used. There is no an universally applicable formula to measure soil quality. Although the methods exist, indices are never used on a larger scale, nor even in similar climatological, agronomic, etc. conditions. In this sense, a clear definition of the conditions in which an index has been obtained must be kept in mind so that it can be applied at least at regional scale by the group concerned. In this case identifying and using some important site-specific factors for the study area, such as climate parameters and vegetation type and density are essential to decrease the poor of standardization and solve problems related to spatial scale. In addition, a soil quality index to some extent should be defined use-dependent, so that it will be applicable in a larger scale. It will help us to select a minimum set of indicators that can address the maximum capacity of soil to a specify function. Finally, soil quality indices and indicators should be selected according to the soil functions of interest and the defined management goals for the system.

Biological and Biochemical Indicators

Generally, the greatest problems posed by the use of biochemical properties as soil quality indicators include the lack of reference values, the contradictory behavior shown by these properties when a soil is degraded, and the regional variations in expression levels. Most of these problems are derived from the scarce information available on the biochemical properties of soil. For this reason, obtaining soil quality indicators of general use will require a coordinated effort from the international scientific community to standardize the analytical methods and to compile databases of biochemical properties from soils under diverse geographic conditions and with different uses and management (Gil-Sotres et al. 2005).

The selection of indicators that enable the quantification of soil quality is important. In the correct functioning of a soil an immense number of physical, chemical and biochemical properties are involved. However, due to the impossibility of considering all these properties, it is necessary to make a selection. The selected indicators must satisfy a series of requisites: (a) sensitivity to the presence of the greatest possible number of degrading agents; (b) consistency in the direction of the change undergone in response to a given contaminant; and (c) ability to reflect the different levels of degradation (Elliott 1994). With regard to the selection of properties for use as indicators, Doran and Parkin (1996) consider a '*minimum data set*' for use in soil quality evaluation, which includes physical (texture, rooting depth, infiltration rate, bulk density, water retention capacity), chemical (pH, total C, electrical conductivity, nutrient level) and biological (C and N microbial biomass, potentially mineralizable N, soil respiration) properties, although many of the properties included in this dataset (Gil-Sotres et al. 2005) (Table 14).

Soil microorganisms are assumed to be one of directly responsible for soil quality according to their significant roles in the decomposition of soil organic matter and cycling of plant nutrients, e. g. the ecological processes. Soil microbial biomass and soil enzyme activities respond much more quickly to the changes in soil management practices as compared to total soil organic matter. Enzymes may react to changes in soil management more quickly than other variables and therefore may be useful as early indicators of biological changes. In fact, they may also indicate the soil's potential to sustain microbiological activity. Therefore, measurement of microbial biomass and enzymatic activities provides a sensitive indication of soil quality (Tejada et al. 2008).

The biological activity in soil is largely concentrated in the topsoil, the depth of which may vary from a few to 30 cm. In the topsoil, the biological components occupy a tiny fraction (<0.5 %) of the total soil volume and make up less than 10 % of the total organic matter in the soil. These biological components consist mainly of soil organisms, especially microorganisms. Microorganisms possess the ability to give an integrated measure of soil quality, an aspect that cannot be obtained with physical/chemical measures and/or analyses of diversity of higher organisms. Microorganisms respond quickly to changes; hence they rapidly adapt to environmental conditions, and thus they can be used for soil health assessment, and changes

Table 14 Key biological functions, the groups of soil biota principally responsible for these functions and management practices most likely to affect them (From Giller et al. 1997)

Biological function	Biological/functional group	Management practices
Residue comminution/decomposition	Residue-borne microorganisms, meso/macrofauna	Burning, soil tillage, pesticide applications
Carbon sequestration	Microbial biomass (especially fungi), macrofauna building compact structures	Burning, shortening of fallow in slash-and-burn, soil tillage
Nitrogen fixation	Free and symbiotic nitrogen fixers	Reduction in crop diversity, fertilization
Organic matter/nutrient redistribution	Roots, mycorrhizas, soil macrofauna	Reduction in crop diversity, soil tillage, fertilization
Nutrient cycling, mineralization/immobilization	Soil microorganisms, soil microfauna	Soil tillage, irrigation, fertilization, pesticide applications, burning
Bioturbation	Roots, soil macrofauna	Soil tillage, irrigation, pesticide applications
Soil aggregation	Roots, fungal hyphae, soil macrofauna, soil mesofauna	Soil tillage, burning, reduction in crop diversity, irrigation
Population control	Predators/grazers, parasites, pathogens	Fertilization, pesticide application, reduction in crop diversity, soil tillage

in microbial populations and activities may therefore function as an excellent indicator of change in soil quality (Das and Varma 2011).

It could be addressed some of the most important soil biological indicators as follows:

1. *Soil microbial counts*

Considering benefits of inoculations procedures to plant growth, the microbial associations have been pointed as an important strategy to guarantee plant survival under arid- and semi-arid conditions. In view of the fact that biological and biochemical parameters are more sensitive to slight soil modifications by any degrading agent and the dependence of semi-arid plants to symbiotic microorganisms (Scotti and Correa 2004), these soil populations may be considered strong candidates as biological indicators of soil quality. Indeed, soil microbial taxa and community structure have been considered a strong candidate as biological indicator for monitoring soil quality (Ritz et al. 2009).

Soil biology is directly linked to agricultural sustainability as it is the driving force behind decomposition processes that break down complex organic molecules and substances and convert them to plant available forms. Soil microorganisms play a crucial role in mineralization and breakdown of complex organic compounds in soil. Microbial populations and functional diversity are greatly influenced by quantity and quality of crop residue and other incorporate organic amendments (Nair and Ngouajio 2012). Microorganisms are the most diverse and abundant class of organisms on Earth, comprising millions of species (Torsvik et al. 2002). Our understanding of their biogeography and how it is affected by environmental factors is improving. An improved understanding is imperative due to the role of soil microbes in carbon and nitrogen cycling (Lucas et al. 2007), ecosystem interactions (Hines et al. 2006), ecosystem functioning (Stroud et al. 2007) and global climate change (Schimel and Gulledge 1998). There have been many studies of the composition of microbial communities and their interactions with environment factors, but mostly at small spatial scales. It was also found that the relative importance of various environmental variables in governing the composition of microbial communities in agricultural soils could be ranked in the order of soil type > time > management such as cover crop incorporation or supplying mineral fertilizer > spatial variation in the field (Wu et al. 2009).

Soil microbes are a key component in soil ecosystems, dominating the cycling of nutrient elements and playing a major role in maintaining soil quality. Unfortunately, the soil microbial community is still a black box because of its complexity and the limitations of methodologies for quantification of the soil community. One gram of soil contains thousands of species and billions of individuals of microorganisms, but only approximately 2–3 % of soil microbes have been described and less than 1 % of the microbes are cultivable (Wang et al. 2008).

It is well documented that, the total bacteria, fungi and actinomycetes counts under faba bean rhizosphere are higher comparing with these microbial counts under rhizosphere of wheat, sugar beet, clover, onion and garlic. However, the total microbial counts of previous microbes increased in bulk soil than rhizosphere under onion and garlic plants. The highest values of soil microbial counts, in general, are recorded for integrated nutrient management (mineral, organic and biofertilizer) and mineral and organic fertilizer, whereas the lowest values recorded for the control (Alshaal et al. 2012).

Therefore, it could be concluded that, soil microbes are a key component in soil ecosystems, dominating the cycling of nutrient elements and playing a major role in maintaining soil quality. Soil organisms are assumed to be one of directly responsible for soil quality according to their significant roles in the decomposition of soil organic matter and cycling of plant nutrients, e. g. the ecological processes.

2. *Soil enzyme activities*

Biological variables, such as enzyme activities, have been highlighted as potential indicators of soil quality as they are frequently more sensitive to management than physical and/or chemical properties. Thus, the early identification of unsustainable agricultural practices might be attained through the monitoring of these variables (Sant'anna et al. 2009). Soil enzymes catalyze reactions in soils that are important in cycling of nutrients such as C, N, P, and S. Accumulated enzymes are primarily of microbial origin but may also originate from plant and animal residue (Dick et al. 1994).

Soil enzyme activities have been suggested as suitable indicators of soil quality because of their intimate relationship with soil biology, ease of measurement, and rapid response to change in soil management. Many long-term studies have shown that soil enzyme activities are sensitive in discriminating among soil management practices, such as fertilization by means of animal manure or green manures/crop residues (Martens et al. 1992) and municipal refuse amendment (Perucci 1992), as well as among tillage treatments (Gupta and Germida 1988). The response of soil enzyme activities to specific soil practices has been used to compare agricultural systems (combinations of soil practices) such as organic versus conventional farming (Garcia-Ruiz et al. 2009).

Soil enzymes form a part of the soil matrix as exo-enzymes and as endo-enzymes in viable cells. Soil enzyme activities commonly correlate with microbial parameters. Microorganisms and plants synthesize enzymes, and in the soil they act as biological catalysts of important reactions to produce essential compounds for both soil microorganisms and plants. Assays of soil enzymatic activities include all of the enzymatic forms (biotic and abiotic) present in the soil (Nannipieri 1994). They also determine the potential enzymatic activity of a soil under optimum conditions of moisture, pH, temperature and substrate concentration. Enzymatic activities may vary under stress, as when soil is contaminated by heavy metals (Dick 1997). Soil enzymes are important for catalyzing innumerable reactions necessary for life processes of micro-organisms in soils, decomposition of organic residues, cycling of nutrients, and formation of organic matter and soil structure (Balota et al. 2004).

All soils contain a group of enzymes that determine soil metabolic processes which, in turn, depend on its physical, chemical, microbiological, and biochemical properties. The enzyme levels in soil systems vary in amounts primarily due to the fact that each soil type has different amounts of organic matter content, composition, and activity of its living organisms and intensity of biological processes. In practice, the biochemical reactions are brought about largely through the catalytic contribution of enzymes and variable substrates that serve as energy sources for microorganisms. These enzymes may include amylase, arylsulphatase, β-glucosidase, cellulose, chitinase, dehydrogenase, phosphatase, protease, and urease released from plants, animals, organic compounds, and microorganisms and soils (Das and Varma 2011).

Since the soil rhizosphere represents a complex of living communities, it is considered that soil alkaline phosphatase (AlP) and acid phosphatase (AcP) that are responsible for organic P transformation in soil, might be originating from extracellular and intracellular enzyme activities (Eichler et al. 2004). AcP activity in soil originates from many sources, including plant roots (Dinkelaker and Marschner 1992), fungi (Tarafdar et al. 1988), mycorrhizal fungi (Tarafdar and Marschner 1994) and bacteria (Tarafdar and Claassen 1988). Soil microorganisms and soil fauna produce AlP, whereas higher plants are devoid of AlP (Tarafdar and Claassen 1988). The activity of soil AlP and AcP that are responsible for hydrolysis of both

Table 15 Response of some soil enzyme activities for some plants – rhizosphere dressed with bio-, organic and chemical fertilizers after 3 months from sowing for wheat, sugar beet, faba bean, onion and garlic and after first cut for Egyptian clover

Treatments	Wheat	Sugar beet	Clover	Faba bean	Onion	Garlic
Phosphatase activity (μg *p*-nitrophenol g^{-1} soil h^{-1})						
T1	98.7 a	150.1 a	112.6 a	88.5 a	44.7 a	43.4 a
T2	91.0 a	160.9 a	124.9 a	85.5 a	54.6 a	56.6 a
T3	116.8 a	151.2 a	131.1 a	64.7 a	58.8 a	45.8 a
T4	111.1 a	162.0 a	137.7 a	45.0 a	56.3 a	46.4 a
Dehydrogenase activity (μg TPF kg^{-1} soil day^{-1})						
T1	4.62 b	6.02 a	6.91 a	17.04 a	1.03 a	2.99 a
T2	4.78 b	6.97 a	10.13 a	16.61 a	0.88 a	3.73 a
T3	8.51 a	7.47 a	6.65 a	20.01 a	0.68 a	2. 65 a
T4	3.77 b	7.94 a	8.98 a	12.94 a	0.87 a	2.95 a
Catalase activity (μmole H_2O_2 g^{-1} soil min^{-1})						
T1	200.5 b	256.1 a	304.8 a	245.5 a	226.2 a	248.9 b
T2	214.0 b	219.5 b	287.3 a	263.5 a	235.2 a	288.9 a
T3	243.2 a	254.1 ab	287.3 a	243.7 a	255.7 a	286.7 a
T4	175.6 c	243.9 ab	287.3 a	234.2 a	251.2 a	277.8 a
Invertase activity (μmole glucose g^{-1} soil day^{-1})						
T1	6.50 c	7.21 b	6.86 b	6.99 c	6.14 b	5.82 c
T2	7.33 ab	8.05 a	7.57 a	7.93 ab	6.64 a	6.47 a
T3	7.00 bc	7.36 b	6.81 b	7.55 bc	5.86 b	6.04 b
T4	7.77 a	7.81 ab	7.46 a	8.21 a	6.70 a	6.52 a

Treatments: T1: inorganic recommended P, K ha^{-1}

T2: Biofertilizer + inorganic recommended P, K ha^{-1}

T3: T2 + recommended N fed^{-1} which added as (1:1) inorganic and organic sources (sewage sludge and poultry manure)

T4: Inorganic recommended P, K ha^{-1} + recommended N ha^{-1} (added as 1:1 inorganic and organic sources)

esters and anhydrous H_3PO_4 of soil organic matter depends on various factors as soil type and its fertility, type of fertilization and nutrient management, soil microbiological activity, organic matter, soil pH, soil moisture and varieties of higher plant species. Roots and microorganisms release acid phosphatase, whereas microorganisms only produce alkaline phosphatase. Acid and alkaline phosphatase activities are often increased in the rhizosphere compared to the bulk soil (Table 15; El-Ramady 2008).

Enzyme activities have been associated with indicators of biogeochemical cycles, degradation of organic matter and soil remediation processes, so they can determine, together with other physical or chemical properties, the quality of a soil. Soil enzyme activities (1) are often closely related to soil organic matter, soil physical properties and microbial activity or biomass, (2) changes much sooner than other parameters, thus providing early indications of changes in soil health, and (3) involve simple procedures (Dick et al. 1996). In addition, soil enzyme activities can be used as measures of microbial activity, soil productivity, and inhibiting effects of pollutants. These include dehydrogenase, glucosidases, urease, amidases, phosphatases, arylsulphatase, cellulases, and phenol oxidases (Das and Varma 2011). Nevertheless, due to enzyme origin (from bacteria, fungi, plants, and a range of macroinvertebrates), different enzyme locations (intra or extracellular), matrix association (alive or dead cells, clays or/and humic molecules) and assay laboratory conditions, it has been demonstrated that it is of great importance to optimize the procedures for enzymatic activity determination in order to obtain the best values and indices according to intrinsic soil properties Because enzymes are difficult to extract from soils and regularly loose their integrity, enzyme activity determination must be made under strict laboratory conditions paying particular attention to temperature control, incubation time, pH buffer, ionic strength of the solution, and substrate concentration (Martinez-Salgado et al. 2010).

Soil enzymes are a kind of bioactive substances sensitive to environment. So, scientists suggested that enzymes might serve as indicators of evaluating the degree of soil quality. Dehydrogenase activity is considered as a suitable indicator of microbial activity because dehydrogenase only occurs within living cells, unlike other enzymes that can occur in the extracellular state. Brookes et al. (1984) reported that dehydrogenase activity was lower in metal-contaminated soil than in similar uncontaminated soil, whereas soil phosphatase activity was unaffected. Dehydrogenase activity is an intracellular process that occurs in every viable microbial cell and is measured to determine overall microbiological activity of soil (Burns and Dick 2002).

Stable extracellular enzyme activities are associated with soil colloids and persist even in harsh environments that would limit intracellular microbiological activity (Nannipieri et al. 2002). Thus, only strictly intracellular enzyme activities can truly reflect microbial activity because the contribution of free extracellular enzyme released by active soil microbial cells is negligible; indeed, these enzymes are short-lived because they are degraded by proteases unless they are adsorbed by clays or immobilized by humic molecules (Burns 1982).

Investigations on a limited number of enzymes show that agricultural management practices affect their activities (Dick et al. 1994). Soil enzyme assays provide quantitative information on soil chemical processes, nutrient mineralization rates, and organic matter accumulation. Soil enzyme assays among different management practices may also indicate short-term differences in soil quality improvement, and can be used to evaluate rapid responses to changes in management and in understanding sensitivity to environmental stresses (Dick 1997). Acid and alkaline phosphatase activities are often increased in the rhizosphere compared to the bulk soil (Tarafdar and Claassen 1988).

Therefore, it could be concluded that, soil enzymes are a group of enzymes whose usual inhabitants are the soil and are continuously playing an important role in maintaining soil ecology, physical and chemical properties, fertility, and soil health. These enzymes play key biochemical functions in the overall process of organic matter decomposition in the soil system. Soil enzyme activities are widely used as reliable soil quality indicators. There is currently great interest in the use of extracellular enzymes as biological indicators of soil quality, as they are closely related to important soil properties such as content of organic matter, soil physical properties, as well as microbial activity or biomass. Therefore, soil enzymes have ecological significance, are sensitive to environmental stress and respond rapidly to changes in land management. In particular, they have been increasingly used to investigate changes in functions due to anthropogenic impacts. In agricultural soils, under different organic amendments, differences in microbial biomass and microbial activity may in fact influence nutrient availability to crops stimulating microbial synthesis of enzymes involved in nutrient transformations.

3. *SOM, MBC and soil respiration*

Soil organic matter (SOM) has been suggested as the most important single indicator of soil quality and agricultural sustainability since it affects other physical, chemical and biological soil properties (Reeves 1997). However, the measure of SOM content does not give any insight into the biogeochemical mechanisms that influence SOM turnover and are responsible for the observed modifications. Moreover, SOM changes slowly with time and management-induced effects require a long time before being experimentally detectable (Körschens 2006). Long-term experiments are then essential to providing the empirical data necessary to establish the cause–effect relationship between management practices and SOM content changes (Eivazi et al. 2003). Besides affecting SOM content, the repeated incorporation of organic and mineral fertilizers may also influence the composition of the organic matter accumulating in soils. Recent advances in infrared spectroscopy allow the application of the technique directly on bulk soil samples without any specific pre-treatment or fractionation. This new approach represents a simple and powerful means for the chemical characterization of SOM (Giacometti et al. 2013).

Soil organic matter (SOM), microbial biomass carbon (MBC) and soil respiration are very important biological indicators. It is well established that, the biochemical indicators such as soil organic carbon content (SOC), microbial biomass carbon (MBC), soil respiration (SR) and soil enzymes activities has been extensively used for soil quality measurement (Karlen et al. 1997). Generally, the highest biochemical indicators which are found under clover and faba bean may be due to the highest amounts of released synthetic growth factors, carbon and biologically fixed N in the rhizosphere region more than other field crops (sugar beet, wheat, onion and garlic). With regard to onion and garlic which have condensed fibrous roots, it may conclude that garlic showed the height amounts of post harvest organic matter and released soluble material, due to its higher fertilization treatments than other plants (El-Ramady et al. 2013).

Soil properties associated with soil organic matter have been recognized as key indicators and to have an effect on other properties. Soil organic matter defines the energy supply to microorganisms, availability and quality of substrates, and the biodiversity necessary to sustain many soil functions. However, SOM content varies with changes in climate, soil and crop management, being higher in places with larger average annual precipitation, lower mean annual temperature, and higher clay content (Burke and Cole 1995). Similarly, SOM content is affected by intermediate grazing intensity, incorporation of crop residues or the addition of organic matter fractions and by soil management practices such as minimum or conservation tillage.

Franzluebbers et al. (2002), proposed stratification ratios of soil properties, i.e. N and C pools, including total and particulate organic C and N, soil microbial biomass C, and potential C and N mineralization to explain differences respect to soil quality in soils with conventional tillage and no tillage. Regarding SOM decomposition, there are factors such as N and P concentration, clay or polysaccharides content that affect its decay, altering soil properties associated with soil quality. Some fractions, like starch or protein, are easily metabolized while humic substances are more resistant to decay (Tate 1987); the latter participates in nutrient exchange processes, formation of aggregates between organic substances and mineral particles, and in the immobilization of toxic materials (Martinez-Salgado et al. 2010).

It is well established that, application of manure and compost on agricultural lands has been shown to positively increase and enrich soil food web (bacteria, fungi, protozoan and nematode density) and also affect a number of soil characteristics, including SOM, and soil respiration (Treonis et al. 2010). With increasing number of growers using cover crops and organic amendments in their production systems, it becomes all the more important to better understand the effects of such strategies on soil microorganisms as they are directly involved in organic matter decomposition and nutrient cycling. After soil incorporation, nutrients available in cover crops and organic amendments have to pass through a decomposition pathway which involves a number of soil microorganisms including, bacteria, fungi, and actinomycetes. Thus, the quality and quantity of plant residues entering the soil can significantly influence soil microorganisms and soil microbial processes (Govaerts et al. 2007). Both crop residue and SOM quality have the potential to increase functional diversity in soil microbial communities (Nair and Ngouajio 2012).

The following indicators SOM, MBC and soil respiration in the rhizosphere under tested vegetations treated with the used bio-, organic and chemical dressings were investigated. The highest value of SOM (29.8 g kg^{-1}) was recorded under garlic treated using mineral plus biofertilizer, whereas the lowest (12.8 g kg^{-1}) value of SOM obtained from the rhizosphere under onion treated with control. Under clover, the highest values for MBC and soil respiration (460.6 μg g^{-1} and 112.13 meq CO_2 elevated 100 g^{-1} soil day^{-1}, respectively) treated with bio-, organic and chemical fertilizers and organic and chemical fertilizers, whereas the lowest values (300.7 μg g^{-1} and 106.8 meq CO_2 elevated 100 g^{-1} soil day^{-1}, respectively) were recorded under wheat and sugar beet rhizosphere, respectively. These findings could be considered as a result of substantial growth of cultivated plants and hence more post harvest SOM was present due to biochemical dressings (El-Ramady et al. 2013).

Therefore, it could be concluded that, there are several biological soil properties that can be used as soil quality indicators, alone or in combination with other chemical or physical properties. However, they are far from being universal and should be chosen according to the situation under consideration. On the other hand, there are several properties difficult to determine and to interpret that many times explain about the same as simpler and less costly measurements; similarly, only properties that are sensitive to management changes should be used; Proper sampling strategies and multivariate analysis of the results are key factors to consider when using biological soil indicators.

Chemical Indicators

As reported by the Soil Quality Institute (USDA 2006), the ultimate purpose of assessing soil quality is not to achieve high aggregate stability, biological activity, or some other soil property. The purpose is to protect and improve long-term agricultural productivity, water quality, and habitats of all organisms including people. By assessing soil quality, a land manager will be able to determine if a set of management practices is sustainable. For example, agricultural management systems located on the most suitable lands, according to their agroecological potentialities and limitations, are the best way to achieve sustainability. There is a need to investigate coordinated and multidisciplinary approaches to assessing soil quality, evaluating long-term potential and limitations (inherent soil aspects), and monitoring the short-term changes (dynamic soil aspects) in response to sustainable soil use and management (De la Rosa and Sobral 2008).

A unique balance of chemical, physical, and biological (including microbial especially enzyme activities) components contribute to maintaining soil health. Evaluation of soil health therefore requires indicators of all these components. Healthy soils are essential for the integrity of terrestrial ecosystems to remain intact or to recover from disturbances, such as drought, climate change, pest infestation, pollution, and human exploitation including agriculture. Deterioration of soil, and thereby soil health, is of concern for human, animal, and plant health because air, groundwater, and surface water consumed by humans, can be adversely affected by mismanaged and contaminated soil (Das and Varma 2011).

De la Rosa and Sobral (2008) reviewed about soil attributes which could be used as indicators of soil quality as follows:

(1) ***Physical attributes***: soil texture, stoniness, soil structure, bulk density, porosity, aggregate strength and stability, soil crusting, soil compaction, drainage, water retention, infiltration rate, hydraulic conductivity, and topsoil depth.
(2) ***Chemical attributes***: color, soil pH, carbonate content, salinity, sodium saturation, cation exchange capacity, plant nutrients and toxic elements.
(3) ***Biological attributes***: organic matter content, populations of organisms, fractions of organic matter, microbial biomass, respiration rate, mycorrhizal associations, nematode communities, enzyme activities, fatty acid profiles and bioavailability of contaminants.

Soil quality assessment must account for both inherent and dynamic soil properties and processes and must be holistic, accounting for all soil processes and interactions within soils (Karlen et al. 2003). For a specific site, assessment will be influenced by many factors including tillage, crop rotation, animal- or green manure applications and other management factors, as well as climate and soil type. Ideally soil quality should be easy to measure, able to reflect changes in soil functions, sensitive to variations in management, and accessible to as many users as possible (Shukla et al. 2006). Furthermore, the site-specific nature of soil quality may actually require different soil property measurements depending upon the specific agroecosystem for which the assessment is being made (Marinari et al. 2006). The first step toward soil quality assessment is the selection of soil quality indicators, that is the soil properties and processes that will provide a minimum data set for evaluation (Andrews et al. 2004). Care must be taken to ensure that these indicators accurately represent both human-induced and natural or inherent changes in the soil for which the evaluation is being made (Imaz et al. 2010).

Soil quality can not be measured directly, so certain indicators must be used, which are measurable properties of soil and plant that provide clear information about how well the soil can function. In this study, some chemical indicators were measured under different cover vegetations treated with bio-chemical fertilizers. The need to define soil quality is associated with questions about how to assess and evaluate impacts on it. The fundamental challenges encountered in doing so, besides the complexity of the soil system, include spatial and temporal variability of soil characteristics at all scales and the influence of external drivers such as climate and management practices. Soil quality assessment is part of the larger objective of assessing the environmental impact of agriculture (or other human activities). Various methods exist, and some aspects of soil quality are considered in a few of them (Garrigues et al. 2012).

Some chemical indicators such as pH, soil salinity (EC), cation exchange capacity (CEC), NPK and micro-elements were used as indicators for soil quality in soil treated with different bio-, organic and chemical dressing and cultivated with various cover vegetations (Table 16; El-Ramady et al. 2013). Chemical conditions in the rhizosphere soils are often different from the bulk soil as plant roots exude organic compounds including low-molecular-weight organic acids (LMWOAs). It is also expected that roots exudate components to regulate their bioavailability and transport in the soil environment. Moreover, root exudation may be an important mediation in altering the species composition of rhizosphere microflora that function in nutrient transformations, decomposition and mineralization of organic substances, and formation of soil organic matter, all of which are related to soil quality (Petra et al. 2004). This latter aspect is particularly in need of clarification, in view of the ever increasing threat of global environmental change and soil pollution caused by anthropogenic activity.

1. ***Soil reaction*** **(pH)**

Soil pH is soil chemical characteristic to be included as basic indicator of soil quality and one of the chemical parameters of nutrient availability with specific scoring functions to be used for plant productivity, and/or environmental components of soil quality. There is a positive relationship between crop yield and this indicator of soil acidity in tropical Oxisols, Ultisols, and Alfisols, whereas it is not considered a sensitive indicator of soil acidity; critical limits around pH 5.

Soil pH helps to predict the relative availability of most inorganic nutrients, as well as the suitability of different plants to be cultivated. Data presented in Table 16 shows that soil pH values slightly decreased as a residual effect of bio-inorganic fertilizes in comparison with the control under clover, faba bean, onion and garlic. The soil pH decreased from 8.20 (control) under clover and garlic to 7.9 under

Table 16 Assessment of some indicators of soil chemical characteristics of tested plants-rhizosphere dressed with bio-inorganic fertilizers after 3 months from sowing

Treatments	Wheat	Sugar beet	Clover	Faba bean	Onion	Garlic
			Soil pH			
T1	8.16	8.37	8.20	8.02	8.20	8.20
T2	8.19	8.45	8.13	7.93	8.10	8.10
T3	8.13	8.44	8.15	7.93	7.90	8.10
T4	8.18	8.40	8.11	7.92	7.90	8.00
			Soil salinity, EC (dS m^{-1})			
T1	0.78	0.43	0.65	0.98	1.17	0.7
T2	0.85	0.57	0.80	1.21	1.47	1.1
T3	0.84	0.46	0.82	1.22	1.71	0.8
T4	0.71	0.59	0.67	0.95	1.19	0.8
			Cation exchange capacity, CEC (c $mole_c$ kg^{-1} soil)			
T1	51.2	46.8	49.4	42.2	34.4	43.1
T2	45.8	45.7	45.0	49.0	41.2	46.1
T3	39.2	50.0	49.1	48.0	43.5	46.2
T4	55.9	49.5	48.8	45.5	45.3	46.7

T1: inorganic recommended P, K ha^{-1}

T2: Biofertilizer + inorganic recommended P, K ha^{-1}

T3: T2 + recommended N fed^{-1} which added as (1:1) inorganic and organic sources (sewage sludge and poultry manure)

T4: Inorganic recommended P, K ha^{-1} + recommended N ha^{-1} (added as 1:1 inorganic and organic sources)

onion for integrated fertilizer (T3 and T4). It is clear that, the pH values were higher under sugar beet more than the other crops which may be attributed to excreted sodium from plants or to nature of the treatments used. It could be indicated also that, the reduction in soil pH under legumes vegetables crops was pronounced in T4 which received sewage sludge and poultry manure.

2. ***Soil salinity*** **(EC, dS m^{-1})**

Soil salinity is a part of minimum dataset for agronomic soils; used in pedotransfer function for soil productivity attribute and could be characterized to be included as basic indicator of soil quality. The effects of bio-inorganic fertilizers under different cultivated crops on soil salinity after 3 months from sowing are shown in Table 16. The EC values ranged between 0.43 and 1.71, the lowest value was in case of control under sugar beet, and the highest was in T3 under onion. Values of soil salinity under cultivated crops were in the following order: onion > faba bean > garlic wheat > berseem > sugar beet.

3. ***Cation exchange capacity*** **(CEC, $cmole_c$ kg^{-1} soil)**

It is well established that, chemical fertilizers have contributed significantly toward the pollution of water, air and soil. Therefore, the current trend is to explore the possibility of supplementing chemical fertilizers with organic ones that are eco-friendly and cost effective (Banerjee et al. 2010). In case of CEC, a high value was obtained with T4 treatment under wheat plants with average value 55.9 followed by control treatment under wheat crop with mean value 51.2, then T3 treatment under sugar beet with average value 50.0 and the lowest value was obtained by control under onion with mean value 34.4 (Table 16). The higher growth response of wheat to T4 may lead to more residual organic matter pools and consequently the soil CEC. Values of soil-N content under cultivated crops were in the following order: sugar beet > faba bean > onion > clover > garlic > wheat.

Therefore, it could be concluded that, the need to understand and assess soil quality indicators has been identified as one of the most important goals for modern soil science, because of growing public interest in sustainability and the desire to determine effects of land use and management practices on soil resources. As environments differ as well as the soil functions of interest, there is no methodology to characterize soil quality based on a universal set of indicators. The most important chemical indicators include soil pH, soil salinity (EC), cation exchange capacity (CEC), NPK and micro-elements.

Physical Indicators

As mentioned before, soil-quality indicator is a simple attribute of the soil which may be measured to assess quality with respect to a given function. It is important to be able to select attributes that are appropriate for the task, given the complex nature of the soil and the exceptionally large number of soil parameters that may be determined. The selection of soil indicators will vary, depending upon the nature of the soil function under consideration. These soil attributes can be classified in three broad groupings: physical, chemical, or biological indicators. Many of the physical and chemical soil attributes are permanent in time (inherent parameters) (De la Rosa and Sobral 2008). In contrast, biological and some physical attributes are dynamic and exceptionally sensitive to changes in soil conditions and in management practices (dynamic parameters). They appear to be very responsive to different agricultural soil conservation and management practices such as non-tillage, organic amendments, and crop rotation. The selection of soil indicator attributes should be based on: (i) land use; (ii) soil function; (iii) reliability of measurement; (iv) spatial and temporal variability; (v) sensitivity to changes in soil management; (vi) comparability in monitoring systems; and (vii) skills required for the use and interpretation (Nortcliff 2002).

In general, the physical and physico-chemical parameters are of little use as they alter only when the soil undergo a really drastic change (Filip 2002). On the contrary, biological and biochemical parameters are sensitive to the slight modifications that the soil can undergo in the presence of any degrading agent (Nannipieri et al. 1990). Hence, whenever the total sustainability of soil natural functions and its different uses has to be evaluated, key indicators must include biological and biochemical parameters (Gil-Sotres et al. 2005).

The physical quality of agricultural soil refers primarily to the soil's strength and fluid transmission and storage characteristics in the crop root zone (Topp et al. 1997). An agricultural soil with "*good physical quality*" is one that is "strong" enough to maintain good structure, hold crops upright, and resist erosion and compaction; but also "weak" enough to allow unrestricted root growth and proliferation of soil flora and fauna. Soil with good physical quality also has fluid transmission and storage characteristics that permit the correct proportions of water, dissolved nutrients, and air for both maximum crop performance and minimum environmental degradation (Topp et al. 1997). Intensive field-crop production can cause the physical quality of agricultural soils to decline. Reduced soil physical quality is, in turn, linked to declining crop performance and/or profitability, as well as negative environmental impacts related to the off-field movement of soil (wind/water erosion) and agrochemicals (pesticide/nutrient leaching into surface and ground waters). Progress in the development of practicable new strategies for maintaining or improving the physical quality of intensively cropped soils has been difficult and slow, however, because of complex interactions among tillage practices, soil texture, crop types, and climate. In addition, "optimal" soil physical quality parameter values for maximum field-crop production with minimum environmental degradation are still largely unknown, although various empirical "guideline" parameter values have been proposed for improved plant growth in agricultural and nonagricultural soils. The most important of these guideline values/criteria are reviewed below (Reynolds et al. 2002).

Optimal values of soil physical quality (SPQ) parameters for enhancing field-crop productivity while maintaining or improving environmental health are still largely unknown. the most important SPQ parameters include organic carbon (OC), bulk density (BD), porosity (POR), air capacity (AC), field capacity (FC), permanent wilting point (PWP), and plant-available water capacity (PAWC). Whereas, physical indicators commonly used to assess soil function and quality include aggregate stability, available water capacity, bulk density, infiltration, slaking, soil crusts, soil structure and macropores were reported by UDSA (2008).

Good root growth and function requires adequate soil air and soil water storage capacities, in addition to appropriate soil strength or density. Substantial work over the last 30 years suggests that near-surface air-filled soil pore space (i.e. air capacity) should be at least 0.10–0.15 m^3 m^{-3} (Cockroft and Olsson 1997). It has also been proposed that plant-available water capacity should be >0.20 m^3 m^{-3} (Cockroft and Olsson 1997), or within the range 0.15–0.25 m^3 m^{-3} (Table 17; Reynolds et al. 2002).

It could be concluded that, the biological and some physical attributes are dynamic and exceptionally sensitive to changes in soil conditions and in management practices. They appear to be very responsive to different agricultural soil conservation and management practices such as non-tillage, organic amendments, and crop rotation. The physical and physico-chemical parameters are of little use as they alter only when the soil undergo a really drastic change. On the contrary, biological and biochemical parameters are sensitive to the slight modifications that the soil can undergo in the presence of any degrading agent. Whereas, physical indicators

Table 17 Selected soil physical quality and related parameters (Adapted from Reynolds et al. 2002)

Parameter, symbol, and units	Parameter definition[a]	Soil physical quality property measured
Total organic carbon content, OC (wt.%)	Amount of carbon in soil derived from organic sources	Not a true soil physical quality parameter, but affects many aspects of soil physical quality
Bulk density of total soil, BD (Mg m^{-3})	Mass of dry soil solids per unit bulk soil volume	Index of soil strength. Also used to obtain water/air storage parameters
Porosity of total soil, POR_t (m^3 m^{-3})	$POR_t = [1 - (BD/PD)]$ PD = 2.65 Mg m^{-3}	Total volume of soil pore space including macropores, matrix pores, and occluded pores
Air capacity of total soil, AC_t (m^3 m^{-3})	$- AC_t = \theta\ (h = 0)\ \theta\ (h = -\ 1{,}000$ mm)	Index of soil aeration on total soil basis
Field capacity, FC (m^3 m^{-3})	$FC = \theta\ (h = -\ 1{,}000$ mm)	Index of water holding or storage capacity of soil
Permanent wilting point, PWP (m^3 m^{-3})	$PWP = \theta\ (h = -1.5 \times 10^5$ mm)	Estimate of soil water volume not readily available to crops
Plant available water capacity, PAWC (m^3 m^{-3})	PAWC = FC–PWP	Soil water readily available for crop growth

[a]θ (h) = volumetric soil water content as a function of pore water pressure head, *h*

[b]Organic carbon content method based on the dry combustion – carbon dioxide evolution technique (e.g. Tiessen and Moir 1993); bulk density method based on Culley (1993); tension table and pressure plate extraction methods based on Topp et al. (1993)

commonly used to assess soil function and quality include aggregate stability, available water capacity, bulk density, infiltration, slaking, soil crusts, soil structure and macropores.

Conclusion

The concepts of soil quality, soil health, and soil quality/health assessment are highly contentious within the soil science community, because many believe those terms have generalized and oversimplified the collective knowledge and wisdom developed through several centuries of intensive, indepth, global studies of soil resources. A common theme is that soil quality/health assessments are impossible and meaningless because of the complexity of soil resources. The definition of soil quality encompasses physical, chemical and biological characteristics, and it is related to fertility and soil health. Many indicators can be used to describe soil quality, but it is important to take into account sensitivity, required time, and related properties, than can be explained. The words fertility and quality of a soil are two distinct philosophical categories. The fertility is the fundamental feature of an agricultural soil, having all characteristics of a body impregnated with life. Its level can be quantified by certain parameters, corresponding to certain physiological and enzymic processes and certain specific substance accumulations.

One of the most important challenges facing humanity today is to conserve/sustain natural resources, including soil and water, for increasing food production while protecting the environment. As the world population grows, stress on natural resources increases, making it difficult to maintain food security. Integrated plant nutrition system could improve the soil quality under different cropping systems. Soil fertility is a measure of the ability of soil to sustain satisfactory crop growth in the long-term, and can be determined by physical, chemical and biological processes intrinsically linked to soil organic matter content and quality.

Acknowledgment The authors wish to acknowledge the Hungarian Ministry of Education and Culture (Hungarian Scholarship Board, **HSB** and the Balassi Institute) and the Egyptian Ministry of Higher Education (The Partnership and Ownership initiative, **ParOwn** grant) for funding and supporting this work.

References

Acton DF, Gregorich LJ (1995) The health of our soils: toward sustainable agriculture in Canada. Publication Number 1906/E, Centre for Land and Biological Resources Research, Agriculture and Agri-Food Canada, Ottawa, 138 pp

Agency E (2002) Agriculture and natural resources: benefits, costs and potential solutions. Environment Agency, Bristol

Alexander M (1971) Agriculture's responsibility in establishing soil quality criteria. In: Environmental improvement – agriculture's challenge in the seventies. National Academy of Sciences, Washington, DC, pp 66–71

Alshaal TA, Abou El-Khir AM, El-Essawi TM, El-Ramady HR (2012) Soil quality indicators as affected by different cultivated crops: I. Effects of wheat, clover and sugar beet on biological and biochemical indicators. In: Proceedings of the 13th international conference on agronomy, Faculty of Agriculture, Benha University, Benha, 9–10 Sept 2012, pp 146–166

Anderson T (2003) Microbial eco-physiological indicators to assess soil quality. Agric Ecosyst Environ 98:285–293

Anderson DW, Gregorich EG (1984) Effect of soil erosion on soil quality and productivity. In: Soil erosion and degradation. In: Anonymous proceedings of 2nd annual western provincial conference on rationalisation of water and soil research and management, Saskatchewan Institute of Pedology, Saskatoon

Andrews SS, Mitchell JP, Mancinelli R, Karlen KL, Hartz TK, Horwath WR, Pettygrove GS, Scow KM, Munk DS (2002) On-farm assessment of soil quality in California's central valley. Agron J 94:12–23

Andrews SS, Karlen DL, Cambardella CA (2004) The soil management assessment framework: a quantitative soil quality evaluation method. Soil Sci Soc Am J 68:1945–1962

Aparicio V, Costa JL (2007) Soil quality indicators under continuous cropping systems in the Argentinean Pampas. Soil Till Res 96:155–165

Arnon DI, Stout PR (1939) The essentiality of certain elements in minute quantity for plants with special reference to copper. Plant Physiol 14:371–375

Arshad MA, Martin S (2002) Identifying critical limits for soil quality indicators in agroecosystems. Agric Ecosyst Environ 88:153–160

Aulakh MS (2010) Integrated nutrient management for sustainable crop production, improving crop quality and soil health, and minimizing environmental pollution. In: 19th world congress of soil science, soil solutions for a changing world, Brisbane, 1–6 Aug 2010, pp 79–82

Aulakh MS, Grant CA (2008) Integrated nutrient management for sustainable crop production. The Haworth Press/Taylor & Francis Group, New York

Baldwin KR (2009) Soil quality considerations for organic farmers. The organic production publication series, Center for Environmental Farming Systems, North Carolina, State University. http://www.cefs.ncsu.edu/resources/organicproductionguide/soilqualityfinaljan09.pdf. Accessed 23 Feb 2013

Balota EL, Kanashiro M, Filho AC, Andrade DS, Dick RP (2004) Soil enzyme activities under long-term tillage and crop rotation systems in subtropical agro-ecosystems. Braz J Microbiol 35:300–306

Banerjee A, Datta JK, Mondal NK (2010) Impact of different combined doses of fertilizers with plant growth regulators on growth, yield attributes and yield of mustard (Brassica campestris cv. B9) under old alluvial soil of Burdwan, West Bengal, India. Front Agric China 4(3):341–351. doi:10.1007/s11703-010-1017-7

Banqueri JA (1802) Libro de Agricultura: Su Autor El Doctor Excelente Abu Zacaria Lahia Aben Mohamed Ben Ahmed Ebu El Awam, vols I and II. Sevillano, Madrid

Bardgett RD, Usher MB, Hopkins DW (2005) Biological diversity and function in soils. Cambridge University Press, Cambridge

Barker AV, Pilbeam DJ (2007) Handbook of plant nutrition. Books in soils, plants, and the environment series, vol 117. CRC Press/Taylor & Francis Group, Boca Raton, FL, USA

Bastida F, Moreno JL, Hernandez T, Garcia C (2006) Microbiological degradation index of soils in a semiarid climate. Soil Biol Biochem 38:3463–3473

Bastida F, Zsolnay A, Hernández T, García C (2008) Past, present and future of soil quality indices: a biological perspective. Geoderma 147:159–171

Batistic L, Mayaudon J (1977) Influence of mineral fertilizer and liquid organic fertilizer (cattle slurry) on soil biological fertility. Revue d'Ecologie et de Biologie du sol 14(4): 499–507

Bationo A, Kihara J, Vanlauwe V, Kimetu J, Waswa BS, Sahrawat KL (2008) Integrated nutrient management: concepts and experience from Sub-Saharan Africa. In: Aulakh MS, Grant CA (eds) Integrated nutrient management for sustainable crop production. The Haworth Press/Taylor & Francis, New York, pp 467–521

Bhupinderpal-Singh B, Rengel Z (2007) The role of crop residues in improving soil fertility. In: Marschner P, Rengel Z (eds) Nutrient cycling in terrestrial ecosystems, vol 10, Soil biology series. Springer, Berlin/Heidelberg/New York, pp 183–214

Blum W, Büsing J, de l'Escaille T (2004) European union soil thematic strategy. The European Commission, DG Environment, Brussels

Bohanec M, Cortet J, Griffiths B, Znidarsic M, Debeljak M, Caul S, Thompson J, Krogh PH (2007) A qualitative multi-attribute model for assessing the impact of cropping systems on soil quality. Pedobiologia 51:239–250

Bone J, Head M, Barraclough D, Archer M, Schei C, Flight D, Voulvoulis N (2010) Soil quality assessment under emerging regulatory requirements. Environ Int 36:609–622. doi:10.1016/j.envint.2010.04.010

Brejda JJ, Karlen DL, Smith JL, Allan DL (2000) Identification of regional soil quality factors and indications in Northern Mississippi Loess Hills and Palouse Prairie. Soil Sci Soc Am J 64:2125–2135

Brennan RF, Bolland MDA, Bowden JW (2004) Potassium deficiency, and molybdenum deficiency and aluminium toxicity due to soil acidification, have become problems for cropping sandy soils in south-western Australia. Aust J Exp Agric 44:1031–1039

Brevik EC (2009) Soil health and productivity. In: Verheye WH (ed) Soils, plant growth and crop production. Encyclopedia of life support systems (EOLSS), Developed under the auspices of the UNESCO. Eolss Publishers, Oxford. http://www.eolss.net. Accessed 26 Aug 2012

Broadley MR, White PJ, Bryson RJ et al (2006) Biofortification of UK food crops with selenium. Proc Nutr Soc 65:169–181

Broadley MR, White PJ, Hammond JP, Zelko I, Lux A (2007) Zinc in plants. New Phytologist 173:677–702

Brookes PC, McGrath SP, Klein DA, Elliott ET (1984) Effects of heavy metals on microbial activity and biomass in field soils treated with sewage sludge. In: International conference on environmental contamination, London, pp 574–583
Burger JA, Kelting DL (1999) Using soil quality indicators to assess forest stand management. For Ecol Manag 122:155–166
Burke IEE, Cole V (1995) Influence of macroclimate, landscape position, and management on soil organic matter in agroecosystems. Ecol Appl 5(1):124–131
Burns RG (1982) Enzyme activity in soil: location and a possible role in microbial ecology. Soil Biol Biochem 14:423–427
Burns RG, Dick RP (2002) Enzymes in the environment – activity, ecology, and applications. Marcel Dekker, New York
Cakmak I (2004) Proceedings of the International Fertiliser Society 552. Identification and correction of widespread zinc deficiency in Turkey – a success story. International Fertiliser Society, York
Cakmak I (2008) Enrichment of cereal grains with zinc: agronomic or genetic biofortification? Plant Soil 302:1–17
Cambardella CA, Moorman TB, Andrews SS, Karlen DL (2004) Watershed-scale assessment of soil quality in the Loess Hills of southwestern Iowa. Soil Till Res 78:237–248
Caravaca F, Masciandaro G, Ceccanti B (2002) Land use in relation to chemical and biochemical properties in semiarid Mediterranean environment. Soil Till Res 68:23–30
Carrera LM, Buyer JS, Vinyard B, Abdul-Baki AA, Sikora LJ, Teasdale JR (2007) Effects of cover crops, compost, and manure amendments on soil microbial community structure in tomato production systems. Appl Soil Ecol 37(3):247–255
Carter MR (2002) Soil quality for sustainable land management: organic matter and aggregation interactions that maintain soil functions. Agron J 94:38–47
Cockroft B, Olsson KA (1997) Case study of soil quality in south-eastern Australia: management of structure for roots in duplex soils. In: Gregorich EG, Carter MR (eds) Soil quality for crop production and ecosystem health, vol 25, Developments in soil science. Elsevier, New York, pp 339–350
Conley DJ, Paerl HW, Howarth RW et al (2009) Controlling eutrophication: nitrogen and phosphorus. Science 323:1014–1015
Culley JLB (1993) Density and compressibility. In: Carter MR (ed) Soil sampling and methods of analysis, Canadian society of soil science. Lewis Publishers, Boca Raton, pp 529–539
Das SK, Varma A (2011) Role of enzymes in maintaining soil health. In: Shukla G, Varma A (eds) Soil enzymology, soil biology, vol 22. Springer, Berlin/Heidelberg
De la Rosa D, Sobral R (2008) Soil quality and methods for its assessment. In: Braimoh AK, Vlek PLG (eds) Land use and soil resources. Springer, Dordrecht, pp 167–200
de Souza M (2009) Draft soil strategy for England and soil framework directive: a brief overview. In: Anonymous proceedings of the future of soil, London
Defra (2004) The first soil action plan for England. Department of Environment, Food and Rural Affairs, London
Delhaize E, Gruber BD, Ryan PR (2007) The roles of organic anion permeases in aluminium resistance and mineral nutrition. FEBS Lett 581:2255–2262
den Biggelaar C, Lal R, Wiebe K, Breneman V (2004) The global impact of soil erosion on productivity. I: Absolute and relative erosion-induced yield losses. Adv Agron 81:1–48
Dexter AR, Zoebisch MA (2006) Degradation: critical limits of soil properties and irreversible degradation. In: Lal R (ed) Encyclopedia of soil science, 2nd edn. Taylor & Francis, Philadelphia, pp 411–415
Dick RP (1997) Soil enzyme activities as integrative indicators of soil health. In: Pankhurst CE, Doube BM, Gupta VVSR (eds) biological indicators of soil health. CAB International, Wallingford, pp 121–156
Dick RP, Sandor JA, Eash NS (1994) Soil enzyme activities after 1500 years of terrace agriculture in the Colca Valley. Peru Agric Ecosyst Environ 50:123–131
Dick RP, Breakwell DP, Turco RF (1996) Soil enzyme activities and biodiversity measurements as integrative microbiological indicators. In: Doran JW, Jones AJ (eds) Methods for assessing soil quality, vol 9. Soil Science Society of America, Madison, pp 9–17

Dinkelaker B, Marschner H (1992) *In vivo* demonstration of acid phosphatase in the rhizosphere of soil grown plants. Plant Soil 144:199–205

Ditzler CA, Tugel AJ (2002) Soil quality field tools of USDANRCS soil quality institute. Agron J 94:33–38

Doran JW (2002) Soil health and global sustainability: translating science into practice. Agric Ecosyst Environ 88:119–127

Doran JW, Jones AJ (1996) Methods for assessing soil quality, vol 49, SSSA special publication. ASA, Madison

Doran JW, Parkin TB (1994) Defining and assessing soil quality. In: Doran JW et al (eds) Defining Soil quality for sustainable environment. SSSA and ASA, Madison, pp 3–21

Doran JW, Parkin TB (1996) Quantitative indicators of soil quality: a minimum data set. In: Doran JW, Jones AJ (eds) Methods for assessing soil quality, vol 49. Soil Science Society of America Special Publication, Madison, pp 25–37

Doran JW, Safley M (1997) Defining and assessing soil health and sustainable productivity. In: Pankhurst C, Doube BM, Gupta VVSR (eds) Biological indicators of soil health. CAB International, Wallingford, pp 1–28

Doran JW, Zeiss MR (2000) Soil health and sustainability: managing the biotic component of soil quality. Appl Soil Ecol 15:3–11

Doran JW, Coleman DC, Bezdicek DF, Stewart BA (1994) Defining soil quality for a sustainable environment, vol 35, SSSA special publication. ASA, Madison

Doran JW, Sarantonio M, Leibig M (1996) Soil health and sustainability. In: Sparks DL (ed) Advances in agronomy, vol 56. Academic Press, San Diego, pp 1–54

Dumanski J, Pieri C (2000) Land quality indicators: research plan. Agric Ecosyst Environ 81:93–102

Edwards CA (1993) The impact of pesticides on the environment. Chapman and Hall, New York

Edwards CA (2002) Assessing the effects of environmental pollutants on soil organisms, communities, processes and ecosystems. Eur J Soil Biol 38:225–231. doi:10.1016/S1164-5563(02)01150-0

Eichler B, Caus M, Schnug E, Koeppen D (2004) Soil acid and alkaline phosphatase activities in relation to crop species and fungal treatment. Landbauforschung Völkenrode 1(54):01–05

Eivazi F, Bayan MR, Schmidt K (2003) Selected soil enzyme activities in the historic Sanborn field as affected by long-term cropping systems. Commun Soil Sci Plan 16:2259–2275

Ekholm P (1997) Effects of selenium supplemented commercial fertilizers on food selenium contents and selenium intake in Finland. University of Helsinki, EKT-series 1047, Helsinki

Ekholm P, Ylinen M, Koivistoinen P, Varo P (1995) Selenium concentration of Finnish foods: effects of reducing the amount of selenate in fertilizers. Agric Sci Finland 4:377–384

Ekholm P, Reinivuo H, Mattila P et al (2007) Changes in the mineral and trace element contents of cereals, fruits and vegetables in Finland. J Food Compos Anal 20:487–495

Elliott ET (1994) The potential use of soil biotic activity as an indicator of productivity. In: Pankhurst CE, Doube BM, Gupta VVSR, Grace PR (eds) Soil biota: management in sustainable farming systems. CSIRO, Melbourne, pp 250–256

El-Ramady H (2008) A contribution on the bio-actions of rare earth elements in the soil/plant environment. PhD thesis, Julius Kühn-Institut, Bundesforschungsinstitut für Kulturpflanzen, Quedlinburg

El-Ramady HR, Alshaal TA, Abou El-Khir AM, El-Essawi TM (2013) Chemical soil quality indicators as affected by different cultivated crops. Egypt Soil Sci Soc J 53(1):1–12

El-Swaify SA, Pathak P, Rego TJ, Singh S (1985) Soil management for optimized productivity under rainfed conditions in the semi-arid tropics. Adv Soil Sci 1:1–63

Emmerling C, Schloter M, Hartmann A, Kandeler E (2002) Functional diversity of soil organisms – a review of recent research activities in Germany. J Plant Nutr Soil Sci 165: 408–420

Enghag P (2004) Encyclopedia of the elements – technical data, history, processing and applications, Wiley-VCH, Verlag GmbH & Co. KGaA, Weinheim

Erkossa T, Itanna F, Stahr K (2007) Indexing soil quality: a new paradigm in soil science research. Aust J Soil Res 45:129–137

Eticha D, Zahn M, Bremer M et al (2010) Transcriptomic analysis reveals differential gene expression in response to aluminium in common bean (*Phaseolus vulgaris*) genotypes. Ann Bot 105:1119–1128

European Commission (2005) The common agricultural policy 2003 review. European Communities, Luxembourg

Evanylo G, McGuinn R (2009) Agricultural management practices and soil quality: measuring, assessing, and comparing laboratory and field test kit indicators of soil quality attributes. Virginia Polytechnic Institute and State University. http://pubs.ext.vt.edu/452/452-400/452-400_pdf.pdf. Accessed 25 Feb 2013

Fageria NK (2009) The use of nutrients in crop plants. CRC Press/Taylor & Francis Group, LLC, Boca Raton, FL, USA

FAO (1995) Integrated plant nutrition system. FAO Fertilizer and Plant Nutrition Bulletin No. 12, Rome, 426 pp

FAO (2006) Plant nutrition for food security – a guide for integrated nutrient management. In: Roy RN, Finck A, Blair GJ, Tandon HLS (eds) Fertilizer and plant nutrition bulletin, vol 16. Food and Agriculture Organization of the United Nations, Rome

FAO (2012) Basic definitions. http://www.fao.org/hunger/en/21.8.2012. Accessed 21 Aug 2012

Fernandez MD, Vega MM, Tarazona JV (2006) Risk-based ecological soil quality criteria for the characterization of contaminated soils. Combination of chemical and biological tools. Sci Total Environ 366:466–484

Ferreira EPdB, Dusi AN, Costa JR, Xavier GR, Rumjanek NG (2008) Rhizosphere bacterial communities of potato cultivars evaluated through PCR-DGGE profiles. Pesquisa Agropecuária Brasileira 43(5):605–612

Ferreira EPdB, Dusi AN, Costa JR, Xavier GR, Rumjanek NG (2009) Assessing insecticide and fungicide effects on the culturable soil bacterial community by analyses of variance of their DGGE fingerprinting data. Eur J Soil Biol 45(05/06):466–472

Ferreira B, Petrônio de E, Henrique PDS, Janaina RC, Helvécio D-P, Norma GR (2010) Microbial soil quality indicators under different crop rotations and tillage management. Revista Ciência Agronômica 41(2):177–183, abril-junio, Universidade Federal do Ceará Brasil

Filip Z (2002) International approach to assessing soil quality by ecologically-related biological parameters. Agric Ecosyst Environ 88:169–174

Franzluebbers A (2002) Soil organic matter stratification ratio as an indicator of soil quality. Soil Tillage Res 66(2):95–106

Garcia-Ruiz R, Ochoa V, Vinegla B, Hinojosa MB, Pena-Santiago R, Liebanas G, Linares JC, Carreira JA (2009) Soil enzymes, nematode community and selected physico-chemical properties as soil quality indicators in organic and conventional olive oil farming: influence of seasonality and site features. Appl Soil Ecol 41:305–314

Garrigues E, Corson MS, Angers DA, van der Werf HMG, Walter C (2012) Soil quality in life cycle assessment: towards development of an indicator. Ecol Indic 18:434–442

Giacometti C, Demyan MS, Cavani L, Marzadori C, Ciavatta C, Kandeler E (2013) Chemical and microbiological soil quality indicators and their potential to differentiate fertilization regimes in temperate agroecosystems. Appl Soil Ecol 64:32–48. http://dx.doi.org/10.1016/j.apsoil.2012.10.002

Giller KE, Beare MH, Lavelle P, Izac AMN, Swift MJ (1997) Agricultural intensification, soil biodiversity and agroecosystem function. Appl Soil Ecol 6:3–16

Gil-Sotres F, Trasar-Cepeda C, Leiros MC, Seoane S (2005) Different approaches to evaluating soil quality using biochemical properties. Soil Biol Biochem 37:877–887. doi:10.1016/j.soilbio.2004.10.003

Glover JD, Reganold JP, Andrews PK (2000) Systematic method for rating soil quality of conventional, organic, and integrated apple orchards in Washington State. Agric Ecosyst Environ 80:29–45

Govaerts B, Mezzalama M, Unno Y, Sayre KD, Luna-Guido M, Vanherck K, Dendooven L, Deckers J (2007) Influence of tillage, residue management, and crop rotation on soil microbial biomass and catabolic diversity. Appl Soil Ecol 37:18–30

Graham RD, Welch RM, Saunders DA et al (2007) Nutritious subsistence food systems. Adv Agron 92:1–74
Gregorich EG, Carter MR, Angers DA, Monreal CM, Ellert BH (1994) Towards a minimum data set to assess soil organic matter quality in agricultural soils. Can J Soil Sci 74:367–385
Griffiths BS, Kuan HL, Ritz K, Glover LA, McCaig AE, Fenwick C (2004) The relationship between microbial community structure and functional stability, tested experimentally in an upland pasture soil. Microb Ecol 47:104–113. doi:10.1007/s00248-002-2043-7
Griffiths BS, Hallett PD, Kuan HL, Pitkin Y, Aitken MN (2005) Biological and physical resilience of soil amended with heavy metal-contaminated sewage sludge. Eur J Soil Sci 56:197–205. doi:10.1111/j.1365-2389.2004.00667.x
Gupta VVSR, Germida JJ (1988) Distribution of microbial biomass and its activity in different soil aggregate size classes as affected by cultivation. Soil Biol Biochem 20:777–786
Hartikainen H (2005) Biogeochemistry of selenium and its impact on food chain quality and human health. J Trace Element Med Biol 18:309–318
Hattori H, Chino M (2001) Growth, cadmium, and zinc contents of wheat grown on various soils enriched with cadmium and zinc. Dev Plant Soil Sci 92:462–463
Herrick JE, Brown JR, Tugel AJ, Shave PL, Havstad KM (2002) Application of soil quality to monitoring and management: paradigms from rangeland ecology. Agron J 94:3–11
Hines J, Megonigal P, Denno RF (2006) Nutrient subsidies to belowground microbes impact aboveground food web interactions. Ecology 87:1542–1555
Hobbie SE (2005) Contrasting effects of substrate and fertilizer nitrogen on the early stages of litter decomposition. Ecosystems 8:644–656. doi:10.1007/s10021-003-0110-7
Howard A (1941) Testament agricole – pour une agriculture naturelle, 1st edn. Oxford University Press, London
Hussain I, Olson KR, Wander MM, Karlen DL (1999) Adaptation of soil quality indices and application to three tillage systems in southern Illinois. Soil Till Res 50:237–249
Imaz MJ, Virto I, Bescansa P, Enrique A, Fernandez-Ugalde O, Karlen DL (2010) Soil quality indicator response to tillage and residue management on semi-arid Mediterranean cropland. Soil Till Res 107:17–25
Janssen BH (1999) Basics of budgets, buffers and balances of nutrients in relation to sustainability of agroecosystems. In: Smaling EMA, Oenema O, Fresco LO (eds) Nutrient disequilibria in agroecosystems: concepts and case studies. CABI Publishing, Wallingford, pp 27–56
Janssen BH, de Willigen P (2006a) Ideal and saturated soil fertility as bench marks in nutrient management 1. Outline of the framework. Agric Ecosyst Environ 116:132–146
Janssen BH, De Willigen P (2006b) Ideal and saturated soil fertility as bench marks in nutrient management. II. Interpretation of chemical soil tests in relation to ideal and saturated soil fertility. Agric Ecosyst Environ 116:147–155
Janvier C, Villeneuve F, Alabouvette C, Edel-Hermann V, Mateille T, Steinberg C (2007) Soil health through soil disease suppression: which strategy from descriptors to indicators? Soil Biol Biochem 39:1–23
Jones JB Jr (2003) Agronomic handbook – management of crops, soils, and their fertility. CRC Press, Boca Raton
Ju X-T, Xing G-X, Chen X-P et al (2009) Reducing environmental risk by improving N management in intensive Chinese agricultural systems. Proc Natl Acad Sci U S A 106:3041–3046
Kabata-Pendias A (2011) Trace elements in soils and plants, 4th edn. CRC Press/Taylor & Francis Group, Boca Raton
Kabata-Pendias A, Mukherjee AB (2007) Trace elements from soil to human. Springer, Berlin/Heidelberg
Kang GS, Beri V, Sidhu BS, Rupela OP (2005) A new index to assess soil quality and sustainability of wheat-based cropping systems. Biol Fertil Soils 41:389–398
Kangas A, Teravainen H (2004) Peltokasvilajikkeet 2004. Maaseutukeskustenliiton julkaisuja no. 1001, Pro Agria, Helsinki (Cited from Ekhlom et al. 2007)
Karanam PV, Wani SP, Sahrawat KL, Jangawad LS (2008) Economic evaluation of sediments as a source of plant nutrients. Curr Sci 95:1042–1050

Karlen DL, Stott DE (1994) A framework for evaluating physical and chemical indicators of soil quality. In: Doran JW et al (eds) Defining soil quality for a sustainable environment. SSSA and ASA, Madison, pp 53–72

Karlen DL, Wollenhaupt NC, Erbach DC, Berry EC, Swan JB, Eash NS, Jordahl JL (1994) Long-term tillage effects on soil quality. Soil Till Res 32:313–327

Karlen DL, Mausbach MJ, Doran JW, Cline RG, Harris RF, Schuman GE (1997) Soil quality: a concept, definition, and framework for evaluation. Soil Sci Soc Am J 61:4–10

Karlen DL, Gardner JC, Rosek MJ (1998) A soil quality framework for evaluating the impact of CRP. J Prod Agric 11:56–60

Karlen DL, Andrews SS, Doran JW (2001) Soil quality: current concepts and applications. Adv Agron 74:1–40

Karlen DL, Andrews SS, Wienhold BJ (2004) Soil quality, fertility and health – historical context, status and perspectives. In: Schjønning P, Elmholt S, Christensen BT (eds) Managing soil quality: challenges in modern agriculture. CABI Publishing, Oxford, pp 17–33

Karlen DL, Andrews SS, Wienhold BJ, Zobeck TM (2008) Soil quality assessment: past, present and future. J Integr Biosci 6(1):3–14

Karlen DL, Ditzler CA, Andrews SS (2003) Soil quality: why and how? Geoderma 114:145–156

Karley AJ, White PJ (2009) Moving cationic minerals to edible tissues: potassium, magnesium, calcium. Curr Opin Plant Biol 12:291–298

Kaschuk G, Alberton O, Hungria M (2010) Three decades of soil microbial biomass studies in Brazilian ecosystems: lessons learned about soil quality and indications for improving sustainability. Soil Biol Biochem 42:1–13

Kellogg CE (1943) The soils that support us: an introduction to the study of soils and their use by men. MacMillan Co., New York

Kibblewhite MG, Ritz K, Swift MJ (2008) Soil health in agricultural systems. Phil Trans R Soc B 363:685–701. doi:10.1098/rstb.2007.2178

Kirkby E (2012) Introduction, definition and classification of nutrients. In: Marschner P (ed) Marschner's mineral nutrition of higher plants. Elsevier Ltd., San Diego, CA, USA, pp 1–5, doi: 10.1016/B978-0-12-384905-2.00001-7

Kleinhenz M, Bierman P (2002) Soil quality management for profitable and sustainable vegetable production. Soil & Water Resources Program, OSU Piketon Res. & Ext. Center. Internet http://www.oardc.ohio-state.edu/kleinhenz

Klingebiel AA, Montgomery PH (1961) Land capability classification, vol 210, USDA handbook. United States Department of Agriculture, Washington, DC

Koivistoinen P (1980) Mineral element composition of Finnish foods. Acta Agric Scand Suppl 22:27–35

Koper J, Piotrowska A (2003) Application of biochemical index to define soil fertility depending on varied organic and mineral fertilization. Electron J Pol Agric Univ 6

Körschens M (2006) The importance of long-term field experiments for soil science and environmental research – a review. Plant Soil Environ 52:1–8

Kumar K, Goh KM (2000) Crop residues and management practices: effects on soil quality, soil nitrogen dynamics, crop yields, and nitrogen recovery. Adv Agron 68:197–319

Laishram J, Saxena KG, Maikhuri RK, Rao KS (2012) Soil quality and soil health: a review. Int J Ecol Environ Sci 38(1):19–37

Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. Science 304(5677):1623–1627

Lal R (2005) World crop residues production and implications of its use as a biofuel. Environ Int 31:575–584

Lal R (2007) Anthropogenic influences on world soils and implications to global food security. Adv Agron 93:69–93

Lal R (2011) Soil health and climate change: an overview. In: Singh BP, Cowie AL, Chan KY (eds) Soil health and climate change, vol 29, Soil biology series. Springer, Berlin/Heidelberg, pp 3–24 (Chapter 1)

Landers JN, DeC Barros GS-A, Manfrinato WA, Weiss JS, Rocha MT (2001) Environmental benefits of zero-tillage in Brazilian agriculture – a first approximation. In: GarciaTorres L, Benites L, Martinez Vilela A (eds) Conservation agriculture – a worldwide challenge, vol 1. XUL, Cordoba, pp 317–326

Larson WE, Pierce FJ (1991) Conservation and enhancement of soil quality. In: Dumanski J, et al (eds) Evaluation for sustainable land management in the developing world. Vol. 2: Technical papers. Proceedings of the international workshop, Chiang Mai, 15–21 Sept 1991. International Board for Soil Research and Management, Bangkok, pp 175–203

Larson WE, Pierce FJ (1994) The dynamics of soil quality as a measure of sustainable management. In: Doran JW et al (eds) Defining soil quality for a sustainable environment, vol 35, SSSA special publication. SSSA and ASA, Madison, pp 37–51

Lee CH, Wu MY, Asio VB, Zueng-Sang C (2006) Using a soil quality index to assess the effects of applying swine manure compost on soil quality under a crop rotation system in Taiwan. Soil Sci 171:210–222

Leigh RA, Johnston AE (1994) Long-term experiments in agricultural and ecological sciences. CAB International, Wallingford

Letey J, Sojka RE, Upchurch DR, Cassel DK, Olson KR, Payne WA, Petrie SE, Price GH, Reginato RJ, Scott HD, Smethurst PJ, Triplett GB (2003) Deficiencies in the soil quality concept and its application. J Soil Water Conserv 58:180–187

Liebig MA, Varvel G, Doran J (2001) A simple performance based index for assessing multiple agroecosystem functions. Agron J 93:313–318

Lilburne L, Sparling G, Schipper L (2004) Soil quality monitoring in New Zealand: decomposition of an interpretative framework. Agric Ecosyst Environ 104:535–544

Lima ACR, Brussaard L, Totola MR, Hoogmoed WB, de Goede RGM (2013) A functional evaluation of three indicator sets for assessing soil quality. Appl Soil Ecol 64:194–200. http://dx.doi.org/10.1016/j.apsoil.2012.12.009

Lindh U (2005) Environmental biology. In: Selinus O, Alloway B, Centeno JA, Finkelman RB, Fuge R, Lindh U, Smedley P (eds) Essentials of medical geology. Elsevier, London, pp 15–16

Li S-X, Wang Z-H (2010) Comprehensive management of nutrients in dry land soils of China for sustainable agriculture. In: Rattan Lal and Stewart BA (eds) Food security and soil quality, Advances in soil science Series, LLC. Taylor & Francis Group, Boca Raton, pp 309–384

Lowdermilk WC (1939) Conquest of the land through 7000 years. USDA-ARS Bulletin 99, Washington, DC, 30 pp

Lucas RW, Casper BB, Jackson JK, Balser TC (2007) Soil microbial communities and extracellular enzyme activity in the New Jersey pinelands. Soil Biol Biochem 39:2508–2519

Lynch JP, St. Claira SB (2004) Mineral stress: the missing link in understanding how global climate change will affect plants in real world soils. Field Crops Res 90:101–115. doi:10.1016/j.fcr.2004.07.008

Lyons GH, Stangoulis JCR, Graham RD (2004) Exploiting micronutrient interaction to optimize biofortification programs: the case for inclusion of selenium and iodine in the HarvestPlus program. Nutr Rev 62:247–252

Ma JF, Ryan PR, Delhaize E (2001) Aluminium tolerance in plants and the complexing role of organic acids. Trends Plant Sci 6:273–278

Mandal DK, Mandal C, Velayutham M (2001) Development of a land quality index for sorghum in Indian semi-arid tropics (SAT). Agr Syst 70:335–350

Maliszewska W (1969) Comparison of the biological activity of different soil types. Agrokém Tlajt 18:76–81

Marinari S, Mancinelli R, Campiglia E, Grego S (2006) Chemical and biological indicators of soil quality in organic and conventional farming systems in Central Italy. Ecol Indic 6:701–711

Marschner H (2002) Mineral nutrition of higher plants, 2nd edn. Elsevier Academic Press, London

Martens DA, Johanson JB, Frankenberger WT (1992) Production and persistence of soil enzymes with repeated additions of organic residues. Soil Sci 153:53–61

Martinez-Salgado MM, Gutiérrez-Romero V, Jannsens M, Ortega-Blu R (2010) Biological soil quality indicators: a review. Current research, technology and education topics in applied microbiology and microbial biotechnology. Formatex, Microbiology Book Series – No. 2, pp 319–328. http://www.formatex.info/microbiology2/319-328.pdf/. Accessed 24 Feb 2013

Marzaioli R, D'Ascoli R, De Pascale RA, Rutigliano FA (2010) Soil quality in a Mediterranean area of Southern Italy as related to different land use types. Appl Soil Ecol 44:205–212. doi:10.1016/j.apsoil.2009.12.007

Masto RE, Chhonkar PK, Singh D, Patra AK (2007) Soil quality response to long-term nutrient and crop management on a semi-arid Inceptisol. Agric Ecosyst Environ 18:130–142

Masto RE, Chhonkar PK, Purakayastha TJ, Patra AK, Singh D (2008) Soil quality indices for evaluation of long-term land use and soil management practices in semi-arid sub-tropical India. Land Degrad Dev 19:516–529

Mausbach MJ, Tugel AJ (1995) Soil quality and the natural resources conservation. Agron Abst 337

McGrath D, Zhang CS (2003) Spatial distribution of soil organic carbon concentrations in grassland of Ireland. Appl Geochem 18:1629–1639

Mengel K, Kirkby EA, Kosegarten H, Appel T (2001) Principles of plant nutrition, 2nd edn. International Potash Institute, Berne

Mohanty M, Painuli DK, Misra AK, Ghosh PK (2007) Soil quality effects of tillage and residue under rice-wheat cropping on a Vertisol in India. Soil Till Res 92:243–250

Moron A (2005) Indicadores para el diagno stico de la calidad de suelos en sistemas agrı´colas. In: Marelli HJ (ed) Indicadores de Calidad de Suelo. Seminario Internacional, Marcos Juarez

Munns R, Tester M (2008) Mechanisms of salinity tolerance. Annu Rev Plant Biol 59:651–681

Nair A, Ngouajio M (2012) Soil microbial biomass, functional microbial diversity, and nematode community structure as affected by cover crops and compost in an organic vegetable production system. Appl Soil Ecol 58:45–55

Nannipieri P (1994) The potential use of soil enzymes as indicators of productivity, sustainability and pollution. In: Pankhurst CE, Doube BM, Gupta VVSR, Grace PR (eds) Soil biota management in sustainable farming systems. CSIRO, Melbourne, pp 238–244

Nannipieri P, Ceccanti B, Grego S (1990) Ecological significance of biological activity in soil. In: Bollag JM, Stotzky G (eds) Soil biochemistry, vol 6. Marcel Dekker, New York, pp 293–355

Nannipieri P, Kandeler E, Ruggiero P (2002) Enzyme activities and microbiological and biochemical processes in soil. In: Burns RG, Dick RP (eds) Enzymes in the environment – activity, ecology, and applications. Marcel Dekker, New York

National Board of Agriculture (2003) Official statistics of Finland. Yearbook of farm statistics, Helsinki

National Research Council (NRC) (1989) Alternative agriculture. National Academies Press, Washington, DC, 448 pp

Nazzareno D, Michele C (2004) Multivariate indicator kriging approach using a GIS to classify soil degradation for Mediterranean agricultural lands. Ecol Indic 4(3):177–187

Niklaus PA (2007) Climate change effects on biogeochemical cycles, nutrients, and water supply. In: Niklaus PA, Newman PCD, Andrew Carran R, Edwards GR (eds) Agroecosystems in a changing climate. Advances in agroecology series. Taylor & Francis Group, LLC, Boca Raton, FL, USA, pp 12–52

Nortcliff S (2002) Standardization of soil quality attributes. Agric Ecosyst Environ 88:161–168

Oenema O, Kros H, De Vries W (2003) Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental policies. Eur J Agron 20:3–16

Orwin KH, Wardle DA (2004) New indices for quantifying the resistance and resilience of soil biota to exogenous disturbances. Soil Biol Biochem 36:1907–1912. doi:10.1016/j.soilbio.2004.04.036

Pathak P, Sahrawat KL, Rego TJ, Wani SP (2005) Measurable biophysical indicators for impact assessment: changes in soil quality. In: Shiferaw B, Freeman HA, Swinton SM (eds) Natural resource management in agriculture: methods for assessing economic and environmental impacts. CAB International, Wallingford, pp 53–74

Patzel N, Sticher H, Karlen DL (2000) Soil fertility – phenomenon and concept. J Plant Nutr Soil Sci 163:129–142
Pavlovschi G, Groza M (1949) Studiul sistemelor fermentative din solul arabil. Analele ICAR XIX 1947:3–17
Perucci P (1992) Enzyme activity and microbial biomass in a field soil amended with municipal refuse. Biol Fert Soils 14:54–60
Petra M, David C, Ching HY (2004) Development of specific rhizosphere bacterial communities in relation to plant species, nutrition and soil type. Plant Soil 261:199–208
Pfeiffer E (1938) La fécondité de la terre. Ed. Triade, Paris, new edition, in 1966
Pierce FJ, Lal R (1992) Monitoring soil erosion's impact on soil productivity. In: Lal R (ed) Soil erosion research methods. Soil and Water Conservation Society, Ankeny
Pierce FJ, Larson WE (1993) Developing criteria to evaluate sustainable land management. In: Kimble JM (ed) Proceedings of the 8th international soil management workshop: utilization of soil survey information for sustainable land use. USDA-SCS, National Soil Survey, Lincoln
Pieri C (1989) Fertilité des terres de savanes. Bilan de trente ans recherché et de developpement agricoles au sud du Sahara. Ministere de la Coopération et CIRAD-IRAT, Paris (cited from Janssen and de Willigen 2006a)
Pieri C, Dumanski J, Hamblin A, Young A (1995) Land quality indicators. World Bank Discussion Papers, 315
Poch RM, Martinez-Casanovas JA (2006) Degradation. In: Lal R (ed) Encyclopedia of soil science, 2nd edn. Taylor & Francis, Philadelphia, pp 375–378
Puget P, Lal R (2005) Soil organic carbon and nitrogen in a Mollisol in central Ohio as affected by tillage and land use. Soil Till Res 80:201–213
Puglisi E, Nicelli M, Capri E, Trevisan M, Del Re AAM (2005) A soil alteration index based on phospholipid fatty acids. Chemosphere 61:1548–1557
Puglisi E, Del Re AAM, Rao MA, Gianfreda L (2006) Development and validation of numerical indices integrating enzyme activities of soils. Soil Biol Biochem 38:1673–1681
Puig S, Penarrubia L (2009) Placing metal micronutrients in context: transport and distribution in plants. Curr Opin Plant Biol 12:299–306
Qi Y, Darilek JL, Huang B, Zhao Y, Sun W, Gu Z (2009) Evaluating soil quality indices in an agricultural region of Jiangsu Province, China. Geoderma 149:325–334. doi:10.1016/j.geoderma.2008.12.015
Qin MZ, Zhao J (2000) Strategies for sustainable use and characteristics of soil quality changes in urban–rural marginal area: a case study of Kaifeng. Acta Geogr Sin 55:545–554 (in Chinese with English abstract)
Rangel AF, Rao IM, Braun H-P, Horst WJ (2010) Aluminium resistance in common bean (*Phaseolus vulgaris*) involves induction and maintenance of citrate exudation from root apices. Physiol Plant 138:176–190
Reeves DW (1997) The role of organic matter in maintaining soil quality in continuous cropping systems. Soil Till Res 43:131–167
Reynolds WD, Bowman BT, Drury CF, Tan CS, Lu X (2002) Indicators of good soil physical quality: density and storage parameters. Geoderma 110:131–146
Rezaei S, Gilkes R, Andrews S (2006) A minimum data set for assessing soil quality in rangelands. Geoderma 136:229–234
Risher JF, Keith LS (2009) Iodine and inorganic iodides: human health aspects. WHO Press, Geneva
Ritz K (2005) Underview: origins and consequences of belowground biodiversity. In: Bardgett RD, Usher MB, Hopkins DW (eds) Biological diversity and function in soils. Cambridge University Press, Cambridge, pp 381–401
Ritz K, Black HIJ, Campbell CD, Harris JA, Wood C (2009) Selecting biological indicators for monitoring soils: a framework for balancing scientific and technical opinion to assist policy development. Ecol Indic 9:1212–1221
Romig DE, Garlynd MJ, Harris RF, McSweeney K (1995) How farmers assess soil health and quality. J Soil Water Conserv 50:229–236

Roy RN, Finck A, Blair GJ, Tandon HLS (2006) Plant nutrition for food security – a guide for integrated nutrient management, vol 16, Fertilizer and plant nutrition bulletin. Food and Agriculture Organization of the United Nations, Rome

Sahrawat KL, Padmaja KV, Pathak P, Wani SP (2005) Measurable biophysical indicators for impact assessment: changes in water availability and quality. In: Shiferaw B, Freeman HA, Swinton SM (eds) natural resource management in agriculture: methods for assessing economic and environmental impacts. CAB International, Wallingford, pp 75–96

Sahrawat KL, Murugappan V, Padma Raju A (2006) Soil and water quality issues vis-a-vis agricultural management practices in Deccan Plateau. In: Proceedings of the international conference on soil, water and environmental quality – issues and strategies, New Delhi, Indian Society of Soil Science, Indian Agricultural Research Institute, New Delhi, pp 173–183

Sahrawat KL, Wani SP, Pathak P, Rego TJ (2010) Managing natural resources of watersheds in the semi-arid tropics for improved soil and water quality: a review. Agric Water Manage 97:375–381. doi:10.1016/j.agwat.2009.10.012

Sanchez-Maranon M, Soriano M, Delgado G, Delgado R (2002) Soil quality in Mediterranean mountain environments: effects of land use change. Soil Sci Soc Am J 66:948–958

Sant'anna SAC, Fernandes MF, Ivo WMPM, Costa JLS (2009) Evaluation of soil quality indicators in sugarcane management in sandy loam soil. Pedosphere 19(3):312–322

Schimel JP, Gulledge J (1998) Microbial community structure and global trace gases. Global Change Biol 4:745–758

Schimel JP, Bennett J, Fierer N (2005) Microbial community composition and soil nitrogen cycling: is there really a connection? In: Bardgett RD, Usher MB, Hopkins DW (eds) Biological diversity and function in soils. Cambridge University Press, Cambridge, pp 172–188

Scotti MRM, Correa EJA (2004) Growth and litter decomposition of woody species inoculated with rhizobia and arbuscular mycorrhizal fungi in Semiarid Brazil. Ann For Sci 61:87–95

Segnestam L (2002) Indicators of the environmental and sustainable development. Theories and practical experience. Environmental Economics Series Paper No. 89. World Bank, Washington, DC

Selinus O, Alloway B, Centeno JA, Finkelman RB, Fuge R, Lindh U, Smedley P (2005) Essentials of medical geology. Elsevier, London, pp 15–16

Setälä H, McLean MA (2004) Decomposition rate of organic substrates in relation to the species diversity of soil saprophytic fungi. Oecologia 139:98–107. doi:10.1007/s00442-003-1478-y

Setälä H, Berg MP, Jones TH (2005) Trophic structure and functional redundancy in soil communities. In: Bardgett RD, Usher MB, Hopkins DW (eds) Biological diversity and function in soils. Cambridge University Press, Cambridge, pp 236–249

Seybold CA, Mausbach MJ, Karlen DL, Rogers HH (1998) Quantification of soil quality. In: Lal R, Stewart BA (eds) Soil processes and the carbon cycle. CRC Press, Boca Raton

Sharma KL, Mandal UK, Srinivas K, Vittal KPR, Mandal B, Kusuma Grace J, Ramesh V (2005) Long-term soil management effects on crop yields and soil quality in a dryland alfisol. Soil Till Res 83:246–259

Shehata SA, El-Ramady H (2012) Micronutrients: uptake and its roles in plants. Print house Fares Abd El-Hameed for Printing and Publishing, ISBN-No. 978-977-403-505-0 (in Arabic), Cairo, Egypt

Shukla MK, Lal R, Ebinger M (2006) Determining soil quality indicators by factor analysis. Soil Till Res 87:194–204

Singh AK (2010) Soil quality parameters as influenced by management practices in rice-wheat and maize-wheat cropping systems. In: 19th world congress of soil science, soil solutions for a changing world, Brisbane, 1–6 Aug 2010, pp 278–281

Smith JL, Halvaorson JJ, Papendick RI (1994) Using multiple-variable indicator kriging for evaluating soil quality. Soil Sci Soc Am J 57:743–749

Sojka RE, Upchurch DR (1999) Reservations regarding the sol quqlity concept. Soil Sci Soc Am J 63:1039–1054

Ştefanic G (1994) Biological definition, quantifying method and agricultural interpretation of soil fertility. Rom Agric Res 2:107–116

Ştefanic G, Gheorghiţă N (2006) Soil fertility or soil quality. Rom Agric Res 23:57–64
Stein AJ (2010) Global impacts of human mineral nutrition. Plant Soil 335:133–154
Steiner R (1924) Geisteswissenschaftliche Grundlagen zum Gedeihen der Landwirtschaft. landwirtschaftlicher Kursus Rudolf Steiner Verlag, Dornach, Schwitzerland. Bibliographie-Nr. 327, ISBN 3-7274-3270-5 7
Stroud JL, Paton GI, Semple KT (2007) Microbe-aliphatic hydrocarbon interactions in soil: implications for biodegradation and bioremediation. J Appl Microbiol 102:1239–1253
Sugden A, Stone R, Ash C (2004) Ecology in the underworld. Science 304:1613
Sullivan P (2001) Sustainable soil management. ATTRA the national sustainable agriculture information center funded by the USDA's rural business. http://soilslab.cfr.washington.edu/Watershed_Stewardship/Sustainable_soil.PDF/. Accessed 10 Feb 2013
Sun B, Zhou SL, Zhao QG (2003) Evaluation of spatial and temporal changes of soil quality based on geostatistical analysis in the hill region of subtropical China. Geoderma 115:85–99
Swift MJ, Vandermeer J, Ramakrishnan PS, Anderson JM, Ong CK, Hawkins BA (1996) Biodiversity and agroecosystem function. In: Mooney HA, Cushman JH, Medina E, Sala OE, Schulze E-D (eds) Functional roles of biodiversity: a global perspective. Wiley, Chichester, pp 261–298
Syers JK (1997) Managing soils for long-term productivity. Phil Trans R Soc Lond B 352:1011–1021
Sylvester-Bradley R, Kindred DR (2009) Analysing nitrogen responses of cereals to prioritize routes to the improvement of nitrogen use efficiency. J Exp Bot 60:1939–1951
Tahvonen R (1995) Contents of lead and cadmium in foods in Finland. Food Chem, University of Turku, Department of Biochemistry and Food Chemistry, Turku
Tarafdar JC, Claassen N (1988) Organic phosphorous compounds as a phosphorous source through the activity of phosphatase produced by plant roots and microorganisms. Biol Fertil Soil 5:308–312
Tarafdar JC, Marschner H (1994) Phosphatase activity in the rhizosphere and hyposphere of VA mycorrhizal wheat supplied with inorganic and organic phosphorus. Soil Biol Biochem 26:387–395
Tarafdar JC, Rao AV, Bala K (1988) Production of phosphatase by fungi isolated from desert soils. Folia Microbiol 33:453–457
Tate R (1987) Soil organic matter: biological and ecological effects. John Wiley & Sons, New York
Tejada M, Gonzalez JL, Garcia-Martinez AM, Parrado J (2008) Effects of different green manures on soil biological properties and maize yield. Bioresour Technol 99:1758–1767
Tiessen H, Moir JO (1993) Total and organic carbon. In: Carter MR (ed) Soil sampling and methods of analysis, Canadian Society of Soil Science. Lewis Publishers, Boca Raton, pp 187–199
Tisdale SL, Nelson WL, Beaton JD, Havlin JL (1993) Soil fertility and fertilizers, 5th edn. Macmillan Publishing Company, New York
Topp GC, Galganov YT, Ball BC, Carter MR (1993) Soil water desorption curves. In: Carter MR (ed) Soil sampling and methods of analysis, Canadian society of soil science. Lewis Publishers, Boca Raton, pp 569–579
Topp GC, Reynolds WD, Cook FJ, Kirby JM, Carter MR (1997) Physical attributes of soil quality. In: Gregorich EG, Carter MR (eds) Soil quality for crop production and ecosystem health, vol 25, Developments in soil science. Elsevier, New York, pp 21–58
Torsvik V, Øvreas L, Thingstad TF (2002) Prokaryotic diversity-magnitude, dynamics and controlling factors. Science 296:1064–1066
Treonis M, Austin EE, Buyer JS, Maul JE, Spicera L, Zasada IA (2010) Effects of organic amendment and tillage on soil microorganisms and microfauna. Appl Soil Ecol 46:103–110
Twomlow S, Shiferaw B, Cooper P, Keatinge JDH (2008) Integrating genetics and natural resources management for technology targeting and greater impact of agricultural research in the semi-arid tropics. Exp Agric 44:235–256
USDA (2006) Soil quality institute. Natural resources conservation service. http://soils.usda.gov/sqi/. Accessed 20 Feb 2006
USDA, United States Department of Agriculture (2008) Soil quality physical indicators: selecting dynamic soil properties to assess soil function. Soil Quality Technical Note No. 10

USDA-NRCS (2008) Soil quality physical indicators: selecting dynamic soil properties to assess soil function. Soil quality – agronomy technical note USDA-NRCS, United States Department of Agriculture
USGS, U.S. Geological Survey (2013) Mineral commodity summaries 2013. http://minerals.usgs.gov/minerals/pubs/mcs/2013/mcs2013.pdf/. Accessed 26 Jan 2013
Vaillant V (1901) Petite chimie de l'agriculteur. Edit. F. Alcan, Paris, pp 26–27
van der Ploeg RR, Böhm W, Kirkham MB (1999) On the origin of the theory of mineral nutrition of plants and the law of the minimum. Soil Sci Soc Am J 63:1055–1062
Vanlauwe B, Wendt J, Diels J (2001) Combining organic matter and fertiliser for the maintenance and improvement of soil fertility. In: Tian G, Ishida F, Keatinge JDH (eds) Sustaining soil fertility inWest Africa. American Society of Agronomy, Madison, pp 247–279
Velasquez E, Lavelle P, Andrade M (2007) GISQ, a multifunctional indicator of soil quality. Soil Biol Biochem 39:3066–3080
Verhulst N, Govaerts B, Verachtert E, Castellanos-Navarrete A, Mezzalama M, Wall PC, Chocobar A, Deckers J, Sayre KD (2010) Conservation agriculture, improving soil quality for sustainable production systems? In: Rattan Lal, Stewart BA (eds) Food security and soil quality. Advances in soil sciences series. Taylor & Francis Group, LLC, Boca Raton, FL, USA, pp 137–208
Von Uexküll HR, Mutert E (1995) Global extent, development and economic impact of acid soils. Plant and Soil 171:1–15
Waksman S (1932) Principles of soil microbiology. London, Edit. Baillière, Tindall et Con., Baillière
Wang XJ, Gong ZT (1998) Assessment and analysis of soil quality changes after eleven years of reclamation in subtropical China. Geoderma 81:339–355
Wang Q, Wang S, Huang Y (2008) Comparisons of litter fall, litter decomposition and nutrient return in a monoculture Cunninghamia lanceolata and a mixed stand in southern China. For Ecol Manage 255(03/04):1210–1218
Wani SP, Pathak P, Jangawad LS, Eswaran H, Singh P (2003) Improved management of vertisols in the semi-arid tropics for increased productivity and soil carbon sequestration. Soil Use Manage 19:217–222
Wani SP, Singh P, Dwivedi RS, Navalgund RR, Ramakrishna A (2005) Biophysical indicators of agro-ecosystem services and methods for monitoring the impacts of NRM technologies at different scales. In: Shiferaw B, Freeman HA, Swinton SM (eds) Natural resource management in agriculture: methods for assessing economic and environmental impacts. CAB International, Wallingford, pp 97–123
Wardle DA (1995) Impacts of disturbance on detritus food webs in agro-ecosystems of contrasting tillage and weed management practices. Adv Ecol Res 26:105–185
Warkentin BP, Fletcher HF (1977). Soil quality for intensive agriculture. In: Anonymous proceedings of the international seminar on soil environment and fertilizer management in intensive agriculture, Society for Science of Soil and Manure – National Institute of Agricultural Science, Tokyo
Watanabe T, Broadley MR, Jansen S et al (2007) Evolutionary control of leaf element composition in plants. New Phytologist 174:516–523
Weil R, Magdoff F (2004) Significance of soil organic matter to soil quality and health. In: Magdoff F, Weil R (eds) Soil organic matter in sustainable agriculture. CRC Press, Boca Raton, pp 1–43
White PJ, Broadley MR (2009) Biofortification of crops with seven mineral elements often lacking in human diets – iron, zinc, copper, calcium, magnesium, selenium and iodine. New Phytologist 182:49–84
White PJ, Brown PH (2010) Plant nutrition for sustainable development and global health. Ann Bot 105:1073–1080. doi:10.1093/aob/mcq085
White PJ, Hammond JP (2008) Phosphorus nutrition of terrestrial plants. In: White PJ, Hammond JP (eds) The ecophysiology of plant–phosphorus interactions. Springer, Dordrecht, pp 51–81
WHO (2003) Diet, nutrition and the prevention of chronic diseases. WHO, Geneva
Wienhold BJ, Andrews SS, Karlen DL (2004) Soil quality: a review of the science and experiences in the USA. Environ Geochem Health 26:89–95

Wilkinson SR, Welch RM, Mayland HF, Grunes DL (1990) Magnesium in plants: uptake, distribution, function, and utilization by man and animals. Met Ions Biol Syst 26:33–56
Wood S, Sebastian K, Scherr SJ (2000) Pilot analysis of global ecosystems: agroecosystem. IFPRI/WRI, Washington, DC
World Bank (2004) Agriculture investment sourcebook. http://web.worldbank.org/. Accessed 25 Dec 2012
Wu Y, Ma B, Zhou L, Wang H, Xu J, Kemmitt S, Brookes PC (2009) Changes in the soil microbial community structure with latitude in eastern China, based on phospholipid fatty acid analysis. Appl Soil Ecol 43:234–240
Yadvinder-Singh, Bijay-Singh, Timsina J (2005) Crop residue management for nutrient cycling and improving soil productivity in rice-based cropping systems in the tropics. Adv Agron 85:269–407
Young IM, Ritz K (2005) The habitat of soil microbes. In: Bardgett RD, Usher MB, Hopkins DW (eds) Biological diversity and function in soils. Cambridge University Press, Cambridge, pp 31–43
Zhang B, Zhang Y, Chen D, White RE, Li Y (2004) A quantitative evaluation system of soil productivity for intensive agriculture in China. Geoderma 123:319–331
Zornoza R, Mataix-Solera J, Guerrero C, Arcenegui V, Mataix-Beneyto J, Gomez I (2008) Validating the effectiveness and sensitivity of two soil quality indices based on natural forest soils under Mediterranean conditions. Soil Biol Biochem 40:2079–2087
Zvomuya F, Janzen HH, Larney FJ, Olson BM (2008) A long-term field bioassay of soil quality indicators in a semiarid environment. SSSAJ 72(3):683–692

Plant Nutrition: From Liquid Medium to Micro-farm

Hassan R. El-Ramady, T.A. Alshaal, S.A. Shehata, É. Domokos-Szabolcsy, N. Elhawat, J. Prokisch, M. Fári, and L. Marton

Abstract Soil fertility and plant nutrition have played an important role in the agricultural science during the twentieth century in increasing crop yields. In the twenty-first century, importance of this field is still expanding due to the limitations of natural land and water resources, sustainable agriculture, and concern about environmental pollution. Under these conditions, improving food supply worldwide with adequate quantity and quality is fundamental. Supply of adequate mineral

H.R. El-Ramady (✉)
Soil and Water Sciences Department, Kafrelsheikh University, 33516 Kafr El-Sheikh, Egypt

Plant Biotechnology Department, Debrecen University, Böszörményi Útca. 138, 4032 Debrecen, Hungary

Institute of Bio- and Environmental Energetics, Debrecen University, Böszörményi Útca. 138, 4032 Debrecen, Hungary
e-mail: ramady2000@gmail.com

T.A. Alshaal
Soil and Water Sciences Department, Kafrelsheikh University, 33516 Kafr El-Sheikh, Egypt

Plant Biotechnology Department, Debrecen University, Böszörményi Útca. 138, 4032 Debrecen, Hungary
e-mail: alshaaltarek@gmail.com

S.A. Shehata
Vegetable Crops Department, Cairo University, El-Gammaa Str., 12613 Giza, Egypt
e-mail: said_shehata2@yahoo.com

É. Domokos-Szabolcsy • M. Fári
Plant Biotechnology Department, Debrecen University, Böszörményi Útca. 138, 4032 Debrecen, Hungary
e-mail: domokosszabolcsy@gmail.com; fari@agr.unideb.hu

N. Elhawat
Plant Biotechnology Department, Debrecen University, Böszörményi Útca. 138, 4032 Debrecen, Hungary

Department of Biological and Environmental Sciences, Al-Azhar University, Cairo, Egypt

H. Ozier-Lafontaine and M. Lesueur-Jannoyer (eds.), *Sustainable Agriculture Reviews 14: Agroecology and Global Change*, Sustainable Agriculture Reviews 14,
DOI 10.1007/978-3-319-06016-3_12,

nutrients in adequate amount and proportion to higher plants will certainly determine such accomplishments. Further, in developing crop production technologies, research work under field and controlled conditions is necessary to generate basic and applied information. In addition, research is very dynamic and complex due to variation in climatic, soil, and plant factors and their interactions. This demands that basic research information can only be obtained under controlled conditions to avoid or reduce effects of environmental factors on treatments. Hence, the objective of this review article is to discuss basic principles of research in soil fertility and plant nutrition under different conditions from to liquid or solid media, micro-farm, green house and field experiments. These information will be included the management of different tools of plant nutrition even on the small or large scale i.e., Petri dishes (in case of medium) or hectare unit (in case of fields). Topics discussed are soil and solution culture experimental techniques including, fertilizer application and planting, experimental duration and observations, considerations of pot or field experimentations.

Keywords Soil fertility • Plant nutrition • Essential plant nutrients • Field experiments • Liquid medium experiments • Microfarm experiments

Introduction

Research is the foundation of technological improvements. The standard of living of a country is correlating the use of technology. In agriculture sciences, soil fertility and plant nutrition is an important area and its contribution in increasing crop yields is well known. Borlaug and Dowswell (1994) reported that as much as 50 % of the increase in crop yields worldwide during twentieth century was due to use of chemical fertilizers. In the twenty-first century, importance of chemical fertilizers in improving crop yields will continue and expected to be still higher due to necessity of increase in yields per unit land area rather than increasing land areas. Further, judicious use of chemical fertilizers along with other complimentary methods such as use of organic manures and exploiting genetic potential of crop species and cultivars within species in nutrients utilization will be extremely useful and necessary (Fageria 2005).

J. Prokisch
Institute of Bio- and Environmental Energetics, Debrecen University,
Böszörményi Útca. 138, 4032 Debrecen, Hungary
e-mail: jprokisch@agr.unideb.hu

L. Marton
Department of Biological Sciences, University of South Carolina, Columbia, SC, USA
e-mail: drlaszlomarton@gmail.com

It is well known that, agricultural sciences are dynamic in nature, and fertilizer practices change with time due to release of new cultivators and other crop production practices in sustainable crop production systems. That means, it should be enhanced the stability of agricultural systems, help agricultural scientists to maximize nutrient use efficiency, improve crop yields at lower cost, and help maintain a clean environment (air, water, and soil), all of which will contribute to the maintenance of sound human and animal health. In the agricultural sciences, soil fertility and plant nutrition played an important role in increasing crop yields. In this context, increasing crop yields will be a major challenge to agricultural scientists, in general, and soil scientists, in particular. Increasing crop yields under these constraints will require a rational use of chemical fertilizers, an increasing use of organic sources of nutrients, a recycling of plant available nutrients, and an exploitation of the genetic potential of crop species and cultivars to make efficient use of nutrients (Fageria 2005).

Sustainability of an agricultural system is influenced by soil physical, chemical and biological properties, in addition to climatic components. Sometimes this environmental change pattern is not well established in short duration experiments. When long term fertility experiment are planned, it is very important to decide the level of soil fertility should be tested, crop rotation, soil preparation methods, cultural practices adapted in the management of the experiment, and observations to be recorded. In addition to appropriate crop rotations, use of some form of organic manures is an important component of sustainable agricultural systems. Further, fallowing may be an important component of a farming system to give rest to the soil for one season. This can bring many favorable changes in soil physical, chemical and biological soil properties, and can stabilize or help in sustainability of a farming system (Fageria 2006).

Soil fertility is defined as the quality of a soil to supply nutrients in adequate amounts and proper balance for the growth of crop plants (SSSA 1997). Generally, soil analysis is used as criteria to make fertilizer recommendations for field crops. If soil analysis is taken as criteria to supply essential nutrients for plant growth, then, soil fertility can be defined as a measure of a quantity of extractable or available nutrients present in a particular soil during a particular period of a season (Fageria and Baligar 2005). Presence of sufficient quantities of essential nutrients in a soil does not guarantee the availability of these nutrients to growing plants. Plant growth may be restricted due to factors such as soil moisture, soil temperature, pH, or the presence of toxic elements and/or salts. This means fertile soil may or may not be productive depending on the level of other production factors. Therefore, a productive soil is one which has optimum environmental condition for plant growth. Since soil is a continuum, it is a matrix in constant change. It is very difficult under practical conditions to have all crop production factors at an optimum (Fageria 2006).

Plant nutrition is the process of nutrient application to soil, movement of nutrients to plant roots, absorption by roots, and translocation and utilization in plants. Numerous soil, plant, microbial, and environmental factors affect nutrient availability to crop plants. These factors vary from region to region and sometimes even from field to field in the same region. Research data are needed for each crop species under different agroecological regions and social-economical conditions of the growers. Experimental work needs to be done under field and controlled conditions to generate basic and applied information. Hence, supply of essential nutrients to crop plants in adequate amounts and proper balance related to soil fertility and plant nutrition research is very dynamic, complex, and challenging issue for agricultural scientists. The information provided in this article may help agricultural scientists and professors in planning, conducting, analysis, and interpretation of their research activities in the field of soil fertility and plant nutrition (Fageria 2006). Therefore, knowledge of the history of plant mineral nutrition may refer to publications by Reed (1942), Browne (1944), Bodenheimer (1958), Fageria et al. (1997), Epstein (2000), Okajima (2001), Fageria (2005) and Epstein and Bloom (2005).

Soil fertility and plant nutrition research activities are mainly conducted under controlled environments such as liquid media, greenhouse or growth chamber and under uncontrolled or field conditions. Basic principles and methodology for conducting controlled (Fageria 2005) and uncontrolled condition experiments have been published (Fageria 2006). Therefore, the objective of this review article is to present basic principles and research methodologies for soil fertility and plant nutrition under different conditions. These information may be very helpful for scientific community for the research needs to meet the challenges of soil fertility and plant nutrition problems in the twenty-first century to improve crop production and reducing environmental degradation. In addition to field experimentation, in agriculture sciences other experimental work is also necessary under control experiments such as greenhouses and growth chambers or *in vitro*. Hence, controlled, as well as uncontrolled field, experimentations are essential for developing a sound, efficient, and economical viable technology for improving crop yields. That means, in the case of soil fertility and plant nutrition, such experiments are mainly conducted to understand nutrients movements, absorption and utilization processes in soil-plant systems. In addition, nutrient/elementally deficiency/toxicity symptoms and adequate and toxic concentrations in plant tissue are also determined under controlled conditions.

Soil as a Subject of Scientific Study and Current Education

Perhaps the oldest written records from humans are cave paintings. In the Chauvet and Lascaux caves in southern France, early artists mixed charcoal and soil of different colors with animal fat or saliva to create a crude paint, spread on the walls of the caves (Lester 1998). Though no cave depictions to date show any attempt at communicating soil information, the early artists almost certainly used soil properties like color, texture and adhesion for their cave drawings, and may have passed that knowledge on to apprentice artists. As early as 5000 BC, ancient Egyptians associated the high productivity of fields in the Nile valley with the deposits of fertile black silt along the river during its annual floods. Ancient Egyptians clearly distinguished between the fertile valley soils, called “*kemet*” or “black earth”, and

Fig. 1 As early as 5000 BC, ancient Egyptians associated the high productivity of fields in the Nile valley with the deposits of fertile black silt along the river during its annual floods. *Above*: Sowing, plowing and harvesting papyrus, from tombs in Giza, Beni Hasan and Luxor. *Below*: Fig-harvesting (note baboons in the trees), granaries and plowing from the tombs of Amenemhat and Khnumhotep III in Beni Hasan (extracted on March 10, 2013 http://www.saudiaramcoworld.com/issue/201301/the.explorations.of.fr.d.ric.cailliaud.htm/)

the "*deshret*" or "red earth" of the surrounding desert. The continued success of Egyptian agriculture relied on a steady supply of soil being eroded out of the highlands of what is now Ethiopia. It was the responsibility of **Khnum**, the god of the First Cataract, to make sure that the annual flooding was of the right duration and height, so that the proper amount of silt would be deposited to ensure good fertility and harvest, and with the harvest ensure the prosperity of Egypt. It might also be noted in Fig. 1 that tilling the soil with implements drawn by animals was evident in ancient Egypt (Harrison et al. 2009).

A scientific and mechanistic understanding of soil came by applying basic science to the study of soil properties. Many soil scientists consider the birth of modern soil science to begin about 1875 with the emergence of the Russian soil scientist **V. Dokuchaiev**. His substantial contributions to soil science were initiated in Russia and Ukraine because of the presence in the semiarid and steppe regions of black soils which were highly enriched by organic compounds. Dokuchaiev literally *put soils on the map* in introducing geographical variations in soil type that could be explained not only by geological factors (i.e. parent material), but also to climatic and topographic factors, and the time needed for soil formation (pedogenesis) to operate. These principles of Dokuchaiev were later utilized by Hans Jenny (1941) in developing his famous '*five factors of soil formation*', i.e. parent material, topography, climate, organisms and time (Harrison et al. 2009).

The broadest scientific definition for soils might be: "*a soil is the upper part of the lithosphere altered by climatic factors and transformed by biological activity*," for which the term pedosphere is sometimes also used (Fedoroff 2004). Soil science in its broad context deals with many sub-disciplines like soil fertility, soil physics, soil microbiology, soil chemistry, crop management, tillage, soil and water conservation, contamination, remediation and so forth. Plants grow and develop through the uptake of water and nutrients from the root system and carbon dioxide from the air, and the transformation of these components into biomass through photosynthesis. The nutritious and economic parts of biomass are useful in the form of grains, fruits, nuts, or leaf vegetables. The quality and quantity of these products depend largely on the intrinsic properties of the soil and climate at a given location, the type and amount of nutrients supplied, and the conditions under which those nutrients are available; a deficiency of any one of these essential nutrients reduces plant growth. The overall status of these conditions is referred to as soil fertility (Verheye 2010).

It is well established that, soil is relatively complex compared to other environmental media. The complexity is confounded by its spatial heterogeneity both over the Earth's land surface but also with depth. Soil is a continuum covering the Earth's surface, not a discrete set of entities, and most soil is below ground and not readily visible (Buol et al. 2003). The complexity of the natural systems is manifested in the subject of soil science, which involves the study of complicated interrelated and interdependent processes. Soil science is interdisciplinary and includes soil physics, soil chemistry, soil pedology, and soil biology (Bone et al. 2010). There is some variability in the definition of soil; a selection of definitions is presented in Table 1 (Bone et al. 2010).

Soil is the most basic of all natural resources. It is the three-dimensional layer of earth's crust, which, through numerous biophysical/chemical interactive processes, is capable of supporting plant and animal life and moderating air and water environment quality. Soil is a living entity, it is teeming with life, it is a substrate for plant growth, and ceases to support plant growth and purify water and air when life in it ceases to exist. Soil and life have evolved together and will continue to develop together. Soil, or the pedosphere, lies at the interface of the atmosphere and the lithosphere and interacts with all facets of the environment. Indeed, soil is in dynamic equilibrium with its environment, it influences and is influenced by the environment. Soil's interaction with the lithosphere leads to weathering of rocks and new soil formation through leaching of organic and inorganic chemicals into the rock, penetration of plant roots and encroachment of other organisms. Soil's interaction with atmosphere involves exchange of gases, notably CO_2 and N_2, with a profound impact on global climate and plant growth. Soil's interaction with hydrosphere affects water quality because of its ability to filter, denature and buffer against natural and synthetic compounds. It is soil's interaction with the biosphere that has led to co-evolution of life and soil. Soil is the most basic of all natural resources to human survival on the earth. Soil governs all basic processes that regulate the existence of life on earth. These processes are: plant growth and biomass productivity, purification of water, detoxification of pollutants, recycling of elements, and resilience and restoration of ecosystems (Lal 2004).

The scientific study of soil is sometimes done as a pure science without any particular thought towards practical uses. However, in most cases, soil is studied

Table 1 Definitions of soil in legislation and literature (Adapted from Bone et al. 2010)

Soil definition (jurisdiction)	Reference
The upper layer of the Earth's crust, as far as this layer fulfils the soil functions, and including its liquid components (soil solution) and gaseous components (soil air), except groundwater and beds of bodies of water (Germany)	FMENCNS (1998)
The solid part of the Earth including liquid and gaseous compounds and organisms therein (Netherlands)	VROM (1986)
Soil is the zone where plants take root, the foundation for terrestrial life and the basis for a large amount of economic production and varies in depth from a few centimetres to several meters (UK)	Environment Agency (2004)
Solid part of the Earth, including the groundwater and the other components and organisms that are present in it (Belgium, Flanders)	OVAM (2007)
Soil is generally defined as the top layer of the Earth's crust, formed by mineral particles, organic matter, water, air and living organisms, European Commission	EC (2006)
The top layer of the Earth's crust situated between the bedrock and the surface. The soil is composed of mineral particles, organic matter, water, air and living organisms (EU)	Council of the EU (2009)
(i) The unconsolidated mineral or organic material on the immediate surface of the Earth that serves as a natural medium for the growth of land plants (ii) The unconsolidated mineral or organic matter on the surface of the Earth that has been subjected to and shows effects of genetic and environmental factors of: climate (including water and temperature effects), and macro- and micro-organisms, conditioned by relief, acting on parent material over a period of time. A product soil differs from the material from which it is derived in many physical, chemical, biological, and morphological properties and characteristics	Soil Science Glossary Terms Committee (2008)
(i) A dynamic natural body composed of mineral and organic solids, gases, liquids, and living organisms (ii) The collection of natural bodies occupying parts of the Earth's surface that is capable of supporting plant growth and that has properties resulting from the integrated effects of climate and living organisms acting upon parent material, as conditioned by topography, over periods of time	Brady and Weil (2008)

Abbreviations: *VROM* The Netherlands Ministry of Housing, Physical Planning and the Environment, *FMENCNS* Federal Ministry for the Environment Nature Conservation and Nuclear Safety, *EC* European Commission

either as a contributing component to a larger system, i.e. as part of a terrestrial ecosystem such as a forest or wetland, or as a basic element in a larger renewable resources network, i.e. a production system for food or fiber. One of the results of Liebig's research was demonstrating that nutrients could be added into soil to increase plant growth, and that in theory soil could be eliminated entirely as part of the food production system. In this context Sir Francis Bacon published the book "Sylva Sylvarum" in 1627 with detail on the methodology for this "*solution culture*". The method was developed in more detail in the mid 1800s, though only a relatively small amount of food was ever produced in that way. Other scientists have further promoted solution or soilless culture, and gave it a new name '*hydroponics*' (Harrison et al. 2009).

The importance of soil in shaping ecosystems and human civilization is hard to exaggerate, but since soil is hard to see and study, it often isn't considered at all. Numerous studies have shown that the availability of nutrients originating from soil limit the productivity of terrestrial ecosystems, and often limit the local availability of food. Past civilizations have risen when the fertility of the local soils allowed the production of food in excess of need, allowing human efforts to focus on government, industry, artistic and military pursuits. It is clearly impossible to consider all of the potential informal and formal ways in which soil education is delivered, so it will consider just a few methods including formal and informal school education, informal methods, and online and other means of delivering informal education on soils. In addition, online education in various disciplines is advancing rapidly. For such an important resource on which humans rely so much for their food supply and other important renewable resources and environmental services, it appears that society has lost much of its previous direct and practical knowledge of soil. On the other hand, the realization that soil is a critical resource is widely acknowledged, and a fairly large amount of material about soil is now available through the internet and in published form, aimed at audiences from young children to higher education levels. Informing and educating the public about the importance and basic properties of soils is also part of more holistic materials published about ecosystems, where soil is not considered individually as a separate, but as part of a functioning ecosystem (Harrison et al. 2009).

Therefore, it could be concluded that, soil is the most basic of all natural resources, which governs all basic processes that regulate the existence of life on earth. These processes include plant growth and biomass productivity, purification of water, detoxification of pollutants, recycling of elements, and resilience and restoration of ecosystems. It is the three-dimensional layer of earth's crust, which, through numerous biophysical/chemical interactive processes, is capable of supporting plant and animal life and moderating air and water environment quality. Soil is a living entity, it is teeming with life, it is a substrate for plant growth, and ceases to support plant growth and purify water and air when life in it ceases to exist. A scientific and mechanistic understanding of soil came by applying basic science to the study of soil properties.

Soils for Sustainable Agriculture

Soils are a fundamental, but largely off-balance-sheet resource which nevertheless sustain the entire food and agriculture sector from farm to fork. Meeting the urgent challenges outlined by scientists will not only ensure the sustainability of this resource and hence of the sector, but also presents a range of opportunities to significantly increase the value of the food supply chain while avoiding the impacts of negative societal responses to, for example, plant biotechnology. It is well identified a series of high-priority, high-impact objectives for research and science-led strategy development to address the urgent needs of soil and food security and agricultural sustainability (RSC 2012). Applied research priorities in soil and agriculture, strategic objectives for soil science and agriculture were highlighted. Meeting attendees identified four future projects that offer the potential to provide solutions to ensure there is adequate soil management in the future:

1. Creation of closed loop systems for recovery of major nutrients, water and micronutrients from low-grade farm and food wastes to reduce dependence on primary stocks and global markets;
2. Development and application of high sensitivity, high resolution biosignalling and sensor technologies to support precision agriculture and more sophisticated regulatory testing;
3. Detailed and robust understanding of molecular scale biogeochemical processes associated with phosphorus uptake at and around plant roots, to stimulate the development of target-specific, 'smart' agrochemical agents;
4. Integrated models of plant-soil-water interactions and development of methodologies to upscale from laboratory to field and landscape to inform soil management policies, climate change mitigation and adaptation to environmental change.

It is well known that, chemistry, alongside biology, physics and engineering, has a critical role in soil science. Chemists need to take on the challenge of using their skills to address problems in complex areas such as the deployment of physical techniques to determine soil structure, probing the mechanisms of nutrient cycling and understanding the chemical interactions between soil organisms and plants. The challenges described above all require a strongly interdisciplinary approach to achieve effective solutions. A key factor in improving outputs in soil science research is increased funding for cross-cutting and integrated research. For example, research that encompasses both biology and chemistry in the rhizosphere and integration with geospatial science will allow new knowledge to be integrated into assessment and practices at field and landscape scale. It could be identified four priority areas around which clear interdisciplinary research can be developed. The following priority areas include biosignalling and sensors, closed-loop systems for recovering nutrients from waste, integrated models of plant-soil-water and nutrient/water use efficiency. Each project is based on a substantial framework for rapid development, contains targeted key challenges in soil and agricultural sustainability, and is the basis for the development of long-term integrated programmes of research (RSC 2012).

It is well documented that, goals of soil management during the nineteenth century and the first half of the twentieth century was to maintain agronomic productivity to meet the food demands of two to three billion inhabitants (Lal 2008). Demands on soil resources are different of a densely populated and rapidly industrializing world of the twenty-first century. In addition to food supply, modern societies have insatiable demands for energy, water, wood products, and land area for urbanization, infrastructure, and disposal of urban and industrial wastes. There is also a need to alleviate rural poverty and raise the standard of living of masses dependent on subsistence farming. In addition, there are several environmental issues which need to be addressed such as the climate change, eutrophication and contamination of natural waters, land degradation and desertification, and loss of biodiversity. To a great extent, solutions to these issues lie in sustainable management of world's soil resources, through adoption of agronomic techniques which are at the cutting edge of science (Lal 2008).

The concept of "*sustainable agriculture*" needs to be revisited in the context of the need for increasing productivity in developing countries which will entirely inherit the future increase in population of 3.5 billion by the end of the twenty-first century. With reference to the densely populated countries of Asia and Africa, sustainable agricultural practices are those which: (1) maximize productivity per unit area, time and input of fertilizers, water and energy, (2) optimize the use of off-farm input, (3) increase household income through increase in production, trading of carbon credits, off-farm employment, and value addition of farm produce, (4) improve quality and quantity of fresh water resources at the farm level, (5) provide education opportunities especially for women, (6) create clean household cooking fuel for the rural population to improve health of women and children and spare animal dung and crop residues for use as soil amendments, and (7) address concerns of the farm family especially food security until the next harvest. It is a fact that indiscriminate use of chemicals, excessive tillage and luxury irrigation have degraded soils, polluted waters and contaminated air. The problem is not with the technology. Thus, the concept of sustainable agriculture must be based on the simple fact that agricultural ecosystems are only sustainable in the long-term if the outputs of all components produced balance the inputs into the system. Whether the required amount of input (nutrients) to obtain the desired yield is supplied in organic rather than inorganic form is a matter of availability and logistics. While advancing and improving the knowledge of basic processes, soil scientists must also work with geologists, hydrologists, climatologists, biologists, chemists, physicists, computer scientists, nano technologists, system engineers, economists and political scientists to address these emerging issues of the twenty-first century. The key strategy is to reach out to other disciplines while strengthening and advancing the science of soil and its dynamics in an ever changing physical, social, economic and political climate. Agriculture, implemented properly, is an important solution to the issue of achieving global food security but also of improving the environment. The agricultural history of 10–13 millenia has taught us that the motto of modern civilization must be "*in soil we trust*" (Lal 2008).

Therefore, it could be concluded that, there is no sustainable agriculture without sustainable soils. It could be identified four priority areas around which clear inter-disciplinary research can be developed. Sustainable agricultural practices are maximize productivity per unit area, time and input of fertilizers, water and energy, optimize the use of off-farm input, increase household income through increase in production, trading of carbon credits, off-farm employment, and value addition of farm produce, improve quality and quantity of fresh water resources at the farm level, provide education opportunities especially for women, and address concerns of the farm family especially food security until the next harvest.

Soil Fertility vs. Infertility and Food Security

Food security is critical to human health. Food security is achieved when all people have constant access to adequate, safe, and nutritious food that is economically accessible, socially acceptable, and allows for an active and healthy life. The world's population continues to grow rapidly but large areas of cropland have to be abandoned every year due to soil degradation. This combination has lead to a worldwide decrease in per capita cereal production since the 1980s (Brevik 2009). The trends of lost croplands and decreased per capita production will need to be stopped or reversed if we are to meet increasing food needs in the future. Building and maintaining soil health will also be critical in the supply of safe and nutritious food for future populations. Most people recognize that soil plays a significant role in food production, but fewer are aware of the role of soils in food security from a health perspective. Many of the elements that are required for human health come from the soil through either plant or animal products consumed by humans. Some essential elements may also be acquired directly through the voluntary and/or involuntary consumption of soil. There are also a number of ways that soils can have a detrimental affect on human health. Heavy metals in soil can be taken up by plants and passed on to those who consume them. Ingestion or inhalation of soil particles can expose humans to heavy metals, organic chemicals, and pathogens, and airborne dust can cause direct health problems through irritation of the respiratory passages. Despite the obvious connections between soils and human health, there has not been a great amount of research done in this area when compared to many other fields of scientific and medical study. More research in this area is essential to protect and enhance human health (Brevik 2009).

The concept of food security has several facets. These include an appropriate volume of stable food supplies, access to available supplies, food safety, nutritional balance, and social or cultural food preference. This concept of food security has developed over several decades, starting in the 1970s and being constantly and steadily refined through the 2000s. By 2001, the FAO definition of food security had been refined to: "*Food security is a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life.*" Basically, food security is seen as being achieved when all people have physical, social, and economic access to adequate, nutritious, and safe food that meets their dietary needs and their food preferences, allowing for an active and healthy lifestyle. This means the concept of human health is intricately linked to the concept of food security and, therefore, soil properties and processes that influence the quantity and quality of food will also be viewed as influencing human health (Brevik 2009).

Therefore, food security implies physical, social and economic access to sufficient, safe and nutritious food by all people at all times to meet their dietary and food preferences for an active and healthy life (FAO 1996). Food security has four distinct components: (a) food production through agronomic management of soil resources, (b) stability of food production and availability at all times, (c) food access through economic capacity of household or community, and (d) food safety through nutritious and biological quality (Moyo 2007). In this regard, a sustainable food production/agronomic system is the one that: (a) maintains or enhances quality of soil resources, (b) provides sufficient, accessible, safe and nutritious food supply, and (c) creates adequate, economic and social rewards to all members of the society (Lal 2009).

It is well documented that, soil fertility is defined as the quality of a soil to supply nutrients in adequate amounts and proper balance for the growth of crop plants (SSSA 1997). Presence of sufficient quantities of essential nutrients in a soil does not guarantee the availability of these nutrients to growing plants. Plant growth may be restricted due to factors such as soil moisture, soil temperature, pH, or the presence of toxic elements and/or salts. This means fertile soil may or may not be productive depending on the level of other production factors. Therefore, a productive soil is one which has optimum environmental condition for plant growth. Since soil is a continuum, it is a matrix in constant change. It is very difficult under practical conditions to have all crop production factors at an optimum (Fageria 2006). Generally, soil analysis is used as criteria to make fertilizer recommendations for field crops. If soil analysis is taken as criteria to supply essential nutrients for plant growth, then, soil fertility can be defined as a measure of a quantity of extractable or available nutrients present in a particular soil during a particular period of a season (Fageria and Baligar 2005).

Soil infertility or nutrient imbalance, caused by deficiency of some and toxicity owing to excess of others, is a principal cause of yield decline in degraded/desertified soils. Those prone to deficiency include both macro nutrients such as N, P, K, Ca, Mg, S and micro elements, e.g. Zn, Cu, Mo, B, Se and those prone to toxicity have excess Al, Mn, As, and Fe. Nutrient deficit is caused by prevalence of extractive farming practices including removal of crop residues, lack of or low rate of application of inorganic fertilizers and organic amendments, excessive and uncontrolled grazing etc. Nutrient depletion is exacerbated by accelerated erosion (Stocking 2003), which also has strong adverse impacts on crop yields and agronomic production such as in Sub-Saharan Africa (Lal 1995). In addition to land area affected by accelerated erosion, it is estimated that 95 M ha of arable land in Africa have reached such a state of degradation that only huge investments could make them productive again. Nutrient mining is worst in East and Central Africa and in the West African Sahel. Mining of soil nutrients in Africa is estimated at annual depletion rates of 22 kg N, 2.5 kg P and 15 kg K per hectare of cultivated land over the past 30 years since 1975 (Henao and Baanante 2006). This annual loss is equivalent to US $4 billion in fertilizers (Sanchez and Swaminathan 2005). Nutrient mining is also a serious problem in South Asia in general but India in particular. Annual rate of soil NPK depletion is estimated at >80 kg ha^{-1} for the states of Jammu and Kashmir, Tripura and Rajasthan. High rates (40–80 kg ha^{-1} $year^{-1}$) of K_2O depletion are observed in most of northern India (Roy 2003). In addition to macronutrients, deficiency of Zn and other micronutrients is also a serious problem in soils of Sub-Saharan Africa and South Asia (Lal 2009).

While doomsayers expressed apprehension and pointed fingers, agricultural scientists ushered in the Green Revolution and saved hundreds of millions from starvation during the 1960s and 1970s (Borlaug 2007). Globally, the implementation of Green Revolution technology increased average cereal yield from 1.2 t ha^{-1} in 1951 to 3.4 t ha^{-1} in 2008 (Ingram et al. 2008). In Europe, grain yields also increased linearly between 1960 and 2005 (Ewert et al. 2005). Despite impressive gains in crop yields and total food grain production in South Asia and elsewhere around the world during the second half of the twenty-first century, the Green Revolution bypassed Sub-Saharan Africa. Crop yields in Sub-Saharan Africa have stagnated at about 1 t ha^{-1} for cereals such as sorghum, millet and maize 3–5 t ha^{-1} for roots and tubers (e.g., cassava, sweet potato and yam) and 100–200 kg ha^{-1} for legumes (e.g., cowpeas), because of soil degradation caused by erosion, nutrient mining, and depletion of the SOC pool. Adoption of proven soil management technologies has a potential to quadruple production of food crop staples in Sub-Saharan Africa and also improve their nutritional quality. Globally, adoption of recommended management practices (RMPs) could enhance average cereal grain yields from 3.4 t ha^{-1} in 2008 to 4.2 t ha^{-1} in 2020 (Ingram et al. 2008).

Therefore, yet application of the Green Revolution technologies has been a debatable issue for both biophysical (Postel 1999) and social reasons (Shiva 1991). Environmental consequences of agricultural intensification in India (Singh 2000) and China (Thajun and Van Ranst 2005) must be addressed. Furthermore, the problem is not with the Green Revolution technology. Rather, it is its misuse and mismanagement, which have created the environmental problems. It is over fertilization, overuse of pesticides, over simplification of crop rotations, excessive application of flood-based irrigation, unnecessary plowing, complete removal of crop residues, and uncontrolled communal grazing which have exacerbated soil and environmental depredation. This problem lies in using "technology without wisdom" (Lal 2007). In view of the increasing demand for food production and improvements in its nutritional quality, there is a need for change in the context of agricultural science (Evans 2005). It is equally important to understand how sustainable agriculture can address both the environmental concerns and human health issues (Horrigan et al. 2002), diffuse and minimize pollution from agricultural practices (Burkart 2007), predict changes in crop productivity over time (Ewert et al. 2005) and adapt to ecological systems (Giloli and Baumgärtner 2007) of changing societal needs. Sustainable and efficient practices must address global environmental impacts (Thajun and Van Ranst 2005). There is a need for a paradigm shift in land husbandry, and principles and practices of soil management. Principles and sustainable practices of soil management must be fine-tuned to site-specific needs and the growing aspirations of rapidly increasing populations in developing countries. Ecologically restored and judiciously managed, global soil resources are adequate to meet the essential needs of the present and future populations. Soil scientists, in cooperation with agronomists and crop breeders, have the technology to feed a population of 10 billion (Lal 2006). Integrating genetics and soil management options is essential to achieving great impact of agricultural technology on food production in harsh environments (Twomlow et al. 2008). The adoption of this technology, however, depends on the infrastructure, support services and political will. Innovative technologies also exist to bring about a quantum jump in food production (Lal 2009).

Therefore, it could be concluded that, food security is seen as being achieved when all people have physical, social, and economic access to adequate, nutritious, and safe food that meets their dietary needs and their food preferences, allowing for an active and healthy lifestyle. There is a strong relationship between food security and soil fertility on the one hand and soil infertility on the other hand. Most people recognize that soil plays a significant role in food production, but fewer are aware of the role of soils in food security from a health perspective. Many of the elements that are required for human health come from the soil through either plant or animal products consumed by humans.

Plant Mineral Nutrition

Plant nutrition is a fundamental science that impacts all aspects of cropping systems, environmental sustainability, and human health and well being. Otherwise, plant mineral nutrition is a science that studies the effects of elements on plant growth and development, determines the forms and conditions of availability and uptake, and establishes the ranges of beneficial and detrimental effects. Therefore, there is a need for increased understanding of the fundamental principles of plant nutrition, which can help develop and extend optimized field practices and improve public policies to ensure sustainable food production. Scientists began to unravel the mysteries of how green plants grow in the 1800s (Jones 2003). A number of theories were put forth to explain plant growth, and through observation and carefully crafted experiments, scientists began to learn what was required for normal growth and development. The early scientists discovered that the mass of a live plant was essentially composed of water and organic substances, and that total mineral matter constituted less than 10 % and frequently less than 5 % of the dry matter of most plants. The analysis of the mineral matter (ash) after the removal of water and destruction of the organic matter provided better understanding of the nutritional requirements of plants by revealing which elements were present in the ash and at what concentrations. By 1890, scientists established plant requirements for C, H, O, N, P, S, K, Ca, Mg, and Fe. Their absence or low availability led to plant death or poor growth after exhibiting visual symptoms. By the early 1900s, 10 of the now-known 16 essential elements required by plants had been identified, but no system existed to scientifically establish their absolute essentiality. Their presence was assumed to be related to their importance (Jones 2003).

It is well known that, higher green plants like all organisms need nutrients for their growth and development. Nutrients are indispensable as plant constituents, for biochemical reactions, and for the production of organic materials referred to as photosynthates (carbohydrates, proteins, fats, vitamins, etc.) by photosynthesis. In agriculture, optimal crop nutrition is an important prerequisite for obtaining high yields and good-quality produce. The nutrients required are obtained by plants both from soil reserves and external nutrient sources such as fertilizers, organic manures, the atmosphere, etc. Almost all of the 90 natural elements can be found in green plants although most of them have no function like gold (Roy et al. 2006).

It is also well established that, at present, 17 trace elements, i.e. Al, B, Br, Cl, Co, Cu, F, Fe, I, Mn, Mo, Ni, Rb, Si, Ti, V, and Zn are known to be essential for plants, several are proved necessary for a few species only, and others are known to have stimulating effects on plant growth, but their functions are not yet recognized (Tables 2 and 3; Kabata-Pendias 2011). A feature of the physiology of these elements is that although many are essential for growth, they can also have toxic effects on cells at higher concentrations. The essential trace elements for plants are those which cannot be substituted by others in their specific biochemical roles and that have a direct influence on the organism so that it can neither grow nor complete some metabolic cycles. The elements needing more evidence to establish their essentiality usually are those thought to be required in very low concentrations (at μg kg^{-1} or ng kg^{-1} ranges) or that seem to be essential for only some groups or a few species of plants. An assessment of toxic contents and effects on plants is very complex since this depends on many factors both external and internal (Kabata-Pendias 2011).

Plants reveal a great behavioral plasticity under chemical stress. Based on a huge database of observations it has been possible to characterize soil properties that can affect deficiency of some elements to crop plants. The most common symptoms of micronutrient deficiency in sensitive plants are: (1) chlorosis and necrosis mainly of young leaves, (2) wilting, (3) melanism: brown, violet, red, (4) stunted growth, and (5) leaf deformation. Schematic plant response to changes in concentrations of essential and nonessential elements differs at the ranges of low contents. Several models have been used to predict the bioavailability of trace metals, and in particular of Cd, Zn, Cu, and Pb (McLaughlin 2001). These models, however, are limited to a given plant and specific growth conditions, and thus the application to crop plants and field condition is still uncertain. Bowen (1979) classified the functions and forms of the elements in organisms, based on the current state of knowledge, by dividing the trace elements that occur in plants into the following groups:

- Elements incorporated into structural materials—Si, Fe, and rarely Ba and Sr.
- Elements bound into miscellaneous small molecules, including antibiotics, and porphyrins—As, B, Br, Cu, Co, F, Fe, Hg, I, Se, Si, and V.
- Elements combined with large molecules, mainly proteins, including enzymes with catalytic properties—Co, Cr, Cu, Fe, Mn, Mo, Se, Ni, and Zn.
- Elements fixed by large molecules having storage, transport, or unknown functions—Cd, Co, Cu, Fe, Hg, I, Mn, Ni, Se, and Zn.
- Elements related to organelles or their parts such as mitochondria, chloroplasts, some enzyme systems—Cu, Fe, Mn, Mo, and Zn.

The requirements of plants and even of individual species for a given micronutrient have been well-demonstrated by Hewitt (1966) and Chapman (1972). If the supply of an essential trace element is inadequate, the growth of the plant is abnormal or stunted and its further development, especially its metabolic cycles, are

Table 2 Principal functions, forms for uptake and average typical plant concentrations of essential nutrients in dry matter of plants

Nutrient or element	Function	Portion of plant	Uptake form
Essential macronutrients		(%)	
Carbon (**C**)	Basic molecular component of carbohydrates, proteins, lipids, and nucleic acids	45.0	CO_2
Oxygen (**O**)	Oxygen is somewhat like carbon in that it occurs in virtually all organic compounds of living organisms	45.0	CO_2, H_2O, O_2
Hydrogen (**H**)	Hydrogen plays a central role in plant metabolism. Important in ionic balance and as the main reducing agent and plays a key role in the energy relations of cells	6.0	HOH from water, H^+
Nitrogen (**N**)	Nitrogen is a component of many important organic compounds and it used by plants to synthesize amino acids and form proteins, nucleic acids, alkaloids, chlorophyll, purine bases, and enzymes	1.50	NH_4^+, NO_3^-
Phosphorus (**P**)	Central role in plants is in energy transfer and protein metabolism. Component of certain enzymes and proteins involved in energy transfer reactions and component of RNA and DNA	0.1–0.4	$H_2PO_4^-$,HPO_4^{2-}
Potassium (**K**)	Helps in osmotic and ionic regulation. It is a cofactor or activator for many enzymes of carbohydrate and protein metabolism. Maintains the ionic balance and water status in plants; involved in the opening and closing of stomata, and associated with carbohydrate chemistry	1.0–5.0	K^+
Calcium (**Ca**)	Major constituent of cell walls, for maintaining cell wall integrity and membrane permeability; enhances pollen germination and growth; activates a number of enzymes for cell mitosis, division, and elongation; may detoxify the presence of heavy metals in tissue	0.2–1.0	Ca^{2+}
Magnesium (**Mg**)	Major constituent of the chlorophyll molecule; enzyme activator for a number of energy transfer reactions	0.1–0.4	Mg^{2+}
Sulfur (**S**)	Sulfur is somewhat like phosphorus in that it is involved in plant cell energetic processes. Constituent of three amino acids (cystine, cysteine and methionine); component of compounds that give unique odor and taste to some types of plants	0.1–0.4	SO_4^{2-}
Essential micronutrients		mg kg^{-1}	
Iron (**Fe**)	An essential component of many heme and nonheme Fe enzymes and carriers, including the cytochromes (respiratory electron carriers) and the ferredoxins. It is required for NO_3 and SO_4 reduction, N_2 assimilation, and energy (NADP) production; associated with chlorophyll formation	50–205	Fe^{2+} or Fe(II), Fe^{3+} or Fe(III)

(continued)

Table 2 (continued)

Nutrient or element	Function	Portion of plant	Uptake form
Zinc (**Zn**)	Essential component of several enzymatic functions as Mn and Mg, dehydrogenases, proteinases, and peptidases, including carbonic anhydrase, alcohol dehydrogenase, glutamic dehydrogenase, and malic dehydrogenase, among others	20–150	Zn^{2+} or Zn(II)
Manganese (**Mn**)	Involved in the O_2-evolving system of photosynthesis and is a component of the enzymes arginase and phosphotransferase, i.e., involved in oxidation–reduction processes in the photosynthetic electron transport system; photosystem II for photolysis; activates IAA oxidases	20–500	Mn^{2+} or Mn(II)
Copper (**Cu**)	Constituent of a number of important enzymes, including cytochrome oxidase, ascorbic acid oxidase, and laccase. Constituent of the chloroplast protein plastocyanin; participates in electron transport system linking photosystem I and II; participates in carbohydrate metabolism and nitrogen (N_2) fixation	5–20	Cu^{2+} or Cu^{+}
Boron (**B**)	The specific biochemical function of B is unknown but it may be associated with carbohydrate chemistry, pollen germination, and cellular activities (division, differentiation, maturation, respiration, and growth); important in the synthesis of one of the bases for RNA formation	6–60	H_3BO_3 boric acid or $H_2BO_3^-$
Molybdenum (**Mo**)	Required for the normal assimilation of N in plants. Component of two enzyme systems, nitrogenase and nitrate reductase, for the conversion of NO_3 to NH_4 (N_2 fixation enzyme)	0.1	MoO_4^{2-}
Chlorine (**Cl**)	Essential for photosynthesis and as an activator of enzymes involved in splitting water. It also functions in osmoregulation of plants growing on saline soils, where raises cell osmotic pressure and affects stomatal regulation; increases hydration of plant tissue	100	Cl^-
Nickel (**Ni**)	Nickel is essential for urease, hydrogenases, and methyl reductase and for urea and ureide metabolism, to avoid toxic levels of these nitrogen fixation products in legumes. Nickel is a constituent of plant enzyme urease, the enzyme that catalyzes the degradation of urea to carbon dioxide and ammonia. Nickel deficient plants accumulate toxic levels of urea in leaf tips, because of reduced urease activity	0.10	Ni^{2+} or Ni(II)

Sources: Compiled from Jones (2003), Havlin (2005), Jones (2005), Roy et al. (2006), Kabata-Pendias and Mukherjee (2007), Fageria et al. (2011), Kabata-Pendias (2011), Kirkby (2012)

Table 3 The new beneficial elements and their roles or forms and principal functions of trace elements that are essential for some plants according to Jones (2005) and Kabata-Pendias (2011), and these elements are known to be essential for some groups or species and whose general essentiality needs confirmation

Beneficial trace elements	Function or role	Uptake form
Silver (**Ag**)	Induces production of male flowers on female plants, blocks the production of ethylene; cut flower life can be enhanced by pretreatment with Ag compounds	Ag^{+}
Aluminum (**Al**)	May be beneficial to plants that accumulate Al; traces found in DNA and RNA. Involved in controlling colloidal properties in the cell, possible activation of some dehydrogenases and oxidases	Al^{3+}
Arsenic (**As**)	Constituent of phospholipid (in algae) and involved in metabolism of carbohydrates in algae and fungi	As^{3+}
Bromine (Br)	Constituent of bromophenols (in algae)	Br^{-}
Cobalt (**Co**)	Constituent of cobamide coenzyme Symbiotic N_2 fixation, possibly also in non-nodulating plants, and valence changes stimulation synthesis of chlorophyll and proteins	Co^{2+} or Co(II)
Fluorine (**F**)	Constituent of fluoracetate (in a few species) and involved in citrate conversions	F^{-}
Iodine (**I**)	Stimulates growth of plants in I-deficient soils; stimulates the synthesis of cellulose and lignification of stem tissue; increases concentration of ascorbic acid; seems to increase the salt tolerance of plants by lowering Cl uptake. Constituent of tyrosine and its derivatives (in angiosperms and algae)	I^{-}
Lithium (**Li**)	Some plants can accumulate Li to high concentrations; may affect the transport of sugars from leaves to roots in sugar beets; increases chlorophyll content of potato and pepper plants. Involved in metabolism in halophytes	Li^{+}
Sodium (**Na**)	Can be a replacement for K in some plants, such as spinach and sugar beet; small quantities have increased tomato yields; an element that can be beneficial at low concentrations and detrimental at high concentrations	Na^{+}
Rubidium (**Rb**)	May partially substitute for K, when P and NH_4-N are high concentration in the plant, may play a role in the sugar beet plant by enhancing yield and sugar content	Rb^{+}
Selenium (**Se**)	Constituent of glycene reductase (in *Clostridium* cells) combined with cysteine and methionine and can replace S in some plants	SeO_4^{2-} or SeO_3^{2-}
Silicon (**Si**)	Constituent of structural components and can improve resistance or tolerance to Al, Mn, salt toxicity and increase tolerance of plants against environmental stress. Available as silicic acid (H_4SiO_4) which is slightly soluble; moves in the plant in the transpiration stream in the xylem; important roles in growth, mineral nutrition, mechanical support, resistance to fungal diseases	$Si(OH)_4$ (non-ionized)
Strontium (**Sr**)	May partially replace Ca when Ca requirement is high, function similar to that of Ca in some plants	Sr^{2+}

(continued)

Table 3 (continued)

Beneficial trace elements	Function or role	Uptake form
Titanium (**Ti**)	May play a role in photosynthesis and N_2 fixation; increases chlorophyll content of tomato leaves; increases yield, fruit ripening, and sugar content of fruit; may be essential for plants but not found so because Ti is almost impossible to remove from the environment	Ti^{4+}
Vanadium (**V**)	Constituent of porphyrins, hemoproteins and involved in lipid metabolism, photosynthesis (in green algae), and possibly in N_2 fixation. Enhances and complements the functioning of Mo, V and Mo participate in the N_2 fixation process, contributes to the initial stages of seed germination	VO_3^- or vandate

disordered. Although deficiency symptoms cannot be generalized, they may be quite characteristic for the particular element. Bergmann and Cumakov (1977) presented comprehensive illustrations of deficiency (and some toxicity) symptoms in cultivars. Visible symptoms are important in diagnosis of deficiencies; however, disturbance of metabolic processes and consequent losses in production of biomass may occur before the deficiency symptoms are recognized. In order to develop a better diagnostic method, biochemical indicators based on enzymatic assays were proposed by Ruszkowska et al. (1975), Rajaratnam et al. (1974) and Gartrell et al. (1979) as a sensitive test for a hidden deficiency of a given micronutrient. The activity of some enzymes is correlated mainly with Cu, Fe, and Mo levels in plant tissues. The practical use of the enzymatic assays is, however, greatly limited because of a high rate of variation and of technical difficulties in the determination of the enzymatic activity (Kabata-Pendias 2011).

It is well known that, plant mineral nutrition—along with availability of water and cultivar; control of diseases, insects, and weeds; and socioeconomic conditions of the farmer—plays an important role in increasing crop productivity. Nutrient concentrations in soil solution have been of interest for many decades as indicators of soil fertility in agriculture (Hoagland et al. 1920). Plant mineral nutrition refers to the supply, availability, absorption, translocation, and utilization of inorganically formed elements for growth and development of crop plants. During the twentieth century (1950–1990), grain yields of cereals (wheat, corn, and rice) tripled worldwide. Wheat yields in India, for example, increased by nearly 400 % from 1960 to 1985, and yields of rice in Indonesia and China more than doubled. The vastly increased production resulted from high- yielding varieties, improved irrigation facilities, and use of chemical fertilizers, especially nitrogen. The results were significant in Asia and Latin America, where the term *green revolution* was used to describe the process (Brady and Weil 2002). Stewart et al. (2005) reported that the average percentage of yield attributable to fertilizer generally ranged from about 40 to 60 % in the United States and England and tended to be much higher in the tropics in the twentieth century. Furthermore, the results of the Stewart et al. (2005) investigation indicate that the commonly cited generalization that at least 30–50 % of crop yield is attributable to commercial fertilizer nutrient inputs is a reasonable, if not conservative, estimate. In addition, they reported that omission of N in corn declined yield of this crop by 41 % and elimination of N in cotton production resulted in an estimated yield reduction of 37 % in the United States. These authors also reported that if the effects of other nutrient inputs such as P and K had been measured, the estimated yield reductions would probably have been greater. Baligar et al. (2001) reported that as much as half of the rise in crop yields during the twentieth century derived from increased use of fertilizers (Fageria 2009).

Fageria and Baligar (2005) reported that soil infertility, due to natural element deficiencies or unavailability, is probably the single most important factor limiting crop yields worldwide. Application of macro- and micronutrient fertilizers has contributed substantially to the huge increase in world food production experienced during the twentieth century. The role of mineral nutrition in increasing crop yields in the twenty-first century will be higher still, because world population is increasing rapidly and it is projected that there will be more than eight billion people by the year 2025. Limited natural resources like land and water and stagnation in crop yields globally make food security a major challenge and opportunity for agricultural scientists in the twenty-first century. It is projected that food supply on the presently cultivated land must be doubled in the next two decades to meet the food demand of the growing world population (Cakmak 2001). To achieve food production at a desired level, use of chemical fertilizers and improvements in soil fertility are indispensable strategies. It is estimated that 60 % of cultivated soils have nutrient deficiency/elemental toxicity problems and that about 50 % of the world population suffers from micronutrient deficiencies (Cakmak 2001). Furthermore, it is estimated that to meet future food needs, the total use of fertilizers will increase from 133 million tons per year in 1993 to about 200 million tons per year by 2030 (FAO 2000). This scenario makes plant nutrition research a top priority in agriculture science to meet quality food demand in this millennium. Public concern about environmental quality and the long-term productivity of agroecosystems has emphasized the need to develop and implement management strategies that maintain soil fertility at an adequate level without degrading soil and water resources (Fageria et al. 1997). Most of the essential plant nutrients are also essential for human health and livestock production. The objective of this introductory chapter is to provide information on the history and importance of mineral nutrition in increasing crop yields, nutrient availability and requirements, and crop classification systems and to discuss yield and yield components for improving crop yields. This information may help in better planning mineral nutrition research and consequently improving crop yields (Fageria 2009).

The target of optimal plant nutrition is to ensure that crop plants have access to adequate amounts of all plant nutrients required for high yields. The nutrients have to be present in the soil or provided through suitable sources in adequate amounts and forms usable by plants. The soil water should be able to deliver these nutrients to the roots at sufficiently high rates that can support the rate of absorption, keeping in view the differential demand at various stages of plant growth. Optimal plant nutrition must ensure that there are no nutrient deficiencies or toxicities and that the maximum possible synergism takes place between the nutrients and other production inputs. The ideal state of optimal plant nutrition may not be easy to achieve in open fields (Roy et al. 2006). However, it is possible to come close to it by basing nutrient application on the soil fertility status within soil test, plant analysis, crop characteristics, production potentials and, finally, the practicality and economics of the approach. Proper selection of nutrient sources and their timing as well as method of application are equally important. In the end, farmers should be able to maximize their net returns from investment in all production inputs including nutrient sources. In many countries, farmers do not have the financial resources or access to credit for fully implementing the constraint-free package of recommended inputs. Thus, for optimal plant nutrition to be of value to most farmers, it should also aim to optimize the benefit at different levels of investment. In spite of all theoretical and practical progress towards efficient crop production, it still depends on some uncontrollable and unforeseeable factors, and on interactions among nutrients and inputs. Decisions on fertilization are normally based on certain assumptions of future events, e.g. weather conditions, that may be assumed to be normal but may not turn out to be so. Because of this general uncertainty, many essential data can only be estimated approximately. Thus, some misjudgements can hardly be avoided—neither by farmers toiling at a low yield level nor by those striving for high yields, and not even in scientific experiments, observations and advice. From the farmers' point of view, optimization of nutrient supply appears difficult considering the many aspects of nutrient supply, uptake, requirements and use efficiency. This is facilitated by improving soil fertility in total, which means, to a large extent, not only offering an optimal uninterrupted nutrient supply but also providing generally favourable preconditions for their effective use. Therefore, extension personnel and farmers are well advised to maintain the fertility of their soils in a good, functioning state and to improve it continuously (FAO 2006).

Therefore, it could be concluded that, plant nutrition is a fundamental science that impacts all aspects of cropping systems, environmental sustainability, and human health and well being. Otherwise, plant mineral nutrition is a science that studies the effects of elements on plant growth and development, determines the forms and conditions of availability and uptake, and establishes the ranges of beneficial and detrimental effects. Therefore, there is a need for increased understanding of the fundamental principles of plant nutrition, which can help develop and extend optimized field practices and improve public policies to ensure sustainable food production.

History of Plant Mineral Nutrition Research

Mineral nutrition includes the supply, absorption, and utilization of essential nutrients for the growth and the yield of crop plants. No one knows with certainty when humans first incorporated organic substances, manures, or wood ashes as fertilizer into the soil to stimulate plant growth. However, it is documented in writings as early as 2500 BC that humans recognized the richness and fertility of alluvial soils in valleys of the Tigris and the Euphrates rivers (Tisdale et al. 1985). Forty-two centuries later, scientists were still trying to determine whether plant nutrients ingested by plant roots were derived from water, air, or soil. Early progress in the development of the understanding of soil fertility and plant nutrition concepts was slow, although the Greeks and Romans made significant contributions in the years 800–200 BC (Westerman and Tucker 1987). It was mainly to the credit of Justus von Liebig (1803–1873) that the scattered information concerning the importance of mineral elements for plant growth was collected and summarized, and that mineral nutrition of plants was established as a scientific discipline (Marschner 1983). In 1840, Liebig published results from his studies on the chemical analysis of plants and the mineral contribution of soils. These studies initiated modern research on plant nutrition and highlighted the importance of individual minerals in stimulating plant growth. From these studies evolved the concept that individual minerals were limiting factors for the growth potential of plants (Sinclair and Park 1993). These findings led to a rapid increase in the use of chemical fertilizers. By the end of the nineteenth century, large amounts of potash, superphosphate, and, later, inorganic nitrogen were used in agriculture and horticulture to improve plant growth, especially in Europe (Marschner 1995). Notwithstanding these, it was not until the twentieth century that the list of 17 essential elements was completed and the fundamental concepts of plant nutrition were developed. The quest for an understanding of plant nutrition is not yet complete (Glass 1989; Fageria et al. 2011).

Plants contain small amounts of 90 or more elements, but only 17 elements are known to be essential for plant growth (Epstein and Bloom 2005). Essential nutrients are divided into two groups on the basis of the quantity required by plants. Those required in large quantities are classified as macronutrients and those required in small amounts as micronutrients. C, H, O, N, P, K, Ca, Mg, and S are known as macronutrients. In the group of micronutrients are Fe, Mn, B, Zn, Cu, Mo, Cl, and Ni. Micronutrients have also been called minor or trace elements, indicating that their concentrations in plant tissues are minor or in trace amounts relative to the macronutrients (Mortvedt 2000). Chlorine has often been referred to as a micronutrient even though its concentrations in plant tissues is often equivalent to that of macronutrients (Fageria et al. 2002). Sodium (Na), silicon (Si), selenium (Se), vanadium (V), and cobalt (Co) are beneficial for some plants but have not been established as essential elements for all higher plants (Tables 2 and 3; Mengel et al. 2001). Possibly, other essential micronutrients will be discovered in the future because of the recent advances in solution-culture techniques and the availability of highly sensitive analytical instruments (Fageria et al. 2011).

Micronutrients are normally constituents of prosthetic groups that catalyze redox processes by electron transfer, such as with the transition elements Cu, Fe, Mn, and Mo, and form enzyme–substrate complexes by coupling an enzyme with a substrate (Fe and Zn) or enhance enzyme reactions by influencing molecular configurations between an enzyme and a substrate (Zn) (Römheld and Marschner 1991). Except for B and Cl, the essential micronutrients are metals (Fageria et al. 2002). Even though micronutrients are required in small quantities by field crops, their influence is as large as that of macronutrients in crop production. Micronutrient deficiencies in crop plants are widespread because of (1) increased micronutrient demands from intensive cropping practices and adoption of high-yielding cultivars that may have a higher micronutrient demand, (2) an enhanced production of crops on marginal soils that contain low levels of essential nutrients, (3) an increased use of high analysis fertilizers with low amounts of micronutrients, (4) a decreased use of animal manures, composts, and crop residues, (5) the use of many soils that are inherently low in micronutrient reserves, and (6) the involvement of natural and anthropogenic factors that limit adequate supplies and create element imbalances (Fageria et al. 2002).

Numerous soil, plant, microbial, and environmental factors affect plant acquisition of micronutrients. Soil pH, redox potential, and organic matter have profound effects on the bioavailability of micronutrients (Fageria et al. 2002). Soil organic matter unquestionably contains the largest pool of micronutrients in soil, and influences micronutrient cycling, the distribution of naturally occurring organic ligands, the speciation and the form (organic or inorganic) of elements in soil solution, and the nature and the stability of micronutrient complexes with humic and fulvic acids (Stevenson 1991). Organic substances like humic and fulvic acids formed during soil OM degradation and transformation are important in micronutrient cycling (Fageria et al. 2002). Macro- and micronutrient classification is simply based on the amount required. All nutrients are equally important for plant growth. If deficiency of any nutrient occurs in the growth medium, plant growth is adversely affected. Soil and plant analyses are commonly used to identify nutritional deficiencies in crop production. The best criterion, however, for diagnosing nutritional deficiencies in annual crops is through the evaluation of crop responses to applied nutrients. If a given crop responds to an applied nutrient in a given soil, this means that the nutrient is deficient for that crop. The relative decrease in yield in the absence of a nutrient as compared to an adequate soil fertility level can give an idea of the magnitude of nutrient deficiency. Macronutrients are needed in concentrations of 1,000 μg g^{-1} of dry matter or more, whereas micronutrients are needed in tissue concentrations equal to or less than 100 μg g^{-1} of dry matter (Fageria et al. 2011).

In the literature, the term "***mineral nutrition***" is very common and is often used to refer to ***essential plant nutrients***. This is a slight misnomer, in that plant nutrients are not minerals. The term comes from the fact that most essential elements combine with other elements to form minerals, which eventually break down into their component parts (Fageria et al. 2011). Mineral nutrients include all essential plant nutrients other than carbon, hydrogen, and oxygen, which are derived from CO_2 and H_2O, and nitrogen that originally came from atmospheric N_2 (Bennett 1993). Essential plant nutrients can also be classified as metals or nonmetals. The metals include K, Ca, Mg, Fe, Zn, Mn, Cu, and Mo. The nonmetals include N, P, S, B, and Cl (Bennett 1993). According to Mengel et al. (2001), the classification of plant nutrients based on their biochemical behavior and their physiological functions seems more appropriate. Based on such a physiological approach, plant nutrients may be divided into the following four groups:

***Group* 1:** C, H, O, N, and S. These nutrients are major constituents of organic material, involved in enzymic processes and oxidation–reduction reactions.

***Group* 2:** P and B. These elements are involved in energy-transfer reactions and esterification with native alcohol groups in plants.

***Group* 3:** K, Ca, Mg, Mn, and Cl. This group plays osmotic and ion balance roles, plus more specific functions in enzyme conformation and catalysis.

***Group* 4:** Fe, Cu, Zn, and Mo. Present as structural chelates or metallo-proteins, these elements enable electron transport by valence change.

In view of the supply of micro nutrients many studies in substrate are carried out in this field, but the addition of Cu in organic substrates is still unclear, while the recommended additions of Mo are abundantly in relation to the need of the crop. Just those both micro elements are the most suspicious with respect to environmental pollution. Another item subject to further research is the addition of an element like Ni, traced as an essential element, but so far scarcely included in plant nutrition studies, especially not in substrate where a possible shortage of such an element can be expected firstly. The risk that such essential elements become insufficiently available to crops increases, if substrates used are free of mineral traces and the fertilizers and the irrigation water added become more and more free from any background concentrations. Plant nutrition also plays a role in the prevention of pathogen infection in crops. This offers possibilities for further development of biological control of greenhouse crops. Elements or compounds as Si, Mn, Zn, NO_3 and Ca are known to be able to play a part in the plant resistance to pathogens. This subject need further attention in future research of plant nutrition in substrates, because the excellent possibility to control the uptake of mineral elements in such growing systems (Sonneveld and Voogt 2009).

Therefore, it could be concluded that in addition to field experimentation in agriculture science experimental work is also necessary in the greenhouses and growth chambers. The main objectives of controlled conditions experiments are to understand basic principles. In the case of soil fertility and plant nutrition, such experiments are mainly conducted to understand nutrients movements, absorption and utilization processes in soil plant systems. In addition, nutrient/elementally deficiency/toxicity symptoms and adequate and toxic concentrations in plant tissue are also determined under controlled conditions. For example, pot experiments with different types of soils can show the degree of response that may be anticipated at different soil-test levels and serve as excellent checks on ratings being used. Since such tests provide no measure of the cumulative effects of treatments on yield or soil buildup or depletion, they have limited value in determining rates of fertilizer that should be recommended for sustained productivity. Greenhouse pot studies, in which plants are used for estimating the relative availability of nutrients, also can provide useful indices of the relative availability of a standard fertilizer source in different soils and fertilizer sources. In this review, the different aspects of different controlled experimental conditions will be discussed. This information will help those who are involved in soil fertility and plant nutrition research to improve and/or better understand the principles of experimentation under controlled conditions.

Soil Fertility and Plant Nutrition Research Under Controlled Conditions

It is well known that, when researcher is involved in conducting a research project or experiment, he generally goes through certain steps. Some of these are directly involved in designing the experiment to test the hypotheses required by the project. Research and experimental development is formal work undertaken systematically to increase the stock of knowledge, including knowledge of humanity, culture and society, and the use of this stock of knowledge to devise new applications. It is used to establish or confirm facts, reaffirm the results of previous work, solve new or existing problems, support or develop new theories. A research project may also be an expansion on past work in the field. To test the validity of instruments, procedures, or experiments, research may replicate elements of prior projects, or the project as a whole. The primary purposes of basic research as opposed to applied research, are documentation, discovery, interpretation, or the research and development (R & D) of methods and systems for the advancement of human knowledge. Scientific research relies on the application of the scientific method, a harnessing of curiosity. This research provides scientific information and theories for the explanation of the nature and the properties of the world. It makes practical applications possible. Scientific research is funded by public authorities, by charitable organizations and by private groups, including many companies. Scientific research can be subdivided into different classifications according to their academic and application disciplines. Scientific research is a widely used criterion for judging the standing of an academic institution, such as business schools, but some argue that such is an inaccurate assessment of the institution, because the quality of research does not tell about the quality of teaching (Armstrong and Sperry 1994).

It could be concluded the steps of scientific research as follows: review pertinent literature to learn what has been done in the field and to become familiar enough with the field to allow you to discuss it with others. Define the objectives and the hypotheses that you are going to test. That means a good hypothesis must be specific, clear enough to be tested, adequate to explain the phenomenon, good enough to permit further prediction and as simple as possible. Evaluate the feasibility of testing the hypothesis. Select of the proper research procedure and the suitable measuring instruments and control of bias in data collection should be considered. Care should be taken in measuring treatment materials such as fertilizers, herbicides, or other chemicals, food rations, etc. and the application of treatments to the experimental units. Careful measurements should be made with the appropriate instruments. It is better to collect too much data than not enough and data should also be recorded properly in a permanent notebook. Be sure to have a plan of analysis, e.g., which analysis and in what order will they be done? Interpret the results in the light of the experimental conditions and hypotheses tested. Statistics do not prove anything and there is always the possibility that your conclusions may be wrong. Finally, prepare a complete, correct, and readable report of the experiment. There is no such thing as a negative result. If the null hypothesis is not rejected, it is positive evidence that there may be no real difference among the treatments tested.

Due to large variation in environmental factors, results of controlled conditions experiments can hardly be extrapolated to field conditions and vice-versa. However, these two types of experiments should serve as complementary components in developing a crop production technology. In the controlled conditions experiments soil and solution culture are generally used as medium of plant growth to test treatment effects. Although, use of nutrient solutions allows precise control of experimental variables, it eliminates entirely the soil-root aspect, an important part of soil-plant system. The pattern of exploration and activity in root systems subjected to zonal salinization as well as the significance of ionic motilities in determining quantities of a given element absorbed from soil suggest the importance of testing hypothesis in a soil system, especially a system similar to that found in the field. Many of the successful conditions and details involved for successful growth of plants in soil and solution cultures are not explained in publications where these methods have been used. Much of the information about conducting controlled-condition experiments is taken for granted and left to the ingenuity and experience of investigators. Many helpful ideas and practices come only from experience. Some of the concerns, problems, and care required to conduct controlled-condition experiments have been discussed. It is hoped that the comments and ideas given will be helpful to others who conduct controlled condition experiments in the field of soil fertility and plant nutrition (Table 4).

Therefore, it could be conclude that, when researcher is involved in conducting a research project or experiment, he generally goes through certain steps. Some of these are directly involved in designing the experiment to test the hypotheses required by the project. Due to large variation in environmental factors, results of controlled conditions experiments can hardly be extrapolated to field conditions and vice-versa. However, these two types of experiments should serve as complementary components in developing a crop production technology. In the controlled conditions experiments soil and solution culture are generally used as medium of plant growth to test treatment effects. Much of the information about conducting controlled-condition experiments is taken for granted and left to the ingenuity and experience of investigators. It is hoped that these ideas given will be helpful to others who conduct controlled condition experiments in the field of soil fertility and plant nutrition.

In Vitro or Plant Tissue Culture Experiments

It is well known that, plant tissue culture is a collection of techniques used to maintain or grow plant cells, tissues or organs under sterile conditions on a nutrient culture medium of known composition. Plant tissue culture is widely used to produce clones of a plant in a method known as micropropagation. Different techniques in plant tissue culture may offer certain advantages over traditional methods of propagation, including the production of exact copies of plants that produce particularly good flowers, fruits, or have other desirable traits. The production of multiples of plants in the absence of seeds or necessary pollinators to produce seeds and

Table 4 Soil and plant parameters and their unit commonly used in soil fertility and plant nutrition research (Adapted from Fageria 2005)

Parameter	SI unit	Symbol or unit preferred
Land area	Square meter, Hectare	m^2, ha
Grain or dry matter yield	Gram per square meter, kilogram per hectare, megagram per hectare, ton per hectare	$g\ m^{-2}$, $kg\ ha^{-1}$, $Mg\ ha^{-1}$, $t\ ha^{-1}$
Ion uptake	Mole per kilogram per second dry plant tissue, mole of charge per kilogram per second dry plant tissue	$Mol\ kg^{-1}\ S^{-1}$, $Molc\ S^{-1}$
Nutrient conc. in plant tissue	Millimole per kilogram, gram per kilogram, milligram per kilogram	$mmol\ kg^{-1}$, $g\ kg^{-1}$, $mg\ kg^{-1}$
Nutrient conc. in solution	Milligram per litter, Centimol perlitter	$mg\ L^{-1}$, $cmol\ L^{-1}$
Soil extractable ion (mass basis)	Centimol per kilogram, milligram per kilogram	$cmol\ kg^{-1}$, $mg\ kg^{-1}$
Fertilizer application rate to soil	Gram per square meter, kilogram per hectare	$g\ m^{-2}$, $kg\ ha^{-1}$
Lime or gypsum application rate to soil	Ton per hectare, megagram per hectare	$t\ ha^{-1}$, $Mg\ ha^{-1}$
Soil bulk density	Megagram per cubic meter, gram per cubic centimeter	$Mg\ m^{-3}$, $g\ cm^{-3}$
Electrical conductivity	Siemen per meter, decisiemen per meter	$S\ m^{-1}$, $dS\ m^{-1}$
Cation exchange capacity	Cation exchange capacity per kilogram	$Cmol\ kg^{-1}$
Absolute growth rate	Milligram per day	$mg\ d^{-1}$
Crop growth rate	Milligram per square meter per day	$mg\ m^{-2}\ d^{-1}$
Relative growth rate	Milligram per gram per day	$mg\ g^{-1}\ d^{-1}$
Leaf area index	Square meter per squaremeter	$m^2\ m^{-2}$
Leaf area ratio	Square meter per kilogram	$m^2\ kg^{-1}$
Leaf weight ratio	Gram per gram	$g\ g^{-1}$
Net assimilation rate	Gram per square meter per day	$g\ m^{-2}\ d^{-1}$
Specific leaf area	Square meter per kilogram	$m^{-2}\ kg^{-1}$

regeneration of whole plants from plant cells that have been genetically modified. The production of plants in sterile containers that allows them to be moved with greatly reduced chances of transmitting diseases, pests, and pathogens. The production of plants from seeds that otherwise have very low chances of germinating and growing, i.e. orchids and nepenthes.

Plant tissue culture relies on the fact that many plant cells have the ability to regenerate a whole plant (totipotency). Single cells, plant cells without cell walls (protoplasts), pieces of leaves, or (less commonly) roots can often be used to generate a new plant on culture media given the required nutrients and plant hormones. Modern plant tissue culture is performed under aseptic conditions under High-Efficiency Particulate Air (HEPA) filtered air provided by a laminar flow cabinet. The tissue obtained from the plant to culture is called an explant. Explants are usually placed on the surface of a solid culture medium, but are sometimes placed directly into a liquid medium, particularly when cell suspension cultures are desired. Solid and liquid media are generally composed of inorganic salts plus a few organic nutrients, vitamins and plant hormones. Solid media are prepared from liquid media with the addition of a gelling agent, usually purified agar. The composition of the medium, particularly the plant hormones and the nitrogen source (nitrate versus ammonium salts or amino acids) have profound effects on the morphology of the tissues that grow from the initial explant.

Plant tissues and organs are grown *in vitro* on artificial media, which supply the nutrients necessary for growth. The success of plant tissue culture as a means of plant propagation is greatly influenced by the nature of the culture medium used. For healthy and vigorous growth, intact plants need to take up from the soil: relatively large amounts of some inorganic elements (the so-called plant macro-nutrients): ions of N, K, Ca, P, Mg and S and small quantities of other elements (plant micronutrients or trace elements): Fe, Ni, Cl, Mn, Zn, B, Cu and Mo. The elements listed above are—together with C, O and H—the 17 essential elements. Certain others, such as cobalt (Co), aluminium (Al), sodium (Na) and iodine (I), are essential or beneficial for some species but their widespread essentiality has still to be established. The most commonly used medium is the formulation of Murashige and Skoog (1962). This medium was developed for optimal growth of tobacco callus and the development involved a large number of dose-response curves for the various essential minerals. A major problem in changing the mineral composition of a medium is precipitation, which may often occur only after autoclaving because of the endothermic nature of the process (George et al. 2008).

Plant tissue culture media provide not only these inorganic nutrients, but usually a carbohydrate (sucrose is most common) to replace the carbon which the plant normally fixes from the atmosphere by photosynthesis. To improve growth, many media also include trace amounts of certain organic compounds, notably vitamins, and plant growth regulators. In early media, 'undefined' components such as fruit juices, yeast extracts and protein hydrolysates, were frequently used in place of defined vitamins or amino acids, or even as further supplements (Fig. 2). As it is important that a medium should be the same each time it is prepared, materials, which can vary in their composition are best avoided if at all possible, although improved results are sometimes obtained by their addition. Coconut milk, for instance, is still frequently used, and banana homogenate has been a popular addition to media for orchid culture. Plant tissue culture media are therefore made up from solutions of the following components: (1) macronutrients (always employed); (2) micronutrients (nearly always employed but occasionally just one element, iron, has been used); (3) sugar (nearly always added, but omitted for some specialized purposes); (4) plant growth substances (nearly always added); (5) vitamins (generally incorporated, although the actual number of compounds added, varies greatly); (6) a solidifying agent (used when a semi-solid medium is required agar or a gellan gum are the most common choices); (7) amino acids and other nitrogen supplements (usually omitted, but sometimes used with advantage); (8) undefined supplements such as coconut milk etc. (which, when used, contribute some of the five components above and also plant growth substances or regulants); (9) buffers (have seldom been used, but the addition of organic acids or buffers could be beneficial in some circumstances) (George et al. 2008).

Fig. 2 Some liquid and solid media experiments on giant reed and tobacco. Different studies on the plant nutrition can be carried out using *in vitro* experiments. Studies about toxicity of Cu or Se can be noticed from these photos (Photos by T. Alshaal and H. El-Ramady)

Table 5 Nutrient solution composition used in the solution culture studies according to Fageria (2005) comparing with this composition of nutrients in MS medium according to George et al. (2008)

Nutrient	Hoagland and Arnon (1950)	Johnson et al. (1957)	Andrew et al. (1973)	Yoshida et al. (1976)	Clark (1982)	Nutrients in MS medium
Macro-nutrients (mM)						(mmol l^{-1})
NO_3^-	14.0	14.0	2.00	2.21	7.26	40.0 (mM)
NH_4^+	1.0	2.0	–	0.64	0.90	20.0 (mM)
P	1.0	2.0	0.07	0.29	0.07	1.25
K	6.0	6.0	1.10	1.02	1.80	20
Ca	4.0	4.0	1.00	1.00	2.60	3.0
Mg	2.0	1.0	0.50	1.64	0.60	1.5
S	2.0	1.0	1.50	–	0.50	1.5
Micro-nutrients (μM)						(mmol l^{-1})
Mn	9.1	5.0	4.60	9.00	7.00	0.1
Zn	0.8	2.0	0.80	0.15	2.00	0.03
Cu	0.3	0.5	0.30	0.16	0.50	0.0001
B	46.3	25.0	46.30	18.50	19.00	0.1
Mo	0.1	0.1	0.10	0.50	0.60	0.001
Fe	32.0	40.0	17.90	36.00	38.00	0.1
Cl	–	50.0	–	–	–	6.0
Na	–	–	–	–	–	0.1

It should be noted that minerals may also have a signalling role altering developmental patterns. This is most obvious in root architecture (Lopez-Bucio et al. 2003) which is logical as roots have a principal function in ion uptake and the root system should be such that uptake is optimal. So growth and branching of roots should be affected by mineral concentrations in the soil. Ramage and Williams (2002) also argue that minerals appear to have an important role in the regulation of plant morphogenesis as opposed to just growth (Table 5; George et al. 2008).

Although the biochemistry and physiology of nutrient uptake in tissue cultures may be similar, it is unlikely to be identical. *In vivo*, plants take up mineral ions with their roots. No studies have been made on how uptake of nutrients occurs in shoot cultures. For IAA, it has been shown that most uptake is *via* the cut surface and that only a small fraction is taken up via the epidermis (Guan and De Klerk 2000). The same likely holds for minerals. It should be noted, though, that in tissue culture the stomata are always open in the portion of the explant exposed to the gaseous phase (De Klerk and Wijnhoven 2005) and the same may apply for tissues that are exposed to semi-solid or liquid medium. Uptake via the stomata is well possible. Once taken up, transport within the plant occurs in the mass flow via the xylem. Plants without roots are often cultured *in vitro* where the atmosphere is very humid, and the flow driven by a difference in water potential consequently reduced. In spite of this, in tissue culture there still seems to be sufficient water flow (Beruto et al. 1999) which may be favoured by the stomata being continuously open (De Klerk and Wijnhoven 2005). There are no indications that the structure of the xylem is altered in such a way as to reduce transport of ions. When explants are first placed onto a nutrient medium, there may be an initial leakage of ions from damaged cells, especially metallic cations (Na^+, Ca^{2+}, K^+, Mg^{2+}) for the first 1–2 days, so that the concentration in the plant tissues actually decreases (Chaillou and Chaussat 1986). Cells then commence active absorption and the internal concentration slowly rises. Phosphate and nitrogen (particularly NH_4^+) are absorbed more rapidly than other ions. In liquid medium, almost all phosphorus and ammonium are taken up in the first 2 weeks of culture (e.g. by five microshoots of *Dahlia* in 50 ml stationary liquid medium). After uptake, phosphorus is massively redistributed to tissues that are formed after the initial 2 weeks (George et al. 2008).

Nutrients, and especially micronutrients, may also be added via impurities, and especially via agar. Such impurities may well be beneficial. This is particularly true of Ni, which has recently been shown to be an essential element (Gerendás et al. 1999) but was not known to be when most medium formulations were established. At the time of the early plant tissue culture experiments, uncertainty still existed over the nature of the essential microelements. Many tissues were undoubtedly grown successfully because they were cultured on media prepared from impure chemicals or solidified with agar, which acted as a micronutrient source. In the first instance, the advantage of adding various micronutrients to culture media was mainly evaluated by the capability of individual elements to improve the growth of undifferentiated callus or isolated root cultures. Knudson (1922) incorporated Fe and Mn in his very successful media for the nonsymbiotic germination of orchid seeds, and, following a recommendation by Berthelot (1934), Gautheret (1939) and Nobécourt (1937) included in their media (in addition to iron) copper, cobalt, nickel, titanium and beryllium. Zinc was found to be necessary for the normal development of tomato root systems (Eltinge and Reed 1940), and without Cu, roots ceased to grow (Glasstone 1947). Hannay and Street (1954) showed that Mo and Mn were also essential for root growth. An advantage adding five micronutrients to tissue culture media was perhaps first well demonstrated by Heller in (1953) who found that carrot callus could be maintained for an increased number of passages when Fe, B, Mn, Zn and Cu were present (George et al. 2008).

Therefore, it could be concluded that, plant tissue culture is a promising field for plant nutrition research. It could be adapted these media for different studies concerning plant nutrition. It could be used the *in vitro* experiments to understand nutrients movements, absorption and utilization processes in liquid or solid media systems. In addition, nutrient/elementally deficiency/toxicity symptoms and adequate and toxic concentrations in plant tissue are also determined under controlled conditions.

Hydroponics/Soilless Culture Experiments

The word hydroponics has its derivation from the combining of two Greek words, *hydro* meaning water and *ponos* meaning labor, i.e., working water. The word first appeared in a scientific magazine article (*Science*, Feb 178:1) published in 1937 and authored by W. F. Gericke, who had accepted this word as was suggested by Dr. W. A. Setchell at the University of California. Dr. Gericke began experimenting with hydroponic growing techniques in the late 1920s and then published one of the early books on soilless growing (Gericke 1940). Later he suggested that the ability to produce crops hydroponically would no longer be "chained to the soil but certain commercial crops could be grown in larger quantities without soil in basins containing solutions of plant food." What Dr. Gericke failed to foresee was that hydroponics would in the future be essentially confined to its application in enclosed environments for growing high cash value crops and would not find its way into the production of a wide range of commercial crops in open environments (Jones 2005). To find how hydroponics is defined Jones (2005) went to three dictionaries and three encyclopedias as shown in Table 6.

Actually, hydroponics is only one form of soilless culture. It refers to a technique in which plant roots are suspended in either a static, continuously aerated nutrient solution or a continuous flow or mist of nutrient solution. The growing of plants in an inorganic substance such as sand, gravel, perlite, rockwool or in an organic material such as sphagnum peat moss, pine bark, or coconut fiber and periodically watered with a nutrient solution should be referred to as soilless culture but not necessarily hydroponic (Table 7).

Most of the books on hydroponic/soilless culture focus on the general culture of plants and the design of the growing system, giving only sketchy details on the rooting bed design and the composition and management of the nutrient solution. Although the methods of solution delivery and plant support media may vary considerably among hydroponic/soilless systems, most have proven to be workable, resulting in reasonably good plant growth. However, there is a significant difference between a "working system" and one that is commercially viable. Unfortunately, many workable soilless culture systems are not commercially sound. Most books on hydroponics would lead one to believe that hydroponic/soilless culture methods for plant growing are relatively free of problems since the rooting media and supply of nutrient elements can be controlled. Most hydroponic/soilless growing systems are not easy to manage by the inexperienced and unskilled. Soil growing is more forgiving of errors made by the grower than are most hydroponic/soilless growing systems, particularly those that are purely hydroponic (Jones 2005).

One definite benefit of research done on soilless agriculture was the recognition that scientific methods similar to those used in chemistry could be utilized to improve soil fertility and productivity, and that agriculture didn't need to be limited to the natural productivity of soil for crop production. More than anything else, it became clear that Liebig's discovery of the role of nutrients could be applied to increase food production and improve agriculture. This is sometimes called the "*modern agricultural revolution*", and its basis was the application of scientific research principles to managing agricultural lands for increased production (Harrison et al. 2009). Education, whether formal or informal, is key to developing an understanding of any subject. Developing a basic understanding of some of the most important physical properties of soils is relatively easy by simple observation, since soils of different properties (texture for example) can be handled,

Table 6 Different definition of hydroponics and related hydroponic terms include "aqua (water) culture," "hydroculture," "nutriculture," "soilless culture," "soilless agriculture," "tank farming," or "chemical culture" according to Jones (2005)

Definition	Reference or source
The science of growing plants in a medium, other than soil, using mixtures of the essential plant nutrient elements dissolved in water	Harris (1977)
The process of growing plants without soil, in beds of sand, gravel, or similar supporting material flooded with nutrient solutions	The Oxford English Dictionary (1989)
The science of growing plants without the use of soil, but by use of an inert medium, such as gravel, sand, peat, vermiculite, pumice, or sawdust, to which is added a nutrient solution containing all the essential elements needed by the plant for its normal growth and development	Resh (1995)
The technique of growing plants without soil, in a liquid culture	Wigriarajah (1995)
The science of growing plants without soil	The World Book Encyclopedia (1996)
Hydroponics is a technology for growing plants in nutrient solutions (water containing fertilizers) with or without the use of an artificial medium (sand, gravel, vermiculite, rockwool, perlite, peat moss, coir, or sawdust) to provide mechanical support	Jensen (1997)
The cultivation of plants in nutrient-enriched water with or without the mechanical support of an inert medium, such as sand or gravel	The New Encyclopaedia Britannica (1997)
The science of growing or the production of plants in nutrient-rich solutions or moist inert material, instead of soil	Webster's New World College Dictionary (1999)
The cultivation of plants by placing the roots in liquid nutrient solutions rather than in soils; soilless growth of plants	The Random House Webster's College Dictionary (1999)
The practice of growing plants in liquid nutrient cultures rather than in soil	The Encyclopedia Americana, International Edition (2000)
One in which all nutrients are supplied to the plant through the irrigation water, with the growing substrate being soilless (mostly inorganic), and that the plant is grown to produce flowers or fruits that are harvested for sale	Devries (2003)
Growing plants without soil, with the sources of nutrients either a nutrient solution or nutrient-enriched water, and that an inert mechanical root support (sand or gravel) may or may not be used	Jones (2005)
Hydroponics is a plant culture technique, which enables plant growth in a nutrient solution with the mechanical support of inert substrate	Nhut et al. (2006)
Hydroponics , also known as soilless culture, is a method of growing plants using mineral nutrient water instead of soil	Oriz et al. (2009)

manipulated, utilized under different conditions, and then the soil response under similar conditions can also be predicted to be similar. For instance, if a child uses soil on the beach to build a sand castle, it quickly finds that when finer types of soil are used to line a moat around the castle, water will stay in the moat longer. In this

Table 7 Characterization of inorganic and organic hydroponic substrates (Adapted from Jones 2005)

Substrate	Characteristics
Inorganic hydroponic substrates	
Rockwool and stonewool	Clean, nontoxic (can cause skin irritation), sterile, lightweight when dry, reusable, high water holding-capacity (80 %), good aeration (17 % air-holding), no cation exchange or buffering capacity, provides ideal root environment for seed germination and long-term plant growth
Vermiculite	Porous, spongelike, sterile material, lightweight, high water absorption capacity (five times its own weight), easily becomes waterlogged, relatively high cation exchange capacity
Perlite	Siliceous, sterile, spongelike, very light, free-draining, no cation exchange or buffer capacity, good germination medium when mixed with vermiculite, dust can cause respiratory irritation
Pea gravel and metal chip	Particle size ranges from 5 to 15 mm in diameter, free draining, low water-holding capacity, high weight density, which may be an advantage or disadvantage, may require thorough water leaching and sterilization before use
Sand	Small rock grains of varying grain size (ideal size: 0.6–2.5 mm in diameter) and mineral composition, may be contaminated with clay and silt particles, which must be removed prior to hydroponic use, low water-holding capacity, high weight density, frequently added to an organic soilless mix to add weight and improve drainage
Expanded clay	Sterile, inert, range in pebble size of 1–18 mm, free draining, physical structure can allow for accumulation of water and nutrient elements, reusable if sterilized, commonly used in pot hydroponic systems
Pumice	Siliceous material of volcanic origin, inert, has higher waterholding capacity than sand, high air-filled porosity
Scoria	Porous, volcanic rock, fine grades used in germination mixes, lighter and tends to hold more water than sand
Polyurethane grow slabs	New material, which has a 75–80 % air space and 15 % water holding capacity
Organic hydroponic substrates	
Coconut fiber	Made into fine (for seed germination) and fiber forms (coco peat, palm peat, and coir), useful in capillary systems, high ability to hold water and nutrients, can be mixed with perlite to form medium that has varying water-holding capacities, products can vary in particle size and possible Na contamination
Peat	Used in seed raising mixes and potting media, can become waterlogged and is normally mixed with other materials to obtain varying physical and chemical properties
Composted bark	Used in potting media as a substitute for peat, available in various particle sizes, must be composted to reduce toxic materials in original pinebark (from *Pinus radiata*), high in Mn and can affect the N status of plants when initially used, will prevent the development of root diseases
Sawdust	Fresh, uncomposted sawdust of medium to coarse texture good for short-term uses, has reasonable water-holding capacity and aeration, easily decomposes which poses problems for longterm use, source of sawdust can significantly affect its acceptability
Rice hulls	Lesser known and used, has properties similar to perlite, freedraining, low to moderate water-holding capacity, depending on source can contain residue chemicals, may require sterilization before use

(continued)

Table 7 (continued)

Substrate	Characteristics
Sphagnum moss	Common ingredient in many types of soilless media, varies considerably in physical and chemical properties depending on origin, excellent medium for seed germination and use in net pots for NFT applications, high water-holding capacity and can be easily waterlogged, provides some degree of root disease control
Vermicast and compost	Vermicast (worm castings) and composts are used for organic hydroponic systems, varying considerably in chemical composition and contribution to the nutrient element requirement of plants, can become water-logged, best mixed with other organically derived materials or coarse sand, pumice, or scoria to alter physical characteristics

way, it learns that finer soils have lower infiltration rates than coarser soils. Children are natural experimenters and often learn a great deal about soil through this type of experimentation. The problem is that as they grow up they are quickly taught to stop this particular type of experimentation. Learning then often becomes more formal (Harrison et al. 2009).

The growing of plants in nutrient-rich water has been practiced for centuries. For example, the ancient Hanging Gardens of Babylon and the floating gardens of the Aztecs in Mexico were hydroponic in nature. Egyptian hieroglyphic records dating back several hundred years B.C. describe the growing of plants in water. The paintings in the temple of *Deir el Bahari* show that in 4,000 year ago the Egyptians attempted to transfer and grow trees in big pots in media culture (Raviv and Lieth 2008). In the 1800s, the basic concepts for the hydroponic growing of plants were established by those investigating how plants grow (Steiner 1985). The soilless culture of plants was then popularized in the 1930s in a series of publications by a California scientist (Gericke 1929, 1937, 1940). During the Second World War, the U.S. Army established large hydroponic gardens on several islands in the western Pacific to supply fresh vegetables to troops operating in that area (Eastwood 1947). Since the 1980s, the hydroponic technique has become of considerable commercial value for vegetable (Elliott 1989) and flower (Fynn and Endres 1994) production, and as of 1995 there are over 60,000 acres of greenhouse vegetables being grown hydroponically throughout the world, an acreage that is expected to continue to increase (Jensen 1995). In a 2004 Hydroponic Merchants Association publication, they report over 55,000 acres of hydroponic greenhouse vegetable production worldwide, with about 1,000 acres in the United States, 2,100 acres in Canada, and 2,700 acres in Mexico. In these three countries, 68 % of the production is in tomato, 15 % in cucumber and 17 % in pepper (Jones 2005).

When hydroponics was initially applied commercially, only three crop species were commonly grown: tomato, herbs, and lettuce. Today a wide range of crops, i.e., cucumber, pepper, strawberry, roses, and potatoes, is being successfully grown hydroponically. Even so, most commercially available hydroponic systems are still based on the requirements for growing either tomato or herbs and lettuce. A wide range of vegetables, flowers, and even tree crops are being grown hydroponically

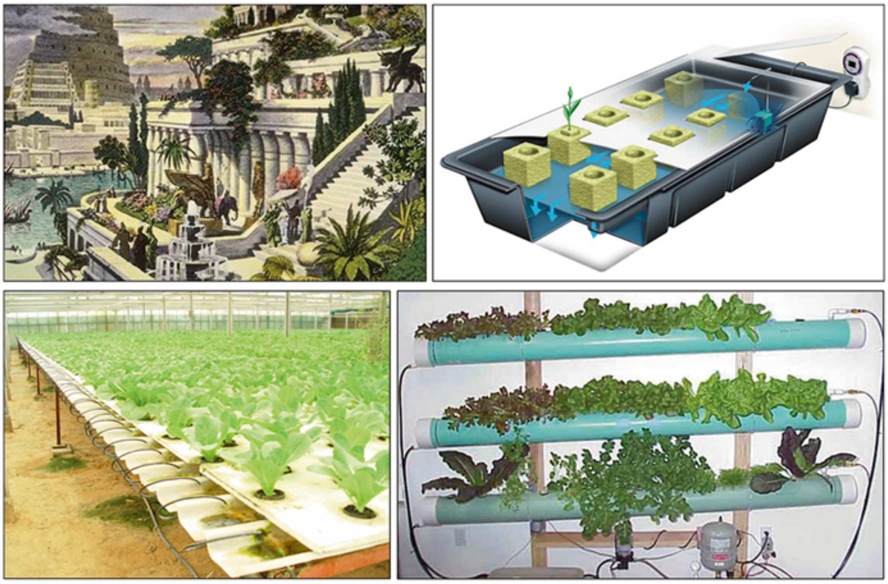


Fig. 3 The Hanging Gardens of Babylon was considered one of the seven wonders of the ancient world and one of the first recorded examples of water gardening. A wide range of vegetables, flowers, and even tree crops are being grown hydroponically using primarily two nutrient solution delivery techniques, ebb-and-flow and drip irrigation. The only exceptions would be for herbs and lettuce, where the Nutrient Film Technique (NFT) method is preferred; the raft system is also used by some lettuce growers (From different websites http://berkeleyssecretgarden.com/?page_id=116, http://www.hydroponicist.com/hydroponic-systems/nft.htm, http://faculty.ksu.edu.sa/Alsadon/Pictures%20Library/lettuce%20in%20hydroponic%20system.JPG and http://www.generalhydroponics.com/blog/wp-content/uploads/2011/07/Hanging_Gardens_of_Babylon.jpg)

using primarily two nutrient solution delivery techniques, ebb-and-flow and drip irrigation. The only exceptions would be for herbs and lettuce, where the Nutrient Film Technique (NFT) method (Alexander 2001; Smith 2002) is preferred; the raft system is also used by some lettuce growers (Jones 2005).

Hydroponics largely applied both in laboratory experiments and in commercial crop production, it is considered as a promising technique not only for plant physiology and plant nutrition experiments but also for commercial production (Nhut et al. 2004). Hydroponics provides numerous advantages: no need for soil sterilization, high yields, good quality, precise and complete control of nutrition and diseases, shorter length of cultivation time, safety for the environment and special utility in non-arable regions. These benefits were crucial in tropical areas, where these pests grow continuously over a year. Application of this culture technique can be considered as an alternative approach for large-scale production of some desired and valuable crops (Fig. 3; Nhut et al. 2006).

The science of hydroponics is characterized by the fact that soil is not needed for plant growth but the elements, minerals and nutrients that soil contains are definitely required. Soil is simply the holder of the nutrients, a place where the plant roots traditionally live and a base support for the plant structure. By eliminating the soil, it also eliminates soil borne diseases and weeds and gains precise control over the plant's nutritional requirements (Sheikh 2006). In a hydroponic solution, one provides the exact nutrients the plant needs in precisely the correct ratios so that they can develop stress-free, mature faster and, at harvest, are the best in quality acceptable both to customer and consumers liking. With the development of plastics, hydroponics took another leap forward and is now a widely accepted method of producing certain specialty crops such as tomatoes, lettuce, cucumbers, bell peppers, herbs, foliage plants, and flowers. Most of the tulips and roses exported from Holland are also grown hydroponically. The controlled environment agriculture and hydroponics seems to be the answer to many of the difficulties associated with the production of outdoor specialty crops in the wake of continued soil degradation, loss of fertility, indiscriminate chemical inputs use, and above all continued depletion of water resources (Sheikh 2006).

Hydroponic culture systems cover a range of techniques, including water culture (Wan et al. 1994), modified water culture (Houghland 1950), nutrient film technique or NFT (Wheeler et al. 1990), and aeroponic systems (Farran and Mingo-Castel 2006). Deep-water culture systems—also called solution culture systems (Lommen 2007)—with roots immersed in unagitated water have the same buffer capacities for pH, nutrients, and temperature as aerohydroponics (Soffer et al. 1991), but on the other hand, they may be prone to inadequate aeration to the root system (Lommen 2007). Also, the NFT system, designed for maintaining adequate root aeration by growing plants in a thin film of nutrient solution (Cooper 1975), can suffer from deficient O_2 concentrations due to consumption by roots and microorganisms (Gislerod and Kempton 1983). The recirculating NFT became the standard approach being studied for production of table potatoes in future space exploration (Wheeler 2006; Chang et al. 2012).

Soilless is a methodology to use for plant cultivation in nutrient solutions (water containing fertilizers) with or without the use of an organic or inorganic medium (sand, clay-expanded, gravel, vermiculite, rockwool, perlite, peat moss, coir, cocopeat and sawdust) to provide mechanical support. Water culture system has no organic or inorganic supporting media for plant roots (Jensen 1999). Additionally soilless methods are classified to open (i.e., once the nutrient solution is delivered to the plant roots, it is not reused) or closed (i.e., surplus solution is recovered, replenished, and recycled) (Raviv and Lieth 2008). Hydroponic or soilless techniques have been used in many aspects of plant biology researches such as plant nutrition, heavy metals toxicity, identification of elements deficiency, screening for abiotic stresses, screening for aluminum toxicity, root functions, root anatomy and so on (Jones 1982). Choosing a proper soilless method based on research purposes, lead us to achieve credible and informative data. Based on temperament of soilless culture, many advantages make soilless culture a specified method for plant biology researches. In soilless culture, the researchers are able to manage plant nutrients, control pH and EC in media, monitor the mutual elements interactions, control the micro and macro nutrient concentrations, and investigate the anions and cations absorption (Sonneveld and Voogt 2009; Torabi et al. 2012).

True hydroponics is the growing of plants in a nutrient solution without a rooting medium. Plant roots are either suspended in standing aerated nutrient solution or in a nutrient solution flowing through a root channel, or plant roots are sprayed periodically with a nutrient solution. This definition is quite different from the usually accepted concept of hydroponics, which has in the past included all forms of hydroponic/soilless growing. Therefore, it could be concluded that, the hydroponics experiment could be provided a useful starting point without extrapolating results from hydroponics culture to field conditions. Obviously due to temperament and various methods of hydroponics or soilless techniques, these methods applied for plant biology researches. Regarding to hydroponics efficiency, capability of modification and possibility of its development, the use of hydroponic systems has been unavoidable for plant biology, soil fertility and plant nutrition researchers.

Micro-farm Experiments

It is well known that, in case of plant nutrition and soil fertility research, the experimental plan and procedure are crucial to its success. In a research project, well-formulated hypothesis and clearly defined objectives are essential part of the experimental techniques. Most of the controlled conditions experiments are conducted in pots using soil, solution culture or sand as a growth medium. Growing plants in solution culture is an important and very traditional technique in mineral nutrition studies. Some important discoveries in mineral nutrition have been made using solution culture techniques such as discovery of essentiality of nutrients. Solution culture studies are useful for developing deficiency symptoms of nutrients essential for plant growth. These symptoms can be used as a guide to identify nutritional disorders in crop plants under field conditions. In addition to deficiency symptoms, it is also possible to develop toxicity symptoms of some element and thus get help in their identification and possible correction measures can be adopted. An example in this respect is Al toxicity in acidic soils, iron toxicity in flooded rice and soil salinity problems in saline soils. Critical tissue concentrations for the diagnosis of nutrient deficiencies and toxicities are frequently established from water culture or sand culture experiments. Although many plant and environmental factors have been shown to affect measured critical concentrations (Johnson et al. 1957), it has been widely assumed that critical tissue concentrations are comparatively stable plant characteristics unlikely to be affected by temporal variation in the external supply of the element concerned (Johnson et al. 1957). However, care should be taken when such results are extrapolated to field conditions because, under field conditions, variability in environmental factors is quite great, which may influence nutrient concentrations in plant tissues. The composition of nutrient solutions commonly used in hydrophonic techniques is given in Table 5. In preparing nutrient solutions, all the chemicals should be reagent grade. In solution culture experiments two points should be given special importance. One is the control of pH and second maintains stable supply of nutrients (Fageria 2005).

Why do symptoms of a plant nutrient element deficiency occur? Because the amount of the nutrient element present in a form the plant can take up and use is insufficient. The reason may be that the soil was infertile and not enough of the nutrient element was added, but other factors affect uptake and lead to the appearance of symptoms. Crops differ a great deal in their development of root systems, and a single crop will show variations in the numbers roots developed, depending on the environment and differences in plant genetics. Since some plant nutrient elements do not move very far in the soil, the extent of the root system will determine whether the plant acquires enough of vital nutrient elements. If root growth is shallow, plants may show deficiency symptoms even when the soil contains a good supply of nutrient elements. Dry surface soil conditions may also limit nutrient element uptake if most of the available nutrient elements are in that zone. This situation is called positional unavailability. When a deficiency symptom is noted, it is good practice to examine the roots to see whether a restricted root zone may be contributing to the deficiency (Jones 2003).

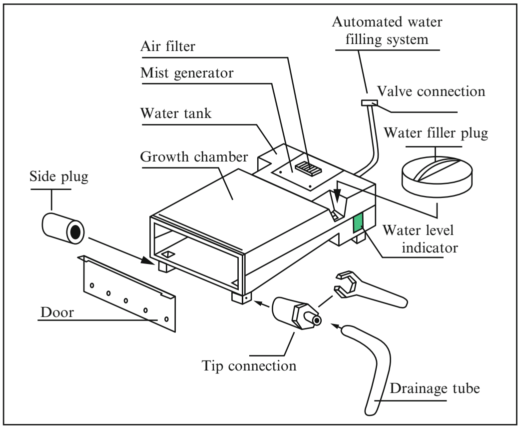
It is well established that, the ancient thinkers wondered about how plants grow. They concluded that plants obtained nourishment from the soil, calling it a "*particular juyce*" existent in the soil for use by plants. In the sixteenth century, van Helmont regarded water as the sole nutrient for plants. Later in the sixteenth century, John Woodward grew spearmint in various kinds of water and observed that growth increased with increasing impurity of the water. He concluded that plant growth increased in water that contained increasing amounts of terrestrial matter, because this matter is left behind in the plant as water passes through the plant. The idea that soil water carried "*food*" for plants and that plants "*live off the soil*" dominated the thinking of the times. It was not until the mid- to late-eighteenth century that experimenters began to clearly understand how, indeed, plants grow (Jones 2005).

In the middle of the nineteenth century, an experimenter named Boussingault began to carefully observe plants, measuring their growth and determining their composition as they grew in different types of treated soil. This was the beginning of many experiments demonstrating that the soil could be manipulated through the addition of manures and other chemicals to affect plant growth and yield. However, these observations did not explain why plants responded to changing soil conditions. Then came a famous report in **1840** by **Liebig**, who stated that plants obtain all their C from CO_2 in the air (Jones 2005). A new era of understanding plants and how they grow emerged. For the first time, it was understood that plants utilize substances in both the soil and the air. Subsequent efforts turned to identifying those substances in soil, or added to soil, that would optimize plant growth in desired directions. The value and effect of certain chemicals and manures on plant growth took on new meaning. The field experiments conducted by **Lawes and Gilbert** at Rothamsted (England) led to the concept that substances other than the soil itself can influence plant growth. About this time, water experiments by **Knop** and other plant physiologists showed conclusively that K, Mg, Ca, Fe, and P, along with S, C, N, H, and O, are all necessary for plant life (Jones 2005).

It is well known that, in soil culture mineralization of organic matter, weathering of primary minerals, biological activities and chemical reaction provides replenishment of mineral nutrients. In addition to this as roots elongates, they came in contacts with more soil volume and more nutrients are available for absorption. This means in soil environment depletion of nutrients takes place over a longer time and soil provides a buffering capacity. Whereas, in water culture, the composition of the nutrient solution is essentially unbuffered and large changes in nutrients concentrations can take place within a relatively short space of time. This may affect nutrients absorption pattern of a crop and consequently growth and yield. The depletion of nutrients by plants nutrient solution depend on original concentration, crop specie or cultivar's rate of absorption, temperature of root rhizosphere and volume of solution in which plants are growing. Looking into these factors some measures can be adapted by the researcher to minimize the rapid depletion of the nutrients in a nutrient culture experiment (Fageria 2005). These measures are use of high concentration, planting in large containers, maintaining adequate temperature and frequent renewal of culture solution. As far as solution renewal is concerned, Yoshida et al. (1976) suggested that change the culture solution once a week at early growth stages and twice a week from active tillering until flowering.

Use of automatic and continuous flow technique, like in micro-farm, is another way to maintain stable nutrients concentration in solution culture studies. A consideration of maintaining stable concentrations of nutrients, together with the amount of labor involved in renewing a large series of solutions, leads obviously to the suggestion that the solution might be made to flow continuously through the culture vessel or tank, the inflow being of known composition and the outflow being discarded or reutilized. This system has many advantages: (1) concentration of the dilute solution can be kept constant at a given value. (2) It is suitable for experiments where pH is to be maintained at a given value. (3) It keeps a constant flow rate of the nutrient solution at a given temperature and humidity. (4) The technique is well suited for comparative studies in the nutrition of plant species. (5) There is no risk of injury to plant material on renewal or replenishment of the solution during the experiment. (6) It is ideally suited for studies of nutrient interactions, because the concentration of all the nutrients can be controlled throughout the period of experimentation. (7) It can also be one of the important techniques in screening crop genotypes for nutrients use efficiency (Fageria 2005).

It could be used micro-farm automatically to grow a large variety of seeds, baby greens, beans, shoots, and wheatgrass, under any climate conditions, at any time of the year, with or without soil. Some micro-farm is supplied with one large tray for wheatgrass and five standard cartridges for sprouts. Some models are stackable, so that it could be purchased one first to suit the present needs and add more modules as the desires change. The micro-farm has a built-in water reservoir so that you can locate the machine in any convenient place, not necessarily near a water source. Micro-farm include built-in mist irrigator, timer, five standard sized cartridges, drainage tube. It could be used this micro-farm to follow plant nutrition sprouter production and plant nutrition research (Fig. 4). It could be modified the micro-farm to follow different plant nutrition studies. The micro-farm sprouter could be used a patented technology of misting water and air on the surface of the seeds. The water management of this micro-farm is unique, and research lead by **Viktor Schauberger**



The micro-farm model structure

Fig. 4 Micro-farm, as a model for plant nutrition and soil fertility research. These photos represent the using of micro-farm for sprouts production as well as for different plant nutrition research. These photos with kind permission from Eric Viard (http://www.easygreeneurope.com/10.3.2013)

has proven that watering plants with water circulating in a vortex strengthens the plants resistance and improves yields.

Therefore, it could be concluded that, micro-farm could be used automatically to grow a large variety of seeds, baby greens, beans, shoots, and wheatgrass, under any climate conditions, at any time of the year, with or without soil. The micro-farm has a built-in water reservoir so that you can locate the machine in any convenient place, not necessarily near a water source. It include built-in mist irrigator, timer, five standard sized cartridges, drainage tube. It could be used this micro-farm to follow plant nutrition sprouter production and plant nutrition research. It could be modified the micro-farm to follow different plant nutrition studies.

Greenhouse Experiments

A term early used to identify a greenhouse was "hothouse," a term that is not in wide use today. In the *Merriam-Webster Dictionary,* hothouse is defined as "*a greenhouse maintained at a high temperature esp. for the culture of tropical plants*." This identification derives from the fact that a greenhouse will collect solar radiant energy that heats the interior (Jones 2005). Jensen and Malter (1995) defined a greenhouse as "*a framed or inflated structure, covered by a transparent or translucent material that permits optimum light transmission for plant production and protected against adverse climatic conditions*." Hanan (1998) states that "*greenhouses are a means of overcoming climatic adversity using a free energy source, the sun*." Beytes (2003) defined a greenhouse as "*a building having glass walls and roof for the production of plants*." That definition would not fit since the glazing (cover) materials in use today include many different types of material other than glass. According to *Webster's New World College Dictionary,* a greenhouse is "*a building made mainly of glass, in which the temperature and humidity can be regulated for the cultivation of delicate or out-of-season plants*," a definition that would fit the concept of design and use in this discussion. The term "glasshouse" "is a European term for an artificially heated structure used for growing plants" (Gough 1993). Beytes (2003) identifies three basic greenhouse designs, single-bay freestanding as the low-cost entrance into the greenhouse business (Thompson 2002); multiple-bay gutter-connected as the most efficient functional greenhouse (Grosser 2003), although it lacks flexibility; and retractable roof, which can be the best of two worlds, providing plenty of ventilation (Vollebrecht 2003). The greenhouse type selected may also be that which best matches the crop to be grown and the local climatic conditions, such as light intensity and duration, temperature extremes, wind, and incidence of hail and snow events (Jones 2005).

At first, the greenhouses were situated merely in areas of moderate climate throughout the year. This means climates where the temperatures do not fall too much below zero, to prevent crops from freezing during winter and where the temperatures do not rise too much during summer to avoid extremely high temperatures inside the greenhouse. Therefore, many greenhouse districts initially developed in coastal areas and on islands. The greenhouse area in the Westland district in the Netherlands and the greenhouses situated on the British Channel Islands were good examples of such developments. The strong development of greenhouses growing all over the world as came about in the second half of the twentieth century was affected by many factors. Among these following are mentioned as being the most important:

- Development of greenhouse construction. The simple glass construction like the lay flat systems and the wooden greenhouse constructions were replaced by metal constructions, possible furnished with heating and cooling systems suitable for a fully automatic climatic control.
- Breeding of new cultivars due to greenhouse cultivation of crops already grown in greenhouses and the increasing diversity of crops grown in this branch. The breeding of new cultivars contributed to increased yield, improved quality and diversity within a produce.
- The development of auxiliary systems, as used in modern greenhouses for climate control, irrigation, fertilization, biological pest control and growing technique. Substrate growing which ensured a better control of the root environment. The small root volume introduced with this growing method strongly improved the management of factors affecting the root development and root functions.
- Flexibility of the branch on the demand of the market and on the competition of products from elsewhere. This means quick adjustments on the demand and quick changes to a different product when the competition from elsewhere cannot be met.
- Successful operations of the greenhouse industry in increasing yields and decreasing costs. In this way the costs per unit produce was stabilized or increased only gradually (Sonneveld and Voogt 2009).

Originally, the greenhouse industry operated in a supply market only, as was common for other agricultural branches. But with the improved transport abilities in the second half of the twentieth century many horticulture products were transported from anywhere to all parts of the world. Thus, from this view point horticulture production in greenhouses had no longer arguments to operate as a supply market. The products of the greenhouse industry joined in free competition with field grown (Sonneveld and Voogt 2009).

In contrary of many other agricultural activities the costs of fertilization in the greenhouse industry are relatively low and amount to only a few percentages of the total costs. Thus, from economic view points were no arguments for a precise and careful application of plant nutrients. In the past an abundant use of fertilizers in the greenhouse industry was common practice and there was no interest by the growers to limitations in the use of fertilizers to prevent in this way the leaching of nutrients to the environment. However, in the last decades of the twentieth century environmental pollution became a subject of permanent attention by the governments of North-West European countries and was quickly followed by regulations from the

European Community. Therefore, in the last decades of the twentieth century extended studies were carried out to factors contributing to a minimum discharge of minerals, like the restrictions on the fertilizer use and an efficient water supply. Besides the supply of minerals indeed restrictions on the quantity of drainage water played an important part in this field. However, restrictions in this field will cause problems with accumulation of salts and an unequal distribution of the moisture content in the soil. For substrate growing the problem was met by reuse of the drainage water and for soil grown crops by a switch to substrate cultivation or by an improvement of the supply of water and fertilizers. Reuse of drainage water and a more precise irrigation pattern strongly aggravate the salt accumulation in the root zone and set high demands on the water quality (Sonneveld and Voogt 2009).

Despite a precise application and an efficient utilization of nutrients in the modern greenhouse industry, the required additions of nutrients will stay high in this horticultural branch. This is related to the high yields usually gained in greenhouses. Greenhouse crops are generally grown at high external nutrient concentrations and realise under these conditions an optimal nutrient status in the plant. A nutrient status in the external solution higher than required does not significantly affect the uptake (Sonneveld and Welles 2005). In the past, fertilization and irrigation in greenhouses was based on the experiences of growers. The addition of farm yard manure and other natural organic products was common practice, supplemented with fertilizers used for field crops. Originally, soil testing in greenhouses was used to check the salt and nutrient status on a yearly basis. The strong changes in the chemical composition of greenhouse soils and the increasing nutrient absorption of the crops resulted from the increasing yields introduced the need for a more frequent check on the nutrient status of the soil. Therefore, the so called "top dressing" samples were introduced as supplemental information about the development of the nutrient status of the soil during cultivation. The greenhouse soils, for example, were sampled and analysed every month and the application of fertilizer to the irrigation water was appointed on basis of this data (Sonneveld and Voogt 2009).

Therefore, it could be concluded that, the combination of plant nutrition research and the development of routine soil testing methods became a fruitful basis for the design of fertilization systems for greenhouse soils. Such systems have been developed by researchers of various research stations all over the world. It could be also concluded that in soil fertility experiment under greenhouse conditions plants can be harvested during flowering legume crops and during initial reproductive growth stage in cereals to evaluate soil fertility treatments. In the soil fertility and plant nutrition experiments yield and yield components should be determined at harvest to understand influence of nutrient treatments on plant growth and yield parameters and their influence on yield. In addition, if objective of the experiment is to determine critical nutrient concentration in the plant tissue at different growth stages, plant sampling should be done at defined plant growth stages. Some of the physiological and nutrient uptake parameters, which are important for mineral nutrition studies can be calculated.

Pot Experiments

As mentioned before, in the case of soil fertility and plant nutrition, pot experiments are mainly conducted to understand nutrients movements, absorption and utilization processes in soil plant systems. In addition, nutrient/elementally deficiency/toxicity symptoms and adequate and toxic concentrations in plant tissue are also determined under controlled conditions (Fageria 2005). Pot experiments with different types of soils can show the degree of response that may be anticipated at different soil-test levels and serve as excellent checks on ratings being used. Since such tests provide no measure of the cumulative effects of treatments on yield or soil buildup or depletion, they have limited value in determining rates of fertilizer that should be recommended for sustained productivity. Greenhouse pot studies, in which plants are used for estimating the relative availability of nutrients, also can provide useful indices of the relative availability of a standard fertilizer source in different soils and fertilizer sources (Fageria 2005).

Nowadays, plastic pots are commonly used in all the controlled conditions experiment-they are most suitable for all soil fertility and plant nutrition experiments (Fageria 2005). A wide variety of sizes and colors are available in the markets. Most suppliers offer pots with drainage holes as well as and plastic saucers for bottom watering or collection of leachate in case of over watering. Pots without drainage holes are also available on order. It could be said that, pots with holes are not necessary, if irrigation water is applied carefully. In the soil fertility and plant nutrition experiments, porous pots may leak some nutrients and it may affect the treatments adversely. Soils containing montmorillonite clays shrink upon drying, thus permitting loss of water and nutrients during routine watering. Pots without holes solve the problems, however, they require careful attention to over watering. In addition, some crops are very sensible to over watering such as common bean. Unglazed or glazed earthen pots are no longer used in greenhouse experiments because of excess weight, water loss, and possible absorption of salts (Fageria 2005). However, they may be satisfactory for some experiments when plastic liners are used. Most of the controlled condition experimental design is completely randomized or randomized complete block design with three or four replications. It is convenient on the part of the researcher to group pots of each replication together on a table and treatments randomized within each replicate (Fageria 2005) (Table 8).

After soil preparation, the next step in experimental technique is application of fertilizer treatments and sowing the crop seeds under investigation. Each pot should be filled with prepared soil and weight should be recorded on a portable balance. To determine optimum levels of a nutrient in greenhouse for a particular crop, a simple experiment with several rates of a single nutrient, and non limiting levels of other nutrients usually supplied the desired information. There should be minimum five nutrient rates (low to high) with four replications. As far as quantity of fertilizer application is concerned, generally researchers use an equivalent quantity that is used under field conditions. However, with experiments conducted at the National Rice and Bean Research Center, Brazil showed that under greenhouse conditions

Table 8 The most important considerations related to pot experiments

Item or property	Consideration or comment
Place of pots	Pots should be rotated twice a week to eliminate any environmental effects, especially the solar radiation
Soil fertility and other properties	It should be noted that soil selected for greenhouse experiments in the area of soil fertility and plant nutrition should be low in fertility
	Selected soil should be as free as possible from soil born diseases, nematodes, insects and weed seeds
	Soils for problem solving must be selected from the site where a specific problem is known to exist, regardless of their suitability by other standard
	Generally, soils should represent the arable soil depth that is 0–20 cm
	After drying the soil, it should be screened to pass through a 0.5–1.0 to 1 cm screen. A screen lower than 0.5 cm mesh can change the soil physical properties too much, especially compaction in the pots
Soil history	Cultivated soils having a history of nonfertilization with a given nutrient for several years and are preferred over virgin or fertilized soils for obtaining yield responses
Soil sample location	Distance from greenhouse to soil collecting site is also an important consideration in order to minimize the cost of transportation
Soil mixing with fertilizers	After applying the fertilizer treatments through mixing the soil is very important. Mixing can be done through a simple soil mixer or by hand-stirring or by rolling on a heavy plastic sheet
Starting time	All the pots for an experiment should be filled at the same time to reduce errors in dry soil weighing caused by drying of the stock soil supply
Adequate plant density in pots	Adequate plant density: for common bean 2 plants per pot of 6 kg soil for wheat 4 plants per pot of 6 kg, and for cowpea 2 plants per 6 kg soil until maturity
Reference experiments	Pot experiment can be used as a reference whether a given site in the field experiment is appropriate for a fertility trial or not

Source: Complied from Fageria (2005)

the quantity of fertilizer required is much higher for rice, common bean, corn, cowpea, and wheat crops on an Oxisol (Fageria et al. 1982). The adequate nutrient levels for upland and irrigated rice cultivated in 6 kg pots were approximately eight times those recommended for field conditions and the optimum plant density was obtained with two to three plants per pot (Fageria 2005).

Length of growth period and other growth limiting factors are equally important. However, if plants are grown for short duration higher plant density can be used. But this density should not be more than double in any case to get meaningful results related to soil fertility and plant nutrition problem. There is no problem in using granular or powder fertilizers in greenhouse studies. Analytical grade reagents should not be used for soil fertility experiment in the greenhouse when soil is used as a growth medium (Fageria 2005). Due to difference in quality, water solubility, and composition, reactions with soil will be different as compared to commercial fertilizers. Results obtained in this way will be far away from the reality. Due to small quantity, it is sometimes difficult to mix with soil of each pot (Fig. 5). During

Fig. 5 Pot experiments using maize and oilseed rape carried out in Julius Kühn-Institut (JKI), Federal Research Centre for Cultivated Plants (Institute of Crop and Soil Science, JKI, Braunschweig, Germany) formerly FAL during 2006 to study the ecotoxicological effects of rare earth elements and the bio-actions of them in soil/plant environment in computerized greenhouse (Photos by H. El-Ramady)

the experimentation, care should be taken of watering, control of insects and diseases and rotation of pots to minimize environmental effects among replications. As far as watering is concerned, it should be used to field capacity of a soil. The weighing method is the most widely used in watering experimental pots. Plastic pots currently available are very uniform in weight and tarring is not necessary. If facilities are available use of deionized water in irrigating the pots is preferred. However, in many developing countries, these facilities are either not available or very expensive; in such situation use of tap water is the only solution. During initial watering, protect the soil surface from washing by a filter paper. Most of the water should be added along the rim of the pot. Depending on the climatic conditions, in the beginning of the experiment, generally watering twice a week is sufficient (Fageria 2005).

Therefore, it could be concluded that, pot experiments are common methods in plant nutrition and soil fertility studies. These experiments are applicable everywhere with slight modifications according to the circumstances of a particular situation. Under controlled conditions like pot experiments, it is better to have separate small experiments with various levels of a nutrient rather than factorial experiments with two or three levels of each nutrient. In these experiments, nutrient use efficiency is an important parameter to know applied nutrient absorption and utilization by the plants. These nutrient use efficiencies have been grouped or classified as agronomic efficiency, physiological efficiency, agro-physiological efficiency, apparent recovery efficiency, and utilization efficiency. There are several considerations related to these experiments should be kept in mind before, during and after performance of these pot experiments. The pot experiments are not applicable to plant nutrition only but also to other disciplines of agricultural sciences.

Soil Fertility and Plant Nutrition Research Under Field Conditions

Research in agriculture is a complex process and demands constant efforts and experimentation due to change in weather conditions, difference in soil properties, difference in adaptation of crop species and different socio-economical conditions of the farmers. Soil fertility and plant nutrition research like any agricultural research involves laboratory, greenhouse or growth chamber, and field experimentation (Fageria 2005). Laboratory and greenhouse experiments are generally short duration experiments conducted to develop and understand some basic principles of subject under investigation. For example, pot experiment with different types of soils can show the degree of response that may be anticipated at different soil-test levels and serve as excellent checks on ratings being used. Since such tests provide no measure of the cumulative effects of treatments on yield or soil buildup or depletion, they have limited value in determining rates of fertilizer that should be recommended for sustained productivity (Fageria 2005).

In 1834 J.B. Boussingault, a French chemist, set up the first field experiments at Bechelbonn, Alsace (France). This started the era of field experimentation, which was placed on a modern scientific basis by Liebig's report of 1840 (Collis-George and Davey 1960). The first field experiments, in the form used today, were established by Lawes and Gilbert at Rothamsted in 1843. Since then, field experiments have sought for and have confirmed the importance of the essential elements in influencing the production of field crops. However, a great deal of the evidence for discovery of the essentiality of nutrients has been in laboratory experiments and in nutrient solution cultures not from field experiments (Collis-George and Davey 1960; Fageria 2006).

It should be kept in mind all basic considerations for conducting field experimentation. A researcher should follow the following items for achieving successful results. These considerations include the following points according to Fageria (2006):

(1) ***Hypothesis and objectives**:*
A scientific experiment is conducted to answer some questions or to solve problems. In agriculture, field experiments are designed on the basis of priority of problems to improve crop production. In the field of soil fertility, it may be necessary to determine optimum levels of nutrients for a crop in a particular soil. When experimental procedures are outlined, the objectives should be clearly defined. What answers does the researcher want from the study under investigation? A review of pertinent literature is a valuable aid in evaluating a hypothesis and achieving the objectives of an experiment. This review of literature can determine what type of experimental work was done in the past to the related problem, how it was done, and what results were obtained. It also will help the researcher from the planning stage of the experiment all the way to the interpretation of results (Fageria 2006).

(2) ***Experimentation site***:
Test plots are the foundation of most modern agricultural research programs. Sites of agronomic field research should ideally represent extensive areas of similar cropland. Where similar areas have been identified and mapped, research results can be extrapolated across a large region. Therefore, a first step in site selection is to take into consideration the key soil, climatic, and socio-economic factors. These factors have to be measured or determined at potential sites and evaluated for transferability of agrotechnology to recommendation domains. The site of the field experiment should be uniform in physical and chemical properties as much as possible. One should try to avoid areas that have been previously used for experiments involving treatments that may have different effects on soil conditions. Treatments involving fertilizers, depth of plowing, different cultivars, and plant densities may have such an effect. Sometimes, of course, the researcher has to carry out the experiment on whatever land is available (Fageria 2006).

(3) ***Land preparation*:**
Experimental area should be well prepared to break hard pan or incorporate crop or weed residues for sowing a test crop under investigation. Soil preparation reflects in seed germination, plant density, water infiltration, erosion, and weeds. This means that if soil is prepared adequately, all these factors will be in favor of higher yield and desired experimental results. Generally, one plowing with a moldboard plow and harrowing once or twice with a disc harrow will be adequate, followed by leveling with spike-tooth or drag harrow (Fageria 2006).

(4) ***Experimental plots*:**
Experimental plots refer to the unit areas on which treatments are tested and the size is the whole unit receiving the treatment. The shape of the plot refers to the ratio of the length to the width. The orientation of plots, on the other hand, refers to the directions along with the lengths that the plots will be placed. The orientation of plots naturally is not defined for square plots (Gomez 1972).

The plot size, shape, and orientation can affect the magnitude of experimental error in a field trial as well as soil preparation, planting, and cultural operations including harvesting. In general, experimental error decreases as plot size increases, but the reduction is not proportional. Gomez (1972) suggested that whatever the size and shape of the plots chosen, it should be essential to make sure that an area not smaller than 5 m^2, free from all types of competition and border effects, is available for harvesting and determining plot yield. Fertilizer trials require larger plots than varietal trials. If a fertilizer trial is of longer duration, there exist possibilities of contamination of adjacent plots of different fertilizer treatments. In these situations, larger plots with ample border area are advisable. In general, the optimum harvest area estimated for relative yield comparison ranges from 5 to 10 m^2 (Gomez and Alicbusan 1969). According to Fageria (2006), a minimum plot size of fertilizer and liming experiments should be 6×5 m for an experimental duration of 3–5 years, if soil preparation operations are done mechanically. In some developing countries, where animal drawn implements are used for soil preparation, a smaller plot size can be used. When soil heterogeneity is large, a large plot should be used in fertilizer trials to reduce the effects of soil properties on yield of tested crop. The choice of field plot shape is not critical when the experimental area is uniform in soil physical and chemical properties.

(5) ***Experimental design*:**
Experimental design refers to the method of arranging the experimental units (plots) and the method of assigning treatments to the units, usually with some replications and randomization. The objective of replication in an experiment is to provide a measure of experimental error. One of the simplest means of increasing precision in an experiment is increasing number of replications. However, beyond a certain number of replications, the improvement in precision is too small to be worth the additional cost. Generally, if an experimental site has uniform soil, using four replications, and good sampling of character under study can provide a coefficient of variation about 8–10 %; a value considered quite low for field experiments. The choice of an experimental design has an important influence on the precision of the experimental results. The best treatment designs provide the greatest precision with a given number of replications or, alternatively, provide a given level of precision with the smallest number of replications. Randomization is essential to avoid anomalies in interpretation of results from systematic assignment of treatments to field plots. The most common experimental designs used in soil fertility and plant nutrition experiments are: complete randomized design, randomized complete block design, and split-plot design (Fageria 2006).

(6) ***Selection of the treatments*:**
A treatment is a single entity in an experiment, and a treatment design refers to the selection of the treatments to be included in an experiment and is one of the components of statistical design (Federer 1979). Selection of the appropriate treatment is one of the most important steps in testing the hypothesis formulated and defined objectives. When defining an optimum level of a nutrient

for a crop in a particular soil, a minimum of five rates should be included to achieve a satisfactory response curve. In such an experiment, a control treatment should always be included to compare the results of fertilized plots.

(7) ***Use of adequate seed rate, row, and plant spacing*:**
In sowing, care should be taken of adequate seed rate, row spacing, plant spacing, and sowing depth. In addition, seeds should be treated with appropriate fungicide and insecticides to minimize disease and insect problems.

(8) ***Cultural practices*:**
After proper installation, proper management of experiment in the field is as important as proper planning. If it is desired that the experiment give valid results, all other variables should be at an adequate level except that or those under study. If an experiment is designed to test levels of soil fertility for a particular crop on a particular soil, all other factors such as weeds, diseases, and insects should be controlled. Similarly, soil moisture should be at an adequate level. All management practices should be conducted on a block basis to control any variation that may occur in the management and operation processes (Fageria 2006).

(9) ***Collection of data*:**
In a soil fertility experiment, data should be collected for plant, soil, water and climate parameters. In relation to plant grain, yield is the most important plant parameter to measure the effects of an applied treatment under field condition. Grain yield refers to the weight of clean and dry grains harvested from a unit area. After discarding border areas on all four sides of a plot, harvest as large an area as possible. Dry matter yield should also be determined to obtain data regarding nutrients accumulation by a crop during the season. In cereals, this can be done at harvesting. In case of legumes, the appropriate time of plant sampling for dry matter determination is around flowering, when dry matter accumulation is supposed to be at maximum. During harvest time, most of the legume leaves fall down, and therefore, do not give good measure of dry matter accumulation (Fageria 2006).

(10) ***Harvesting at physiological maturity*:**
Harvesting at the appropriate time of a crop is an important step in a field experiment to have the right estimate of yield. The crop should be harvested at physiological maturity. If harvesting is delayed after physiological maturity the yield may be reduced owing to shattering of grains or a large percentage of grains falling during harvesting. Moreover, harvesting at inappropriate times may reduce the quality of grains. Physiological maturity of a crop can be determined by a systematic sampling and dry weight determination of grains. When no further increase in grain dry weight is observed, the plant is said to have reached physiological maturity. Data regarding appropriate grain moisture content for harvest of cereals and legume crops are available as a reference point (Fageria 1992). Research plots are generally harvested manually and threshed with a stationary thresher. This is a very effective method for breeding research where samples must be kept pure. However, in soil fertility experiments, small plot combines can be used for harvesting where absolute

seed purity is not necessary. Mechanical harvesting equipment has been developed to reduce labor requirements in field research (Fageria 2006).

(11) ***Replication of field experiment at least for* 2 *years*:**
The use of an adequate statistical method in data analysis is an essential experimental technique. The experimental and treatment designs dictate the proper method of statistical analysis and the basis for assessing the precision of treatment means. The aim of a statistical analysis of data from an agronomic experiment is to provide as much information as possible about the way the experimental units respond to the applied treatments. The common first step in statistical analysis is to subject the data to an analysis of variance to determine whether or not significant differences exist among the treatment means. The data are then further analyzed in an attempt to explain the nature of the response in more detail. A number of statistical procedures may be used for this purpose: (i) fitting response functions using regression techniques, (ii) planned sets of contrasts among means, or groups of means, and (iii) pairwise multiple comparison procedures. All the above cited procedures may not applicable to all situations (Petersen 1977).

(12) ***Duration of the experiment*:**
It is very difficult to define an optimum duration of a soil fertility field experiment. Information on field experiments conducted only 1 year to several years can be found in the literature. An experiment is normally done to test a hypothesis. When the hypothesis is tested and objectives are achieved, the experiment is terminated. A soil fertility field experiment needs to be conducted for several years due to variability in environmental factors from year to year and even within a season of the same year. By repeating the experiment several years, it is possible to have average values of the applied treatment under different environmental conditions. This value can serve as a basis for making fertilizer recommendations for a particular crop under a given agro-ecological region. In addition, a long-term experiment permits a measurement of the effect of the treatment on build-up or depletion of nutrients in the soil, change in soil pH, and organic matter content of the soil. Further, long-term fertility experiment can be useful in providing information on sustainability of a farming system under use (Fig. 5; Fageria 2006).

Therefore, it could be concluded that, field experiments are the basic needed to evaluate nutritional requirements under different agro-ecological regions. It is very hard to transfer experimental results from one region to another due to differences in soil properties, climate, and social-economical conditions of the farmers. All these factors determine the technological development and its adaptation by the farmers. In conducting field experimentation, certain basic principles should be followed to arrive at meaningful conclusions. These field experiments will help the agricultural scientists in the planning and execution of the research trials mainly concerned with the field of soil fertility and plant nutrition. A researcher should follow these steps for achieving successful results. These considerations are hypothesis and objectives should be well defined, selection of appropriate experimentation

Fig. 6 Different field experiments can be used and carried out on different crops such as vegetables, fruits, and field crops. These field experiments will help the agricultural scientists in the planning and execution of the research trials mainly concerned with the field of soil fertility and plant nutrition (Photos from field experiments in Egypt and Italy by H. El-Ramady and M. Fári)

site, adequate land preparation, appropriate plot size, shape, and orientation, selection of appropriate experimental design, selection of adequate nutrient levels or treatments, use of adequate seed rate, row, and plant spacing, conducting required cultural practices such as control of insects, diseases, weeds, topdressing N, and irrigation, collection of yield and yield data components, harvesting at physiological maturity, replication of field experiment at least for 2 years, use of adequate statistical methods for data analysis, and finally appropriate divulgation of experimental results in scientific journal, book chapters, or technical bulletins (Fig. 6).

Conclusion

Research in agriculture is a complex process and demands constant efforts and experimentation due to change in weather conditions, difference in soil properties, difference in adaptation of crop species and different socio-economical conditions of the farmers. Soil fertility and plant nutrition research like any agricultural research involves laboratory *in vitro*, hydroponics, greenhouse or growth chamber, pot and field experimentation. Field experiments are the basic needed to evaluate nutritional requirements under different agro-ecological regions. It is very hard to transfer experimental results from one region to another due to differences in soil properties, climate, and social-economical conditions of the farmers. Soil fertility is one of the important factors in determining crop yields. Further, maintaining soil fertility at an appropriate level is also vital for sustainable agriculture and in reducing environmental pollution. To achieve these objectives, research data are required for different agroecological regions for different crops and cropping systems. A good research project involving experimentation should have appropriate planning to get meaningful results. The planing includes well defined objectives based on priority of problems and to achieve these objectives experimental methodology should be adequate. Statistical analysis and interpretation of experimental data are as important as planning and execution of the experiments.

Acknowledgment Dr. Hassan El-Ramady acknowledges Hungarian Ministry of Education and Culture (Hungarian Scholarship Board, **HSB** and the Balassi Institute) and the Egyptian Ministry of Higher Education (The Partnership and Ownership initiative, **ParOwn** grant) for funding and supporting this work. He also thanks Prof. N. K. **Fageria**, National Rice and Bean Research Center of EMBRAPA, Brazil for his support and help. The authors also acknowledge Prof. **Eric Lichtfouse** for his support and revising this work.

References

Alexander T (2001) The NFT lettuce & herb conference and workshop. Growing Edge 12(4):12–15

Andrew CS, Johnson AD, Sandland RL (1973) Effect of aluminum on the growth and chemical composition of some tropical and temperate pasture legumes. Aust J Agric Res 24:325–339

Armstrong JS, Sperry T (1994) Business school prestige: research versus teaching. Energ Environ 18(2):13–43

Baligar VC, Fageria NK, He ZL (2001) Nutrient use efficiency in plants. Commun Soil Sci Plant Anal 32:921–950

Bennett WF (1993) Plant nutrient utilization and diagnostic plant symptoms. In: Bennett WF (ed) Nutrient deficiencies and toxicities in crop plants. The American Phytopathological Society, St. Paul, pp 1–7

Bergmann W, Cumakov A (1977) Diagnosis of nutrient requirement by plants. G. Fischer Verlag/Priroda, Jena/Bratislava, 295 (Cz)

Berthelot A (1934) Nouvelles remarques d'ordre chimique sur le choix des milieux de culture maturels et sur la manière de formules des milieux synthétiques. Bull Soc Chim Biol Paris 16:1553–1557

Beruto M, Curir P, Debergh P (1999) Influence of agar on *in vitro* cultures II. Biological performance of Ranunculus on media solidified with three different agar brands. In Vitro Cell Dev Biol Plant 35:94–101

Beytes C (2003) Ball redbook: greenhouse and equipment, vol 1, 17th edn. Ball Publishing, Batavia

Bodenheimer FS (1958) The history of biology: an introduction. Dawson, London

Bone J, Head M, Barraclough D, Archer M, Schei C, Flight D, Voulvoulis N (2010) Soil quality assessment under emerging regulatory requirements. Environ Int 36:609–622. doi:10.1016/j.envint.2010.04.010

Borlaug NE (2007) Feeding a hungry world. Science 318:359

Borlaug NE, Dowswell CR (1994) Feeding a human population that increasingly crowds a fragile planet. Paper presented at 15th world congress of soil science, 10–16 Jul 1994. World Congress of Soil Science, Acapulco

Bowen HJM (1979) Environmental chemistry of the elements. Academic, New York, 333

Brady NC, Weil RR (2002) The nature and properties of soils, 13th edn. Prentice Hall, Upper Saddle River

Brady N, Weil R (2008) The nature and properties of soils, 14th edn. Prentice Hall, Upper Saddle River

Brevik EC (2009) Soil, food security and human health. In: Verheye WH (ed) Soils, plant growth and crop production, Encyclopedia of life support systems (EOLSS). Developed under the Auspices of the UNESCO, Eolss Publishers, Oxford. http://www.eolss.net, Retrieved 23 Aug 2012

Browne CA (1944) A source book of agricultural chemistry. Chronica Botanica, Waltham

Buol SW, Southard RJ, Graham RC, McDaniel PA (2003) Soil genesis and classification. Wiley Blackwell, Ames, Iowa State University Press, USA

Burkart MR (2007) Diffuse pollution from intensive agriculture: sustainability, challenges and opportunities. Water Sci Technol 55:17–23

Cakmak I (2001) Plant nutrition research: priorities to meet human needs for food in sustainable ways. In: Horst WJ, Schenk MK, Burkert A et al (eds) Plant nutrition: food security and sustainability of agro-ecosystems. Kluwer, Dordrecht, pp 4–7

Chaillou S, Chaussat R (1986) Changes in mineral concentration of potato organ fragments cultured in vitro. Phytomorphology 36:263–270

Chang DC, Park CS, Kim SY, Lee YB (2012) Growth and tuberization of hydroponically grown potatoes. Potato Res 55:69–81. doi:10.1007/s11540-012-9208-7

Chapman HD (1972) Diagnostic criteria for plants and soils. University of California, Riverside, 793

Clark RB (1982) Nutrient solution growth of sorghum and corn in mineral nutrition studies. J Plant Nutr 5:1039–1057

Collis-George N, Davey BG (1960) The doubtful utility of present day field experimentation and other determinations involving soil-plant interactions. Soil Fertil 23:307–310

Cooper AJ (1975) Crop production in recirculating nutrient solution. Sci Hortic 3:251–258

Council of the European Union (2009) Proposal for a directive of the European Parliament and of the council establishing a framework for the protection of soil–political agreement = presidency proposal. Council of the European Union, Brussels (cited from Bone et al. 2010)

De Klerk GJ, Wijnhoven F (2005) Water retention capacity of tissue cultured plants. Prop Orn Plants 5:14–18

Devries J (2003) Hydroponics. In: Beytes C (ed) Ball redbook: greenhouses and equipment, vol 1, 17th edn. Ball Publishing, Batava, pp 103–114

Eastwood T (1947) Soilless growth of plants, 2nd edn. Reinhold Publishing, New York

Elliott B (1989) Commercial trends in hydroponics. In: Korney S (ed) Proceedings of the 10th annual conference on hydroponics. Hydroponic Society of America, Concord, pp 59–66

Eltinge ET, Reed HS (1940) The effect of zinc deficiency upon the root of *Lycopersicon esculentum*. Am J Bot 27:331–335

Environment Agency (2004) The state of soils in England and Wales. Environment Agency, UK (cited from Bone et al. 2010), Bristol

Epstein E (2000) The discovery of the essential elements. In: Kung SD, Yang SF (eds) Discoveries in plant biology, vol 3. World Scientific, Singapore, pp 1–16
Epstein E, Bloom AJ (2005) Mineral nutrition of plants: principles and perspectives, 2nd edn. Sinauer Associates, Sunderland
European Commission (EC) (2006) Soil protection: the story behind the strategy. European Commission, Brussels
Ewert F, Rounsevelle MDA, Reginster I, Metzger MG, Leemans R (2005) Future scenarios of agricultural land use. I. Estimating changes in crop productivity. Agric Ecosyst Environ 107:101–116
Fageria NK (1992) Maximizing crop yields. Marcel Dekker, New York
Fageria NK (2005) Soil fertility and plant nutrition research under controlled conditions: basic principles and methodology. J Plant Nutr 28:1975–1999. doi:10.1080/01904160500311037
Fageria NK (2006) Soil fertility and plant nutrition research under field conditions: basic principles and methodology. J Plant Nutr 30:203–223. doi:10.1080/01904160601117887
Fageria NK (2009) The use of nutrients in crop plants. CRC Press, Boca Raton
Fageria NK, Baligar VC (2005) Nutrient availability. In: Hillel D (ed) Encyclopedia of soils in the environment. Elsevier, San Diego, pp 63–71
Fageria NK, Barbosa Filho MP, Garber JJ (1982) Adequate nutrient levels and plant density in greenhouse experiments for rice. Pesq Agropec Bras 17:1279–1284
Fageria NK, Baligar VC, Jones CA (1997) Growth and mineral nutrition of field crops, 2nd edn, Books in soils, plants and the environments series. Marcel Dekker, New York
Fageria NK, Baligar VC, Clark RB (2002) Micronutrients in crop production. Adv Agron 77:185–268
Fageria NK, Baligar VC, Jones CA (2011) Growth and mineral nutrition of field crops, 3rd edn, Books in soils, plants, and the environment series. CRC Press, Boca Raton
FAO (1996) Declaration on world food security. World food summit. FAO, Rome
FAO (2000) Fertilizer requirements in 2015 and 2030. FAO, Rome
FAO (2006) Plant nutrition for food security—a guide for integrated nutrient management. In: Roy RN, Finck A, Blair GJ, Tandon HLS (eds) Fertilizer and plant nutrition bulletin, vol 16. Food and Agriculture Organization of the United Nations, Rome
Farran I, Mingo-Castel AM (2006) Potato minituber production using aeroponics: effect of plant density and harvesting intervals. Am J Potato Res 86:47–53
Federer WT (1979) Statistical designs and response models for mixtures of cultivars. Agron J 71:701–706
Fedoroff N (2004) Soils. In: Cilek V (ed) Earth system: history and natural variability, Encyclopedia of life support systems (EOLSS). Developed under the Auspices of the UNESCO, Eolss Publishers, Oxford. http://www.eolss.net/. Retrieved 26 Aug 2012
FMENCNS, Federal Ministry for the Environment Nature Conservation and Nuclear Safety (1998) Federal soil protection act of 17 march 1998. Federal Ministry for the Environment Nature Conservation and Nuclear Safety, Bonn (cited from Bone et al. 2010)
Fynn P, Endres B (1994) Hydroponic rose production. In: Bates P, Korney S (eds) Proceedings of the 15th annual conference on hydroponics. Hydroponic Society of America, San Ramon, pp 1–10
Gartrell JW, Robson AD, Loneragan JF (1979) A new tissue test for accurate diagnosis of copper deficiency in cereals. J Agric West Aust 20:86
Gautheret RJ (1939) Sur la possibilité de réaliser la culture indéfinie des tissus tubercule de carotte. Compt Rend Acad Sci Paris 208:118
George EF, Hall MA, De Klerk G-J (2008) The components of plant tissue culture media I: macro- and micro-nutrients. In: Plant propagation by tissue culture. Vol. 1: The background, 3rd edn. Springer, Dordrecht, pp 65–113
Gerendás J, Polacco JC, Freyemuth SK, Sattelmacher B (1999) Significance of nickel for plant growth and metabolism. J Plant Nutr Soil Sci 162:241–256
Gericke WF (1929) Aquaculture: a means of crop production. Am J Bot 16:862
Gericke WF (1937) Hydroponics crop production in liquid culture media. Science 85:177–178
Gericke WF (1940) Complete guide to soilless gardening. Prentice Hall, New York

Giloli G, Baumgärtner J (2007) Adaptive ecosystem sustainability enhancement in Sub-Saharan Africa. Ecohealth 4:428–444

Gislerod HR, Kempton RJ (1983) The oxygen content of flowing nutrient solutions used for cucumber and tomato culture. Sci Hortic 20:23–33

Glass ADM (1989) Plant nutrition: an introduction to current concepts. Jones & Bartlett Publishers, Boston

Glasstone VFC (1947) Inorganic micronutrients in tomato root tissue culture. Am J Bot 34:218–224

Gomez KA (1972) Techniques for field experiments with rice. International Rice Research Institute, Los Banos

Gomez KA, Alicbusan RC (1969) Estimation of optimum plot size from rice uniformity data. Philip Agric 52:586–601

Gough RE (1993) Glossary of vital terms for the home gardener. Food Products Press, New York

Grosser S (2003) Gutter-connected greenhouses. In: Beytes C (ed) Ball redbook, vol 1, 17th edn. Ball Publishing, Batavia, pp 7–12

Guan H, De Klerk GJ (2000) Stem segments of apple microcuttings take up auxin predominantly *via* the cut surface and not *via* the epidermis. Sci Hortic 86:23–32

Hanan JJ (1998) Greenhouse: advanced technology for protected horticulture. CRC Press, Boca Raton

Hannay JW, Street HE (1954) Studies on the growth of excised roots. III. The molybdenum and manganese requirement of excised tomato roots. New Phytol 53:68–80

Harris D (1977) Hydroponics: the gardening without soil. Pumell & Sons, Cape Town

Harrison R, Strahm B, Yi X (2009) Soil education and public awareness. In: Verheye WH (ed) Soils, plant growth and crop production, Encyclopedia of life support systems (EOLSS). Developed under the Auspices of the UNESCO, Eolss Publishers, Oxford. http://www.eolss.net/. Retrieved 26 Aug 2012

Havlin JL (2005) Fertility. In: Hillel D (ed) Encyclopedia of soils in the environment. Elsevier Ltd., San Diego, pp 10–19

Heller R (1953) Researches on the mineral nutrition of plant tissues. Ann Sci Nat Bot Biol Vg 11th Ser 14:1–223

Henao J, Baanante C (2006) Agricultural production and soil nutrient mining in Africa. International Fertilizer Development Center, Muscle Shoals, p 13

Hewitt EJ (1966) Sand and water culture methods used in the study of plant nutrition. Commonwealth Agriculture Bureaux, Bucks, 547

Hoagland DR, Arnon DI (1950) The water culture method for growing plants without soil. In: California agriculture experimental station circular 347. College of Agriculture, University of California, Berkeley, 32 pp

Hoagland DR, Martins JC, Stewart GR (1920) Relation of the soil solution to the soil extract. J Agric Res 20:381–395

Horrigan L, Lawrence RS, Walker P (2002) How sustainable agriculture can address the environment and human health harms of industrial agriculture. Environ Health Perspect 110:445–456

Houghland GVC (1950) An improved technique for growing potatoes in solution cultures. Am Potato J 27:257–262

Ingram JSI, Gregory PJ, Izac AM (2008) The role of agronomic research in climate change and food security policy. Agric Ecosyst Environ 126:4–12

Jenny H (1941) Factors of soil formation. McGraw-Hill Company, New York, 281 pp

Jensen MN (1995) Hydroponics of the future. In: Bates M (ed) Proceedings of the 16th annual conference on hydroponics. Hydroponic Society of America, San Ramon, pp 125–132

Jensen MN (1997) Hydroponics. Hortic Sci 32(6):1018–1021

Jensen MH (1999) Hydroponics worldwide. Acta Hortic 2:719–730

Jensen MN, Malter AJ (1995) Protected agriculture: a global review. World Bank technical paper #253. The World Bank, Washington

Johnson CM, Stout PR, Broyer TC, Carlton AB (1957) Comparative chlorine requirements of different plant species. Plant Soil 8:337–354

Jones JB (1982) Hydroponics: its history and use in plant nutrition studies. J Plant Nutr 5:1003–1030
Jones JB Jr (2003) Agronomic handbook—management of crops, soils, and their fertility. CRC Press, Boca Raton
Jones JB Jr (2005) Hydroponics—a practical guide for the soilless grower, 2nd edn. CRC Press, Boca Raton/London/New York/Washington, DC
Kabata-Pendias E (2011) Trace elements in soils and plants, 4th edn. CRC Press/Taylor & Francis Group, Boca Raton
Kabata-Pendias A, Mukherjee AB (2007) Trace elements from soil to human. Springer-Verlag, Berlin/Heidelberg/New York
Kirkby E (2012) Introduction, definition and classification of nutrients. In: Marschner P (ed) Marschner's mineral nutrition of higher plants. Elsevier Ltd., Amsterdam, pp 1–5. doi:10.1016/B978-0-12-384905-2.00001-7
Knudson L (1922) Non-symbiotic germination of orchid seeds. Bot Gaz 73:1–25
Lal R (1995) Erosion–crop productivity relationships for soils of Africa. Soil Sci Soc Am J 59:661–667
Lal R (2004) Soil and its life support systems. In: Lal R (ed) Agricultural sciences, Encyclopedia of life support systems (EOLSS). Developed under the Auspices of the UNESCO, Eolss Publishers, Oxford. http://www.eolss.net/. Retrieved 28 Aug 2012
Lal R (2006) Managing soils for feeding a global population of 10 billion. J Sci Food Agric 86:2273–2284
Lal R (2007) Technology without wisdom. Crop Soils Agron News 52:12–13
Lal R (2008). Soils and sustainable agriculture: a review. In: Lichtfouse E et al (eds) Sustainable agriculture. Springer Science+Business Media B.V. – EDP Sciences 2009, pp 15–23. doi:10.1007/978-90-481-2666-8_3
Lal R (2009) Soil degradation as a reason for inadequate human nutrition. Food Sec 1:45–57. doi:10.1007/s12571-009-0009-z
Lester PM (1998) Visual communication: images with messages. Cengage Learning, Portland, 464 pp
Lommen WJM (2007) The canon of potato science: 27 hydroponics. Potato Res 50:315–318
Lopez-Bucio J, Cruz-Ramirez A, Herreraestrella L (2003) The role of nutrient availability in regulating root architecture. Curr Opin Plant Biol 6:280–287
Marschner H (1983) General introduction to the mineral nutrition of plants. In: Lauchli A, Bieleski RL (eds) Encyclopedia of plant physiology, New series, vol 15A. Springer-Verlag, New York, pp 5–60
Marschner H (1995) Mineral nutrition of higher plants, 2nd edn. Academic Press, New York
McLaughlin MJ (2001) Bioavailability of metals to terrestrial plants. In: Allen HE (ed) Bioavailability of metals in terrestrial ecosystems. Importance of partitioning for bioavailability to invertebrates, microbes and plants. SETAC Press, Pensacola, pp 39–68
Mengel K, Kirkby EA, Kosegarten H, Appel T (2001) Principles of plant nutrition, 2nd edn. International Potash Inst, Berne
Mortvedt JJ (2000) Bioavailability of micronutrients. In: Sumner ME (ed) Handbook of soil science. CRC Press, Boca Raton, pp D71–D88
Moyo D (2007) The future of food: elements of integrated food security strategy for South Africa and food security status in Africa. In: Proceedings of the annual meeting-American Society of International Law 101:103–112
Murashige T, Skoog F (1962) A revised medium for rapid growth and bio-assays with tobacco tissue cultures. Physiol Plant 15:473–497
Nhut DT, Dieu Huong NT, Khiem DV (2004) Direct microtuber formation and enhanced growth in the acclimatization of *in vitro* plantlets of taro (*Colocasia esculenta* spp.) using hydroponics. Sci Hortic 101:207–212
Nhut DT, Nguyen NH, Thuy DTT (2006) A novel in vitro hydroponic culture system for potato (*Solanum tuberosum* L.) microtuber production. Sci Hortic 110:230–234. doi:10.1016/j.scienta.2006.07.027
Nobécourt P (1937) Culture en serie des tissus végétaux sur milieux artificial. Compt Rend Acad Sci Paris 205:521–523

Okajima H (2001) Historical significance of nutrient acquisition in plant nutrition research. In: Ae N, Arihara J, Okada K, Srinivasan A (eds) Plant nutrient acquisition: new perspectives. Springer, Tokyo, pp 3–31
Oriz A, Rotatori H, Schreiber E, von Roth G (2009) Hydroponic farming in Mahasarakham. Retrieved 15 Mar 2013 from http://www.wpi.edu/Pubs/E-project/Available/E-project-030409-225133/unrestricted/15.3.2013
OVAM, Public Waste Agency of Flanders (2007) Decree on soil remediation and soil protection. Public Waste Agency of Flanders, Belgium (cited from Bone et al. 2010)
Petersen RG (1977) Use and misuse of multiple comparison procedures. Agron J 69:205–208
Postel S (1999) Pillar of sand: can the irrigation miracle last? Norton, New York, p 313
Rajaratnam JA, Lowry JB, Hock LI (1974) New method for assessing boron status of the oil palm. Plant Soil 40:417
Ramage CM, Williams RR (2002) Inorganic nitrogen requirements during shoot organogenesis in tobacco leaf discs. J Exp Bot 53:1437–1443
Raviv M, Lieth JH (2008) Soilless culture: theory and practice. Elsevier Science Ltd., Amsterdam
Reed HS (1942) A short history of the plant sciences. Ronald Press, New York
Resh HM (1995) Hydroponic food production, 5th edn. Woodbridge Press Publishing, Santa Barbara
Römheld V, Marschner H (1991) Functions of micronutrients in plants. In: Mortvedt JJ, Cox FR, Shuman LM, Welch RM (eds) Micronutrients in agriculture, 2nd edn. Soil Science Society of America, Madison, pp 297–328
Roy A (2003) Fertilizer needs to enhance production: challenges facing India. In: Lal R, Hansen DO, Uphoff N, Slack S (eds) Food security and environment quality in developing world. Lewis, Boca Raton, pp 53–68
Roy RN, Finck A, Blair GJ, Tandon HLS (2006) Plant nutrition for food security: a guide for integrated nutrient management. FAO fertilizer and plant nutrition bulletin 16. Food and Agriculture Organization of the United Nations, Rome
Royal Society of Chemistry (RSC) (2012) Securing soils for sustainable agriculture: a science-led strategy. Optimising soil chemistry for agriculture and resource efficiency (OSCAR), a workshop held at the Royal Society of Chemistry, Burlington House, London, 28 and 29 Nov 2011. http://www.rsc.org/images/081203%20OSCAR%20web_tcm18-222767.pdf/10.3.2013
Ruszkowska M, Lyszcz S, Sykut S (1975) The activity of catechol oxidase in sunflower leaves as indicator of copper supply in plants. Pol J Soil Sci 8:67
Sanchez PA, Swaminathan MS (2005) Hunger in Africa: the link between unhealthy people and unhealthy soils. Lancet 365:442–444
Sheikh BA (2006) Hydroponics: key to sustain agriculture in water stressed and urban environment. Pak J Agri Agril Engg Vet Sci 22(2):53–57
Shiva V (1991) The violence of the green revolution: third world agriculture, ecology and the politics. Zed Books, London
Sinclair TR, Park WI (1993) Inadequacy of the Liebig limiting-factor paradigm for explaining varying crop yields. Agron J 85:742–746
Singh RB (2000) Environmental consequences of agricultural development: a case study from Green Revolution state of Haryana, India. Agric Ecosyst Environ 82:97–103
Smith B (2002) The growing world of hydroponics. Part nine: lettuce and yet more lettuce. Growing Edge 13(5):79–82
Soffer H, Burger DW, Lieth JH (1991) Plant growth and development of Chrysanthemum and Ficus in aero-hydroponics: response to low dissolved oxygen concentrations. Sci Hortic 45:287–294
Soil Science Glossary Terms Committee (2008) Glossary of soil science terms. Soil Science Society of America, Madison
Soil Science Society of America (SSSA) (1997) Glossary of soil science terms. SSSA, Madison
Sonneveld C, Voogt W (2009) Plant nutrition of greenhouse crops. Springer Science+Business Media B.V.
Sonneveld C, Welles GWH (2005) Cation concentrations of plant tissues of fruit-vegetable crops as affected by the EC of the external nutrient solution and by humidity. Acta Hortic 697:377–386

Steiner AA (1985) The history of mineral plant nutrition til about 1860 as source of the origin of soilless culture methods. Soilless Cult 1(1):7–24
Stevenson FJ (1991) Organic matter-micronutrient reactions in soils. In: Mortvedt JJ, Cox FR, Shuman LM, Welch RM (eds) Micronutrients in agriculture, 2nd edn. Soil Science Society of America, Madison, pp 145–186
Stewart WM, Dibb DW, Johnston AE, Smyth TJ (2005) The contribution of commercial fertilizer nutrients to food production. Agron J 97:1–6
Stocking MA (2003) Tropical soils and food security: the next 50 years. Science 302:1356–1359
Thajun T, Van Ranst E (2005) Is highly intensive agriculture environmentally sustainable? A case study from Fugou County, China. J Sustain Agric 25:91–102
The Oxford English Dictionary (1989) Proffitt M (ed) A New English Dictionary on historical principles (NED). Oxford University Press. ISBN 978-0-19-861186-8
The Encyclopedia Americana (2000) Grolier Academic Reference. ISBN-10:0717201333
The Random House Webster's College Dictionary (1999) Random House Reference, 1600pp. ISBN-10:0375407413
The World Book Encyclopedia (1996) ISBN-10:0716600978
The New Encyclopaedia Britannica (1997) Encyclopedia Britannica Inc., April 1997. ISBN-10:085229655X
Thompson G (2002) North American Strawberry Growers Association Newsletter 27(4):1–2. State College
Tisdale SL, Nelson WL, Beaton JD (1985) Soil fertility and fertilizers, 4th edn. Macmillan, New York
Torabi M, Mokhtarzadeh A, Mahlooji M (2012) The role of hydroponics technique as a standard methodology in various aspects of plant biology researches. In: Toshiki Asao (ed) Hydroponics—a standard methodology for plant biological researches. InTech Publishing House, Rijeka
Twomlow S, Shiferaw B, Cooper P, Keatinge JDH (2008) Integrating genetics and natural resources management for technology targeting and greater impact of agricultural research in the semi-arid tropics. Exp Agric 44:235–256
Verheye W (2010) Soils and general agronomy. In: Verheye WH (ed) Soils, plant growth and crop production, Encyclopedia of life support systems (EOLSS). Developed under the Auspices of the UNESCO, Eolss Publishers, Oxford. http://www.eolss.net/. Retrieved 26 Aug 2012
Vollebrecht R (2003) Open-roof greenhouses. In: Beytes C (ed) Ball redbook, vol 1, 17th edn. Ball Publishing, Batavia, pp 13–17
VROM, The Netherlands Ministry of Housing, Physical Planning and the Environment (1986) Wet bodembescherming. Staatsblad van het Koninkrijk der Nederlanden, Netherlands (cited from Bone et al. 2010)
Wan WY, Cao W, Tibbitts TW (1994) Tuber initiation in hydroponically grown potatoes by alteration of solution pH. Hortic Sci 29:621–623
Webster's New World College Dictionary (1999) Webster's New World, 4th edn, 1744pp. ISBN-10:0028631196.
Westerman RL, Tucker TC (1987) Soil fertility concepts: past, present and future. In: Boersma LL (ed) Future developments in soil science research. Soil Science Society of America, Madison, pp 171–179
Wheeler RM (2006) Potato and human exploration of space: some observations from NASA-sponsored controlled environment studies. Potato Res 49:67–90
Wheeler RM, Mackowiak CL, Sager JC, Knott WM, Hinkle CR (1990) Potato growth and yield using nutrient film technique (NFT). Am Potato J 67:177–187
Wigriarajah K (1995) Mineral nutrition in plants. In: Pessarakli M (ed) Handbook of plant and crop physiology. Marcel Dekker, New York, pp 193–222
Yoshida S, Forno D, Cock JH, Gomez KA (1976) Laboratory manual for physiological studies of rice. International Rice Research Institute, Los Banos

Index

H. Ozier-Lafontaine and M. Lesueur-Jannoyer (eds.), *Sustainable Agriculture Reviews 14: Agroecology and Global Change*, Sustainable Agriculture Reviews 14,
DOI 10.1007/978-3-319-06016-3, © Springer International Publishing Switzerland 2014