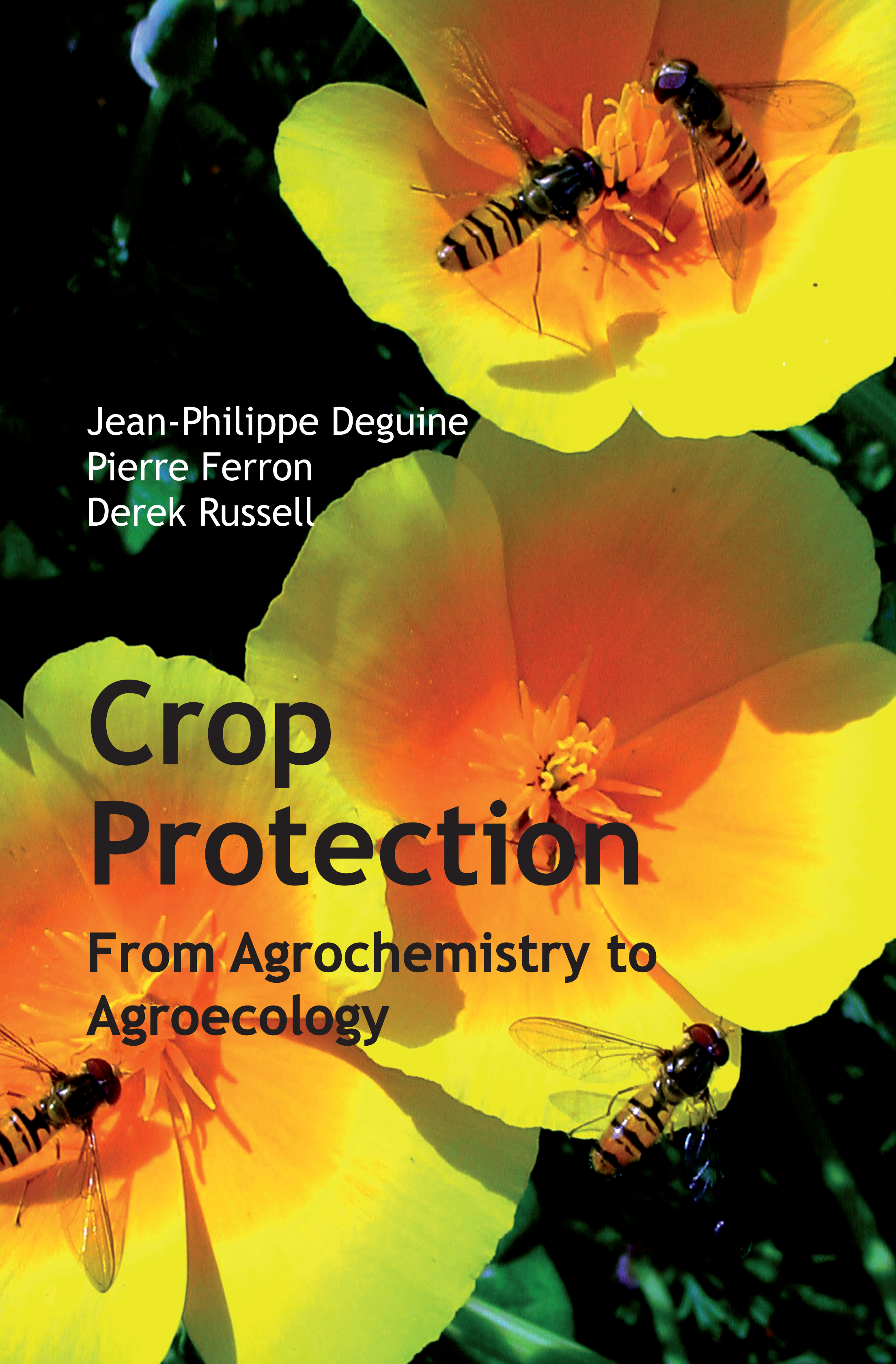

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Crop Protection

From Agrochemistry to Agroecology

CROP PROTECTION

FROM AGROCHEMISTRY TO AGROECOLOGY

Legend of the Cover

Episyrphus balteatus (Diptera: Syrphidae) the marmalade hoverfly, on the flowers of a common garden ornamental, the California poppy, *Eschlotzia californica* (photographed by Jean-Pierre Sarthou, *École Nationale Supérieure Agronomique* of Toulouse, and reproduced with kind permission of the review *Insectes*, Journal of the Office for Insects and their Environment (OPIE)).

Hoverflies, which are often confused with wasps or bees, feed as adults on pollen and nectar. Many species of hoverfly lay their eggs amongst colonies of aphids, which are avidly devoured by the hoverfly larvae. Within their life cycle, these insects alternate between the role of crop pollinators and predators of crop pests, meaning they are highly appreciated by farmers as beneficial insects. They are also considered as good indicators of the biodiversity of natural or cultivated environments.

CROP PROTECTION
FROM AGROCHEMISTRY TO AGROECOLOGY

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Foreword by Steve Wratten

This book is a synthesis and a celebration of a large body of agro-ecological research carried out on the management of the pests of cotton, one of the world's major crops and one which has historically been a very heavy consumer of inputs of pesticides. It demonstrates how agro-ecological approaches to pest management are at last approaching the 'mainstream', with an increasing recognition that farmland delivers a wide range of ecosystem services (nature's goods and services), including but certainly not solely comprising the production of food.

Biological control, pollination, soil formation, carbon dioxide capture through photosynthesis, food mitigation and methanotroph bacterial activity are all ecosystem services which farmland can provide in abundance, if properly managed. The spatial scale over which these services are delivered is also receiving increasing attention. In fact, farming is being re-defined. As a Swedish farmer once said about his profession and role in society: *"I am a photosynthesis manager and an ecosystem-service provider".* The increasing concern, however, is that ecosystem services such as biological control of pests, weeds and diseases have never been more important globally than they are now. Invasive organisms are a major threat to natural and engineered ecosystems, with biosecurity measures to mitigate and manage such incursions costing US$ billions each year. Global warming is likely to produce new pests, weeds and diseases, and change the efficacy of currently effective biological control agents. Much of current worldwide pesticide application is wasted. Insect resistance to insecticides is increasing and with increasingly-discriminating consumers in many countries, pesticide residues in food are increasingly not tolerated, nor are the external costs of pesticide use (damage to human health and the environment). Nearly two billion people worldwide are under-nourished and the prospects for the quality of life of a predicted world population growing to nine billion within a few decades are not good. This book uses a wide array of evidence to inform these important debates and makes a substantial contribution to future, sustainable agriculture. Cotton no longer tops the list of most-heavily sprayed crops, at least in some areas, and the paradigm-changing view that agriculture can deliver provisioning, supporting and regulating ecosystem services 'beyond the farm gate' is a powerful instrument of change and can lead to a form of benign 'contagion' among practitioners and the public, leading, we hope, to widespread adoption of sustainable agro-ecological innovations.

Biological control and other ecosystem services are driven by biodiversity. The latter is declining globally at the fastest rate in the history of humanity and with that decline, ecosystem services are being lost. "Substitution agriculture", with its dependence on mineral oil for fuel, pesticides and fertilisers is being practised increasingly worldwide to replace lost ecosystem services but that is not a sustainable solution. It is vital that we understand more fully the relationship between ecosystem services and biodiversity, and this is the subject of much current ecological research. Future research must be informed by that scientific debate to minimise the risk of failures in, or unexpected consequences of, agro-ecological interventions and to understand the ecological mechanisms behind success and failure. Unless, as David Tilman in the USA suggests, a new paradigm of agriculture is developed, which increases crop yield without continuing to damage vital ecosystem services, the prospects for a sustainable global supplies of fibre and heathy food are not promising. Nor are the chances of humans being able to continue to enjoy a biodiversity-rich world, with all the aesthetic and other services which biodiversity provides. Charles Darwin beatifully expressed this when he first entered a tropical forest: *'My mind is a chaos of delight'*.

Professor Stephen Wratten's early career in Zoology and Applied Entomology at London University and Cambridge University led him to the leadership of an important group at Southampton University (UK) (1975-92) working on ecological processes in Agriculture.

He has been a commanding figure in the area of habitat management for the enhancement of ecological services in agriculture and is widely published in this field in collaboration with many other workers worldwide.

Professor Wratten is the leader of a team working on sustainable agricultural systems at Lincoln University (New Zealand) where he is the Deputy-Director of the National Bio-Protection Centre, New Zealand (a NZ Government-funded Centre of Research Excellence). Dr Wratten is an elected fellow of the Royal Society of New Zealand.

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Foreword by Bernard Chevassus-au-Louis

At first glance, half a century of history of crop protection practices might seem of little interest to anyone beyond specialists. In fact, for readers interested in the epistemology of the ideas and history of science, this is a fascinating work, one which explores the fundamental questions of the dynamics of science and scientific progress, and helps us to understand the subtle interactions between the evolution of scientific tools and their underlying concepts.

If we leave aside, right from the start, the idea that we have two simplistic and opposing schema, chemical pest control versus ecologically based pest management, with each determined by reference to the other, this dialectic in fact comprises a wealth of compelling questions, sometimes disturbing but all supremely topical, such as 'Isn't the acquisition of new tools sometimes more of an obstacle than an incitement to the elaboration of new concepts?' 'Aren't these new concepts as often as not engendered by societal developments rather than by the dynamics of science?'

To try to answer these questions, this work reviews two great developmental sequences: it traces the many technological innovations produced by agronomy, chemistry, genetics and ecology over the last fifty years, and it examines the strategies eventually retained to best exploit them. Cotton is taken as the prime exemplar of these two streams of thought and work.

In the technological area, this work traces the fulfilment of the potential of synthetic chemistry—18% of all insecticides worldwide are used for cotton, even though cotton only occupies 3% of the cultivated land in the world. It covers early agricultural chemistry such as DDT, but also the products of modern chemistry and synthetic bio-pesticides. It reviews the high points of biological control, from the introduction of exotic natural enemies and the massive releases of insects sterilised by radiation, through the biotechnological use of bacteria and viruses which, in their time, were the high-tech equivalents of our modern GMOs. Plant genetics began to play a role in crop protection by developing traits of vegetative earliness, modifying the architecture or chemical composition of plants, and most recently, introducing resistance to pests and diseases through cross breeding and the use of transgenes. Finally agronomy — planting date, plant density, and fertilisation—plays both a traditional and a more modern role.

This work traces the concomitant progression of ideas revealed in the progressive emergence of the concept of 'integration' in pest management, which was defined in 1967 by the FAO in a quasi-tautological manner (Integrated Control is 'the integration of all the techniques of management...'). In practice, the idea of integration, which was initially presented as simple experimentation with combinations of several techniques—for example, chemical control combined with biological control — began slowly to engender a new paradigm, which, in many aspects, moved away from earlier approaches, including aspects of the disciplines which contributed to its emergence.

Without wishing to review all the component parts of this new vision in the preface, a number of salient issues are worth mentioning. The first is a redefinition of the relevant spatio-temporal focus of crop protection, which progressively moved from a focus on one cultivated field and its crop over the course of one vegetative cycle, to a focus on the long term—preceding crops, crop rotations, and the management of intercrops—and on the 'agronomic landscape', i.e. the spatial layout of other crops, bearing in mind that non-cultivated areas have the potential to modulate the dynamics of populations of pests and their natural enemies.

This extension of the scope of crop protection means that we have to re-examine the roles of the range of actors involved. We need to ask ourselves what procedures would be appropriate to ensure that collective strategies are applied, strategies which could, at least in the short term, penalise some of the players, for example when farmers set aside fields for ecological management. With respect to the idea of 'adaptive research', as the reader will discover, a cotton grower is not only a grower of cotton and his choices may involve other economic and social factors which limit his ability to adopt a given practice. Thus, starting from agronomy, we move progressively through environmental engineering and finally to social engineering.

This broadening of scope implies other changes which may appear counter-intuitive and so a few examples are given here. The first is the progress from the belief that a new solution is definitive and universal, which was the case with successive introductions of synthetic pesticides, biological control, and GMOs, to a more tailored approach, i.e. the combination of approaches each of which may be unsatisfactory on its own in the particular local context. This new concept, which has been called 'in-depth protection', sometimes gives rise to proposals which may be disturbing to people who tend to be dogmatic. For example, GMOs, which allow a reduction in insecticide treatments, can be combined with ecological management techniques (e.g. hedgerows as refugia) which have an impact on populations of beneficial organisms.

Also counter intuitively, defending the introduction of spatial and temporal heterogeneity as an agronomic tool may surprise those who manage major monocultures in uniform environments. The position taken in this work draws on the body of theoretical knowledge on ecological disturbances to relegitimise the role of the dynamic management of changes in the environment as a regulator of populations of pests and of natural enemies.

The priority given to the preliminary collection of data as opposed to 'blind' systematic treatment, is also a major change of perspective whose difficulties are felt as much by poorly educated small-scale farmers as by industrial farming systems where 'time is money'.

Finally, and not the least of these inversions, is the renewed interest in indigenous flora and fauna as natural allies in IPM. This interest was disrupted by decades of research into 'miracle' exotic species, but we are now encouraged to take a fresh look at elements of the countryside that have long been disdained—field borders, machinery turning circles, boggy areas — paying them at least as much attention as we do to directly productive areas.

This work therefore introduces the new approaches currently referred to as 'ecological intensification' or 'high value ecological agriculture' and shows that these approaches can incorporate two major strands of current thinking:

- The first consists in confronting ecological intensification with 'technological intensification', represented by new tools called bio-, nano- or info-technologies. Ecological intensification will certainly make use of some of these tools, but will implement them in accordance with the principles mentioned above.
- The second consists in distinguishing the beginnings of ecological engineering from the beginnings of social engineering, and explaining in simple terms the threat of 'ecotechnocracy' which transforms farmers into mere executors of regulatory measures. Ecological intensification is in fact at the core of sustainable development, which considers human beings as an integral part of ecosystems and consequently directly associates humans and the good management of ecosystems.

In conclusion, to return to our point of departure in this preface, the reader will have come to understand—and will perhaps contest—the point of view expressed in this work which to some extent rejects the commonly held idea of 'science without a conscience...'. In these times when these new techniques are sometimes condemned without the right of appeal, or are only unequivocally praised, we need to appreciate that in reality, the tools themselves are ambiguous and are — for better or for worse — only as valuable as the concepts which underlie them and justify their implementation.

Dr Bernard Chevassus-au-Louis, geneticist, is currently Inspector-General of the French Ministry of Agriculture and Fisheries. From 2002 to 2006 he was President of the National History Museum in Paris. As a researcher, he developed new methods for the genetic improvement of aquaculture species.

As Research Director, he had several responsibilities in the agriculture and food sector: as Director General of the National Institute for Agricultural Research (INRA) from 1992 to 1996 he promoted international relationships between INRA and different AROs (Agricultural Research Organisations); from 1995 to 1996 he was Chairman of EURAGRI (Association of European AROs), and he has been member of several advisory committees for international research centres in the field of agriculture and fisheries.

From 1998 to 2002, he was also Chairman of AFSSA (the French Food Safety Agency) and Vice-Chairman of CGB (the French Commission for the assessment of GMOs) during the same period.

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Preface by the Authors

The concept behind this work emerged from the meeting, well into their careers, of the three authors. Coming from different but complementary scientific backgrounds, we have taken the opportunity to confront our experiences and form our differing points of view on the philosophy and practice of the protection of crops against pests and diseases. The initial profusion of ideas was then, little by little, structured into a shared vision of the sustainable protection of crops on an agroecological basis. The second justification for this work lies in the necessity, which has become obvious to us, of crystallising and clarifying the scientific reasoning behind these applications of common agroecological principles in a context in which the inhabitants of the planet are questioning the sustainability of agricultural production and its social, environmental and health impacts; in particular the sustainability of the activities undertaken for the protection of crops from pests and diseases. Our reflections have been fed into by our daily work amongst farmers in both rich and poor countries, and by the questioning surrounding the necessity for sustainable development which has arisen within the framework of the general (but late) raising of consciousness since the United Nations Conference in Rio de Janeiro (1992).

In standing back sufficiently to be able to take a broad view of the events which have marked the spectacular development of crop protection since the middle of last century, one cannot help but be surprised to find that, despite the very significant scientific and technical progress, harvest losses are still at levels which are unacceptable in the context of poverty. To the concern of perhaps not being able to respond to food needs through to 2050, is added the worry of being unable to preserve the functioning of the fundamental ecological processes which govern the sustainable future of the biosphere.

These warnings were voiced when, for example, in the 1960s, the FAO advanced the novel concept of "integrated control" of crop pests, followed a few years later in the United States by that of "integrated pest management" or IPM, which gave a preponderant place to the concept of the management of populations of pests and beneficial organisms and which is still the predominant philosophy today. Experience has nonetheless shown that these warnings have difficulty in being heard by the players in a frenzied development context which has as its sole objective ever growing economic profitability. The easy, but ephemeral, access to sources of fossil fuel has been the engine of this process. Thanks to the selection of highly productive varieties, optimisation of the use of a range of inputs has often allowed the maximum genetic yield potential of crops to be approached, but to the detriment of the biological diversity which we now recognise as indispensable to the provision of major ecological services (pollination and the breakdown of organic matter for example) and to the sustainable functioning of ecosystems.

Today a "second Green Revolution" is in progress, putting agriculture back into its ecological context. It implies a fundamental change of values and attitudes from the time when "Man" presumed he had the right to impose his will on the submissive "Nature" of yesteryear. It defines new practices which, while meeting needs and ensuring an appropriate profitability for farmers, respects fundamental ecological processes. Bearing in mind the importance of the insect fauna, which alone represents in the order of 80% of the total biodiversity of multicellular land organisms, it is not surprising that agricultural entomologists feel particularly concerned, at least those who have survived, as, paradoxically, their scientific discipline no longer has the same fascination for students as it did a few decades ago!

It is in this particular context that we have tried initially, and as objectively as possible, to describe the development of the current state of the art of crop protection, taking as a case study the growing and protection of cotton and have then attempted a projection in time and space of agroecological solutions, for the most part novel but already demonstrated over limited areas. These recommendations have in common a respect for the principle of the management of populations though the planning of their habitats, which leads to a recognition of the need to bring together the two basic disciplines concerned, agronomy and ecology. Certainly the approach followed introduces a bias by limiting the analysis mainly to the domain of insects, when crop protection actually covers a wider spectrum of pests, weeds and the micro-organisms and viruses responsible for plant disease. Nonetheless, we have tried to make proposals which demonstrate the agroecological approach and which can be modified to encompass all pests and diseases, rather than attempting to write a handbook of pest management actions which could be envisaged in all specific pest management situations.

This work is essentially a translation from the French edition recently published by Editions QUAE (ISBN 978-2-7592-0167-9). The authors hope that, understanding this, the reader will find additional pleasure in the subtle amalgam of the French temperament with Anglo-Saxon pragmatism!

Jean-Philippe Deguine
Pierre Ferron
Derek Russell

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Contents

'An agroecological approach to agriculture involves the application of ecological knowledge to the design and management of production systems so that ecological processes are optimised to reduce or eliminate the need for external inputs. Nowhere is this more apparent than in the management of agricultural pests'.

Shennan C., Pisani Gareau T., Sirrine J. R. (1)

Introduction

Forty years ago the American journalist Rachel Carson attracted the attention of the world with the publication of her book 'Silent Spring' (2), which revealed the harmful impacts on human health and on the environment of the uncontrolled use of synthetic pesticides. At that time, the accepted strategy for the progress of developing countries was based on the growth of crop plant varieties selected for their high yields, even though these varieties were major consumers of inputs, particularly fertilisers and pesticides.

Since that time, not only has no really satisfactory solution to this dilemma been found, but the more conflicting positions have been revealed, the more disturbing and problematic it has become. Increasing demand for consumer goods, along with the realisation that we live in a finite world, are factors in an equation for which it is crucial to find a solution at the dawn of the third millennium.

This is why the scientific community was commissioned by the United Nations (UN) to evaluate the state of ecosystems (3). These studies not only showed that more than half of the services ecosystems provide to humanity were on the decline, but that the situation will probably get significantly and rapidly worse in the next 50 years. These changes are put down to the loss of diversity in living things induced by activities directed towards the satisfaction of the world's growing needs in terms of human well-being and economic development. The conclusions of the United Nations Conference on Development and the Environment in Rio de Janeiro (1992) clearly emphasised that the proper functioning of ecosystems was tightly linked to the preservation of their biological diversity. Sustainable development of the planet implies functional mastery of the management of living organisms, by preserving their habitats and by strictly limiting, indeed forbidding, practices that jeopardise their survival.

Bearing in mind the extent of the area consecrated to agriculture and livestock, i.e. around a quarter of the total area of the land surface of the earth, it is easy to see the main factor responsible for the transformation of natural biotopes. Because their specificity of action is often too broad and because their active ingredients are toxic, it is now well established that chemical plant protection products (herbicides, fungicides, insecticides, etc.) have serious secondary effects on human health and on the wider environment. However, in spite of the spectacular progress of agrochemistry, harvest losses are still a major obstacle to meeting human needs and this issue needs to be addressed.

There has been a very active search for biological alternatives to the one dominant method of pest and disease control (agrochemicals), in particular at the initiative of the United Nations Food and Agriculture Organisation (FAO) which has long promoted the concept of integrated control (1967). However, it is remarkable that right up to recent times, this long-awaited development apparently ignored the notion of eco-development which appeared in 1972. On the initiative of the International Union for the Conservation of Nature (IUCN), the science of the biology of conservation has developed for the most part outside the traditional research areas of agronomists, initially to the benefit of species at risk, then of their habitats.

Given the range of the economic players concerned, inevitable conflicts of interest partially explain this situation and have, for example, limited the use of bio-pesticides, which at one time were considered to be a possible way of protecting crops. Today, however, the position appears to be reversed with the spectacular success of bio-engineering and its use in the genetic transformation of plants. Thanks to genetically modified organisms (GMOs), which express genes that provide toxicity to certain pests, and thanks to a better understanding of the ecological phenomena involved in natural regulation of populations, it is now clear that a significant reduction in insecticide treatments favours the positive role of indigenous beneficial organisms. However, how to use these new materials and knowledge is still the subject of a number of questions including agronomic questions, because of the diversity of cropping systems and their different degrees of intensification. Delaying the evolution of resistance to chemicals or GMOs by the intelligent management of pest populations through the use of refugia represents a significant contribution to a new approach to crop protection. The planning of habitats by modifying cropping systems is part of a global movement towards sustainable development, in which agroecology has a significant role to play.

The objective of this work is to review, in their context, changes in the concepts and methods of crop protection as a function of the state of knowledge and the techniques of the time. We show that such developments imply a radical change of logic both in the underpinning philosophy and in the practices, encapsulated today by the expression "Doubly Green Revolution" credited to Michel Griffon (4). This development is illustrated using the growing of cotton as a connecting thread, providing examples from key periods and different areas of the world. Of course, growing cotton has only a limited impact on the satisfaction of human food needs, but its impact on the environment is considerable. Cotton fields have historically been a priority for the application of pesticides because of large-scale losses due to numerous pests and diseases. In exploring the development of methods and techniques for pest and disease control over the last 50 years, this work uses cotton as a case study. The lessons that can be drawn from cotton can be significantly generalised to other crop protection contexts.

The work addresses a wider informed public concerned about the problems society faces, as well as decision makers, development planners, extension staff, farmers, teachers and students at agricultural schools and colleges, and students of ecology and environmental management. It is divided into seven chapters. Chapter 1 presents the current crop protection issues. Chapter 2 gives the reasons for the choice of cotton cultivation to illustrate the case studies throughout the work. Chapter 3 is dedicated to the success of agrochemistry, but also shows how it carries within it the genesis of the pesticide treadmill which has been so disastrous for the environment. Chapter 4 deals with the concept of IPM (integrated pest management). Chapter 5 examines the difficulties of and limits to the use of chemical pesticides and compares them with the issues involved in the use of genetically modified plants. Chapter 6 reviews the agroecological bases of a new phytosanitary strategy capable of responding to the issues of the 21st Century. Chapter 7 explains new agronomic practices which ensure better preservation of the environment, revealing that it is possible to reconcile agronomy with ecology. Finally, the conclusion highlights the required changes in spatio-temporal scale, and the need to break with past behaviour if we are to contribute significantly to the development of crop protection practices which respect the principles of sustainable development.

Bibliographic References in the Introduction

(1) Shennan C., Pisani Gareau T., Sirrine J. R., 2005. Agroecological Approaches to Pest Management in the US. In: *The Pesticide Detox. Towards a More Sustainable Agriculture* (J. Pretty ed.), Earthscan, London, Sterling, VA, pp. 193-211.

(2) Carson R., 1962. *Silent Spring*. The Riverside Press, Cambridge, MA, 368 p.

(3) Millenium Ecosystem Assessment, 2005. *Ecosystems and Human Well-being: Synthesis.* Island Press, Washington, DC, 137 p.

(4) Griffon M., 2006. *Nourrir la planète.* Odile Jacob, Paris, 456 p.

CHAPTER 1

The New Issues in Crop Protection

The protection of crops and harvests has been a historic preoccupation of mankind since the first steps in agriculture 10,000 years ago. Plant extracts were used to protect stored grain well before our era and techniques of biological control were already in use in citrus orchards in China in the 8^{th} Century. The scientific bases of the discipline of agronomy are more recent and are still incomplete despite the development of the natural sciences, which provided an initial description and identification of pest species associated with crops and foodstuffs, and later an understanding of their biology and of their role in the functioning of ecosystems. For example, 1889 is a historic date in the use of beneficial insects, when ladybirds from Australia and New Zealand were released into orange groves in California to control outbreaks of scale insects. The discovery of synthetic pesticides in the 4^{th} decade of the 20^{th} Century was another epic event!

Up until 50 years ago, in the absence of appropriate experiments and techniques, few studies on crop protection paid much attention to the advantages and disadvantages of the different plant protection strategies. Nevertheless, from the end of the 19^{th} Century onwards, agronomists were putting pressure on naturalists to provide them with the bases of proven protection methods to enable them to respond to the growing public demand for consumer goods which was triggered by the success of the industrial revolution. At that time, known techniques such as collecting or trapping insects were not satisfactory, which resulted in sometimes dramatic food shortages. Amongst the classic tragic examples are the great Irish famines (1739 and then 1845-1849) caused by spectacular epidemics of potato blight, in which a total of 750,000 people died and two million emigrated to the United States. Some readers may remember that during the Second World War, collecting Colorado potato beetles in the fields by hand was one of the rare collective distractions!

For more than a century, different methods of control have been proposed with varying degrees of success including cultural practices, chemical treatments, biological or biotechnical methods, varietal selection, organic agriculture and genetic transformation of cultivated plants. In its time, each was welcomed as the long-awaited panacea, but the limits and the drawbacks of each quite rapidly became clear, demonstrating our inadequate understanding of the mechanisms involved. However, it is worth remembering that among these different methods, chemical control based on synthetic products has been the mainstay of crop protection since the middle of the 20th Century. The immediate effectiveness of the products and their ease of application ensured their success despite their lack of specificity and their toxicity to a wide range of organisms (Box 1).

BOX 1 Chronology of important steps in the recent development of crop protection (from 1, modified)

- Beginning of the 20th Century: the use of insecticide powders, mostly based on lead arsenate, was already widespread in tree fruit production and cotton cultivation.
  - 1912: first regulation concerning pest control in the United States; quarantine was introduced to prevent unwanted introductions.
  - 1914: first case of insect (San Jose scale) resistance to an insecticide.
  - 1919: the expression 'biological control' was used to describe the phenomenon of control of pests by predators or parasitoids.

- 1934: the discovery of the fungicidal properties of dithiocarbamate paved the way for the development of many contact fungicides.
- 1930-1940: the discovery of selective herbicides and the extension of the concept of selectivity to insecticides.
- 1939: the discovery of the insecticidal properties of DDT (dichlorodiphenyltrichloroethane), then of HCH (hexachlorocyclohexane), marked the beginning of the era of synthetic insecticides.
- 1946: first case of resistance to the new insecticides.

• From the 1950s to today: the chemical industry has synthesised many new pesticides.

- 1955: description of a method of insect control by releases of sterile males.
- 1959: identification of the sex pheromone of the silk worm.
- 1962: publication of 'Silent Spring' by Rachel Carson.

• End of the 1960s: first case of resistance to a herbicide, and in 1968, the appearance of the expressions 'systems for integrated pest management' and 'Green Revolution'.

- 1967: the FAO defined the concept of 'Integrated Control'.
- 1969: the United States Academy of Sciences defined the principles of the management of pest populations.
- 1972: President Richard Nixon used the expression 'integrated pest management' (IPM) in a message to Congress.
- 1987: M. A. Altieri developed the concept of agroecology and H. G. Brundtland defined sustainable development as a development which responds to the needs of the present without compromising the capacities of future generations to respond to theirs.
- 1992: signing of the Convention on Biological Diversity in Rio de Janeiro.
- 1995: sale of genetically modified crops (cotton, maize, potato) expressing entomotoxins from the bacteria *Bacillus thuringiensis.*
- 1996: the World Food Summit in Rome adopted the concept of food security.
- 2003: Dalgaard et al. defined agroecology as the study of the interactions between plants, animals, humans and their environment in the context of agricultural systems.
- 2005: Publication by the UN of the 'Summary report on the evaluation of ecosystems for the millennium', the fruit of the work of 1,300 experts from 95 countries.

- 2007: close to 115 million hectares were cultivated with genetically modified plants following a remarkable annual growth rate (+12% compared with 2006) in part because of the rush to produce biofuels (7 million ha of maize for the production of ethanol and 4.2 million ha of canola for biodiesel). Some authors envisage 200 million hectares of GMOs by 2015!

At the beginning of the 1960s, the publication of 'Silent Spring' (2) revealed to a global audience the magnitude of the environmental threats already encountered. A few years later, Jean Dorst, Professor at the French National Museum of Natural History in Paris, confirmed this alarming diagnosis in his book 'Before Nature Dies' (3). Around the same time, two events, one scientific and the other political, emphasised the ambiguity of the situation. In 1948, the Nobel prize for medicine and physiology went to a Swiss scientist, Paul Muller, for his discovery of the insecticidal properties of the DDT (dichlorodiphenyl-trichloroethane) molecule in 1939; but in 1972, the American government was the first to prohibit its use in agriculture given its harmful effects on the health and reproduction of animals due to its concentration (bioaccumulation) in the food chain. This authoritarian measure was a reaction to the environmental problems caused by the use of this particular active ingredient in crop protection, particularly in cotton. Very recently (2006), localised application of DDT at low doses was once again approved by the World Health Organisation (WHO) for the control of the mosquito vectors of malaria.

However, after the middle of the 20th Century, the strategy of global aid to enhance agricultural production considerably increased farmers' recourse to inputs, and particularly synthetic pesticides, as part of a technical revolution which came to be known as the 'Green Revolution' (1960-1990). Today this policy has been called into question for both economic and environmental reasons. However, according to experts of the International Food Policy Research Institute (IFPRI) (4), agricultural production in developing countries will have to be increased by around 70% before 2020 and even doubled by 2050.

For this reason, various hypotheses are again being explored as our understanding and techniques advance, especially with the recognition that humanity lives in a finite world and that the management of its resources is a precondition for sustainable development. This includes managing the extension of cultivated land, the increase in irrigated land, the selection of plant and animal varieties with even higher yields than those already obtained, and improving agronomic practices, further reducing harvest losses and losses during storage, managing global markets, changing food preferences, etc. Individually, none of these solutions seems to be an adequate response to the scale of the challenge. The concept of a second 'Green Revolution' based on entirely different premises is slowly making its way into the public arena.

1.1 REDUCING HARVEST LOSSES STILL FURTHER

At the beginning of the 18th Century, planet Earth had around 600 million inhabitants; today it has more than 6 billion and medium-term projections estimate the world population at 9 billion by 2050! It is easy to understand why agronomists have been unhappy. Since the 19th Century, not only have crop protection methods and the resulting harvests proved inadequate, but there has not been a sufficient increase in yields or in the efficient exploitation of agricultural land to fully meet the needs of the growing population.

By 1950 malnutrition had become critical with over 1.5 billion people affected, even though the world population had not yet reached 2.5 billion! In 1996, the World Food Summit meeting in Rome fixed the goal of reducing malnutrition by half by 2015, an ambitious target but one which was already recognised to be inadequate. Given the subsequent spectacular increase in the world population, there are probably currently around one billion victims of hunger and around 820 million people still suffer from chronic malnutrition despite all the efforts taken since the second world war.

Satisfying food needs implies availability of, and access to, food in sufficient quantities following the concept of food security adopted at the World Food Summit. Combining these criteria with the commitments made during the Earth Summit in Rio de Janeiro in 1992, enabled the face of agriculture and particularly that of crop protection and of harvests (Table 1) to be redesigned for the third millennium.

TABLE 1 Some of the new constraints faced by agriculture in the third millennium

Earth Summit (1992)	*World Food Summit (1996)*
- integrated conception of the planning and management of land use - control of deforestation, desertification and aridification - promotion of sustainable agriculture and rural development - preservation of biological diversity - protection of water resources and their quality	- availability of food products (internal self-sufficiency, improved importation, storage and food aid capacities - access (a function of purchasing power and local infrastructures) - stability (of infrastructures, political milieu and climate) - cleanliness and quality (healthiness of products and particularly access to water)

Since the 1950s, global food production per head has in fact increased by 25%, while prices have decreased by 40%. Globally, agricultural production has doubled in quantity over the last 35 years. This result was obtained thanks to the extension of agricultural land, increased productivity in exporting countries, and increased global productivity in countries with a food deficit, who hope to become self-sufficient before long. Overall, despite vigorous crop protection action, harvest losses caused by a range of pests have increased from 4 to 10% (for wheat, barley, rice, and potatoes), or have remained stable, or slightly diminished (for maize, soya, cotton, and coffee) (5). In the absence of any crop protection measures, 82% of the world rice harvest, 73% of the potato harvest, and 52% of the wheat harvest would be lost. These considerable potential losses have only been partially reduced by the systems of crop protection used in recent years, to around 55% for cotton and 34 to 38% for rice, wheat and maize, with marked regional variability. Today actual harvest losses are estimated at 26 to 30% for sugar beet, barley, soya, wheat and cotton, 35% for maize, 39% for potatoes and 40% for rice. These levels are intolerable in a context of poverty. They are due to the combined effects of weeds and the action of animals (insects, rats, etc.), and to the damage caused by the agents of plant disease (bacteria, fungi and viruses). There is consequently a large margin for improvement in pest, weed and disease management.

1.2 LEARNING LESSONS FROM THE FIRST GREEN REVOLUTION

The main component of the Green Revolution was using seeds selected for their high productivity and agronomic practices which allowed the seeds to express their potential. Along with economic facilities, these seeds were the basis of the agricultural aid programmes supported by the United Nations after the Second World War (Box 2). They were a response to the crying

BOX 2 What do we mean by the 'Green Revolution'? (6)

At the beginning, the Green Revolution could have been defined as the combination of:

- a group of production techniques for agricultural areas in the humid tropics irrigated by flooding using:
  - short-stalked and high-yielding varieties of wheat and rice,
  - fertiliser and crop health products.
- a group of supportive political measures in agriculture:
  - guaranteed purchase prices fixed in advance by the public sector
  - subsidies for fertilisers, plant protection products, and equipment,
  - increased access to credit,
  - tariff protection,
  - support for effective extension systems.

The concept was subsequently expanded to include all types of agriculture (not only irrigated but also rain-fed) and to livestock production,

- using improved varieties or breeds,
- the intensive use of chemical inputs,
- agricultural policy measures to reduce risks and improve profit margins, during a transition period to improve understanding of technological know-how.

need for basic foods in several parts of the world and particularly in Asia, by an increase in production area and in yields per unit area. These objectives were achieved, to the point at which some of the countries concerned are now able to satisfy their needs and have even started to export food. Between 1963 and 1983, total rice production increased by an average of 3.1% per year, that of wheat by 5.1% and that of maize by 3.8%. This appears to be a sustainable step towards satisfying human food requirements, even though growth subsequently slowed in the period 1983-1993, with average annual increases of 1.8% in rice production, of 2.5% in wheat, and of 3.4% in maize. This strategy was also successfully used for cotton production, particularly in the savannah of West Africa, where it took the name of 'the White Revolution'. In the period from 1961 to 1993, both the area cultivated and yields doubled, and production increased spectacularly from 50,000 to 750,000 tonnes (7).

In spite of these results, these aid policies foundered because of the high cost incurred by the functioning of the production and supply chains, and of financial systems. In his recent work 'Feeding the planet', Griffon emphasised that the related political problems of access by small-scale farmers to finance, markets, technical training and economic information, and consequently to the agrarian reform as a whole, was also a major obstacle in many countries (6). By limiting itself to the agronomic aspects of the problem, expansion of the Green Revolution avoided raising serious questions such as 'Is there a genuine hope of increasing the cultivated area of rain-fed agriculture?' 'What is the objective potential of increasing irrigation?' 'Can we reduce inputs?' 'What can be done about the plateauing of yields and the harmful effects on the environment?' The drying out of the Aral Sea during the period from 1960 to 1990 and the wind-borne pollution of the soil caused by the diversion of the water of two rivers, the Amou-Daria and the Syr-Daria, to irrigate cotton monoculture, are dramatic examples of the harmful effects of such intensification. This experience was worsened by excessive applications of organochlorine insecticides and defoliants (Box 3). In the light of our current vision of the sustainable development of the planet, this vision of the Green Revolution, although recent, seems not only to be outdated but also inappropriate.

BOX 3 The progressive drying out of the Aral Sea with disastrous ecological and environmental consequences

The Aral Sea, which in the early 20th Century, was the fourth largest landlocked body of water in the world, has undergone a 75% reduction in its surface area in less than 40 years! This is the consequence of a political decision made in the 1960s to transform a desert region into a cotton granary for the then Soviet Union.

The transformation was to be achieved by diverting two rivers, the Amou-Daria and the Syr-Daria, to irrigate around ten million hectares of cotton and rice. The excessive off-take of fresh water caused an increasingly noticeable process of soil movement. The Syr-Daria, which was artificially connected to the Caspian Sea by an irrigation canal across the Karakoum desert, lost itself in the sands around 160 km from the shores of the Aral Sea, even though the Amou-Daria carried no more than 10% of its original volume of water.

The ecological balance of the Aral Sea was profoundly modified: increases in salinity were heightened by a reduction in precipitation due to reduced overall evaporation, by a drop in the groundwater, some of which became salty, and the Aral Sea separated into two parts, the Small Sea to the north and the Big Sea to the south. The aquatic fauna underwent an almost complete depletion of its fish species, which had up to then been the basis of a flourishing fishery. The terrestrial fauna and flora of the entire region are subjected to winds laden with salt picked up by the wind from the dried up bed of the Aral Sea, the shores having receded by an average of a hundred kilometres! The arable land disappeared under a salty crust. The standard of living and the health of those who depended on the lake are badly affected in the long term.

At the beginning of the 1980s, a number of technical solutions were proposed to safeguard the system. As a result of concerted action in an evolving political context, one solution attempted by the Kazak authorities was building a sand dike to isolate the Small Sea. This initiative has recently been supported by the intervention of the World Bank (the co-financing of the Kokaral dam). Today, the Big Sea, which is only fed by subterranean sources, appears unlikely to survive in the medium term (8).

Short-term economic interests based on the size of the export crop of Uzbek cotton in particular, weighed heavily on the decisions. However, it is wrong to blame cotton production alone for the ecological disaster, even though the intensive DDT-based pesticide applications, which were repeated up to recent times, aggravated the situation by severe, persistent chemical pollution of the soils and water. A sustainable vision for the development of the region needs to begin with a review of the water management strategy and then to improve planning of the cropping systems (replacement of cotton monoculture by polyculture associated with fish rearing, for example).

1.3 ADVANCING THE CONCEPT OF RATIONAL CROP PROTECTION

Today, the problem of food security is perceived in a different context, which includes the liberalisation of markets, climate change and awareness of the limits of planetary resources. It thus makes sense to work towards significantly reducing the costs of production and to be ready to address the new crop health problems provoked by the effects of global warming on indigenous pests and by the appearance of invasive species of animals or plants, by developing new growing systems which better fit the framework of sustainable development.

Right now, we are beginning to face up to this worrying situation through the promotion, at least in the industrialised world, of an agricultural system called *'raisonné'* (reasoned) in French and 'integrated farming' in English. These expressions signal the beginning of a move towards a form of management of natural resources which, beyond abiding by the regulatory system in force, aims to strengthen the positive impacts and reduce the negative effects of agricultural practices on the environment without jeopardising economic profitability. For its promoters, it is a way of achieving sustainable development through voluntary acceptance of changes by farming enterprises. This implies reasoned planning of industrial agriculture without significantly disrupting the existing agro-business model. Several other strategies — all of which are considered to fit the framework of sustainable agriculture — have been proposed under the headings 'integrated farming' or 'farmscaping'. These include small-scale farming, traditional production, integrated production and precision agriculture, which vary in their approaches and in their sensitivity to the environment, to land use, and to technical, scientific, institutional, societal and ethical issues (9).

In France, *'agriculture raisonnée'* or 'integrated farming' is undertaken in a context that emphasises the need to take into account the environment, the mastery of plant health risks, the health and security of workers, and the well-being of animals. In the field of crop protection, this implies planning 'available cultural and biological methods, in choosing the appropriate plant varieties, and in not having recourse to chemical pesticides except when necessary and justified and then only when planned in such a way as to minimise the quantity of crop health products used' (10). The originality of this system is that it identifies the needs of the farming area which are complementary to national requirements relevant to the "good agricultural practices" discussed below. These local requirements are revealed by considering a farm in its own environmental context, and are intended to identify the actions a farm needs to implement to qualify for certification as 'integrated farming'. Connections are established between crop health strategies, management of cropping systems, and planning ecological compensation (planting trees and creating grasslands, for example) to ensure water of good quality and in the right quantities, and to respect biodiversity. Although the certification appears feasible, so far it has had only modest success. The percentage of agricultural enterprises in France that qualify using these criteria had not even reached 0.5% (around 2,500 businesses) at the end of 2007, more than three years after the national launching of the certification. It is likely that the technical and financial requirements for assessment are limiting access to the qualification.

At the European level, the programmes appear to be even more ambitious. The international organisation EISA *(European Initiative for Sustainable Development in Agriculture)*, which was established in 2001, is a federation of seven national organisations (including FARRE in France, and LEAF in the United Kingdom) whose common goal is the development and promotion of sustainable agricultural systems. In the area of crop protection, the recommended strategy is based on the establishment of a management plan for each individual enterprise (a crop protection management plan) (Box 4). These recommendations obviously target industrialised countries which have knowledgeable entrepreneurs and appropriate professional bodies. The FAO drew up recommendations for developing countries which include the implementation of good agricultural practices, while the World Bank fundamentally modified its criteria for the provision of financial support by prioritising projects relevant to sustainable development (11).

BOX 4 Foundations of a management plan in rational crop protection (12, modified)

- use appropriate strategies to avoid the emergence of resistance to different types of pesticides,
- be able to identify pests, weeds and diseases,
- take advantage of the help of a crop protection specialist,
- reorganise the fields in mosaics within the farm leaving non-treated strips at the field margins, or, if necessary, embedded within the field,
- follow a crop rotation plan,
- use trap crops for pests and host plants for indigenous natural enemies,
- leave weeds in the crop if they have not been shown to be genuine competitors, and around the field borders, to provide food for the natural fauna,
- undertake continuing education in the field of IPM,
- use decision tools to minimise the environmental impacts of planned technical solutions.

1.4 ENSURING THE MAINTENANCE OF BIODIVERSITY AND THE SUSTAINABLE FUNCTIONING OF AGROECOSYSTEMS

Even today, the concept of agriculture as a sub-set of applied ecology can shock. Yet, in 1967, the definition given by S. Hénin to agronomy (a science if ever there was one), was 'ecology applied to the production of communities of cultivated plants and to the planning of agricultural land' (13). In the contemporary history of plant protection, the 1992 Earth Summit at Rio de Janeiro undoubtedly represents a significant milestone, perhaps even more significant than the discovery of synthetic pesticides. In emphasising the importance of biological diversity for the sustainable functioning of ecosystems, it questioned the impact of agriculture, which was widely accepted as being responsible for the reduction of biodiversity and particularly emphasised the non-selective nature of chemical pest control measures. More broadly, the Earth Summit drew attention to the need to preserve the adaptive capacity of species and the functional organisation of communities in the living systems exploited by human beings. Based on comparisons of the modalities of functioning of natural ecosystems and agroecosystems, a new way of tackling agricultural problems progressively emerged, initially with the elaboration of the concept of agroecology in the tradition of the Californian school of thought (Box 5). In summarising, S. Gliessman (16) defined agroecology as the application of

BOX 5 Agroecology, definitions and interpretations

- A science proposed in the 1980s by M. A. Altieri (14), agroecology is still the subject of different definitions aimed at elaborating its principles, methods and field of application (see Chapter 7).
- T. Dalgaard et al. (15) defined agroecology as the study of the interactions between plants, animals, people and their environment within agricultural systems. As a discipline, agroecology covers multidisciplinary studies of agronomy, ecology, sociology and economics.
- S. R. Gliessman (16) defined agroecology as the application of the concepts and principles of ecology to the explanation and management of agroecosystems following a procedure that allows their conversion into sustainable production systems.
- M. A. Altieri and C. I. Nicholls (17) defined agroecology as the science of the management of natural resources for poor farmers in marginal environments.

Even though it has achieved the status of a separate scientific discipline, agroecology has thus already been the subject of confusion which is doubtless the result of rivalry between different schools of thought.

ecological principles to the explanation and management of agroecosystems following a breakthrough in procedures allowing their conversion to sustainable production systems. To this end, Gliessman initiated multidisciplinary studies associating agronomy, ecology, sociology and economics. These studies encouraged the use of approaches at temporal and spatial scales that were previously rarely taken into account in intensive agriculture, approaches which lead to the effective mobilisation of the communities of stakeholders and decision makers. His (not exclusive) focus in the application of these ideas was the small-scale farmer.

These studies confirmed the significance of the basic role of habitats in any strategy intended to preserve biodiversity. The principle is well known to hunters, who are aware of the need for good game management, and to naturalists concerned by the fact that many species are becoming rare or disappearing. For agriculturalists, for whom these practices are new, recommendations of this type have been made in vain on several occasions. In vain because they are considered to be incompatible with the intensive production systems farmers have been encouraged to try to achieve. Under the name of ecoagriculture, these ideas are now actively promoted by the crop health industry (Box 6).

BOX 6 Ecoagriculture, definition and strategy (18)

Ecoagriculture is a landscape approach to the management of natural resources which seeks to make agricultural production sustainable, and to conserve biological diversity by providing ecosystem services, while continuing to meet food requirements locally.

Strategy:

- create reservoirs of biological diversity that also benefit local agricultural communities,
- create networks of habitats in uncultivated areas,
- reduce (or reverse) the transformation of natural areas into agricultural land by increasing the productivity of agro-businesses,
- minimise pollutants used in agricultural activities,
- modify the management of resources (soil, water, vegetation),
- modify cropping systems to mimic the functioning of natural ecosystems.

Even though they are built on the same ecological and agronomic bases, agroecology and ecoagriculture are distinguishable by their respective areas of application: one addresses itself preferentially to the small-scale farmer, the other to large-scale industrial agriculture, with objectives that are apparently so different that they alarmed the managing body of the International Union for the Conservation of Nature (IUCN) (19). Ecoagriculture considers an increase in the productivity of agricultural land through the production techniques of precision agriculture to be a priority. Precision techniques allow localised and differentiated application of seed, fertiliser or pesticide, in different areas of the same field, as a function of the variability of soil fertility or of the precise distribution of pests and diseases. The environmental measures envisaged are essentially focussed on the field margins. On the other hand, according to M. A. Altieri, agroecology, by preferentially targeting the small-scale farmer, emphasises production techniques that effectively mimic the natural functioning of ecosystems while considering agrarian structures in their totality, whether cultivated or not. However, in a recent report, a development of the concept of ecoagriculture was presented by the authors of this new paradigm, S. Scherr and J. McNeely, who now consider rural landscape planning to be the main objective, requiring the preservation of biodiversity. It is worth pointing out that this latest development removes all reference to the scientific bases of agroecology (20).

In practice, the two approaches are complementary but they have not yet been integrated into a coherent whole, which could overcome the differences between the two schools of thought, reconcile their arguments, and even overcome the antagonism between pressure groups on both sides. The similarity between the names of these two approaches need not cause confusion. One, agroecology, is directly connected to fundamental science, while the other, ecoagriculture, is by nature a technological application to agriculture of knowledge acquired elsewhere. Nevertheless, different interpretations can be made and distinctions drawn between the two different strategies, no doubt because of the economic importance of the issues linked to the possible development of agrarian systems. This situation recalls the adoption of the concepts of IPM 30 years ago, which was characterized by a large number of different definitions which ended up masking the underlying concepts (see Chapter 4). In this controversial context we also include the practice of organic agriculture, which is characterised by its refusal to use synthetic chemical inputs such as fertilisers and pesticides, but also GMOs. Organic agriculture is certainly an area of investigation and experimentation that needs to be taken more fully into account than in the past. In Europe, since 2005, under the Luxembourg Accord, the new Common Agricultural Policy (CAP) states that the payment of direct aid is governed by certain criteria, particularly environmental criteria. Some research organisations, including CIRAD (Centre for International Agronomic Co-operation in Agronomic Research for Development) in France, recently embraced this development by proposing a new scientific strategy called 'ecological intensification', which they define as "an alternative to production underpinned by the consumption of inputs, which profits from functional biodiversity and from biological regulatory systems to manage the different functions of agro systems: protection against erosion, maintenance or restoration of fertility, symbiotic fixation of nitrogen, recycling of mineral elements, and protection from pests and weeds" (21).

This new orientation is supported by the conclusions of the expert report by around 400 international experts of IAASTD (International Assessment of Agricultural Science and Technology) assembled under the auspices of the World Bank and the UN (22) and published in 2008. Launched in 2002 during the World Summit on Sustainable Development in Johannesburg, this evaluation dealt with modern science and technology alongside local and traditional knowledge and with the productivity and impact of agricultural activities on the environment. The aim of the evaluation was to propose solutions for the worsening food crisis facing the developing world at the beginning of the third millennium. According to an analysis by the World Bank (23), the spectacular progress achieved in the field of biotechnology applied to industrial agriculture is not easily transferable, given the huge number of small-scale farmers in the developing world, due to inadequate investment in ensuring the expression of the agronomic potential of improved varieties. However, the success of genetically modified cotton among small-scale farmers in China — and now to a similar extent in India — make it clear that it would not be prudent to generalise the conclusions of this analysis and that the diversity of socio-economic and agronomic circumstances should be kept in mind.

The above-mentioned IAASTD expert panel recommended strategic reorganisation of aid policies to target improvement in productivity, profitability and in the viability of small-scale farming operations through an innovative agroecological process which takes local and community knowledge into account. By prioritising the production of subsistence crops, food security would be favoured. The multifunctional character of agriculture — economic, social and environmental—which often gives rise to offensive comparisons with the high production model of industrial agriculture, also needs to be recognised.

The IAASTD recommendations proposed strengthening agroecological research, which is considered to favour the productivity and sustainability of local agriculture. Addressing itself essentially to the countries of the tropical South, where crop health constraints often constitute a production bottleneck, research into the agroecological management of pests is seen as a priority. This fits well with the orientation proposed in this work which, however, also concerns intensive agriculture.

Bibliographic References in Chapter 1

(1) Norris R. F., Caswell-Chen E. P., Kogan M., 2003. *Concepts in Integrated Pest Management.* Prentice Hall, Upper Saddle River, N.J., 586 p.

(2) Carson R., 1962 (see reference n° 2 of the introduction)

(3) Dorst J., 1969. *Avant que nature meure.* Delachaux Nestle, Paris, 424 p.

(4) Yudelman M., Ratta A., Nygaard D., 1998. Pest Management and Food Production. Looking to the Future. *IFPRI, Discussion Paper 25,* Washington, D.C., 53 p.

(5) Oerke E.-C., 2006. Crop losses to pests. *Journal of Agricultural Science,* 144, 31-43.

(6) Griffon M., 2006 (see reference n° 4 of the introduction)

(7) Fok M., 1995. Le coton en Afrique francophone: revolution verte ou evolution institutionnelle? *In: Succès et limites des révolutions vertes. Séminaire* (M. Griffon, ed.), 6 septembre 1995, Montpellier, 80-92, CIRAD, Montpellier.

(8) Parriaux A., Hertig J. A., Berthoud G., 2007. *Le Projet Aral.* Rapport d'études de Master. Ecole Polytechnique Fédérale de Lausanne, section du Génie Civil. UE Environnement et Génie Civil, 203 p.

(9) CIVAM, 2002. Evaluer la durabilité d'un systéme de production. Approche globale, méthodes et diagnostics. *Cahiers techniques de l'agriculture durable,* avril 2002, 60 p.

(10) Ministére de l'Agriculture et de la Pêche, 2002. Référentiel de l'agriculture raisonnée. CSO du 8 janvier 2002, 26 p. <www.agrisalon.com/AR080102.pdf> (consulted August 17, 2008).

(11) Rajalahti R., Lagnaoui A., Schilhorn-van Veen, Pehu E., 2005. *Sustainable Pest Management: Achievements and Challenges.* The World Bank, Agriculture and Rural Development, Washington, D.C., 42 p.

(12) EISA, 2006. Dispositif européen de l'agriculture raisonnée. <http://www.sustainable-agriculture.org> (consulted April 10, 2007).

(13) Henin S., 1967. Les Acquisitions techniques en production végétale et leur application. *Economie rurale,* 74, 37-44.

(14) Altieri M. A., 1987. *Agroecology: The scientific basis of alternative agriculture.* Westview Press, Boulder, CO, 227 p.

(15) Dalgaard T., Hutchings N. J., Porter J. R., 2003. Agroecology, scaling and interdisciplinarity. *Agric. Ecosys. Environ.,* 100, 39-51.

(16) Gliessman S. R., 2004. Integrating Agroecological Processes into Cropping Systems Research. *In: New Dimensions in Agroecology* (Clements D., Shrestha A., eds.), Food Product Press, The Haworth Press, Inc., Binghampton, NY, 61-80.

(17) Altieri M. A., Nicholls C. I., 2005. *Agroecology and the search for a truly sustainable agriculture.* UNEP, Mexico, 290 p.

(18) Scherr S. J., Meredith A., 2005. *Ecoagriculture outcome measures.* Technical Workshop Report. Ecoagriculture Partners, Washington, D.C., 23 pp., <http://www.ecoagriculturepartners.org/resources/publications.php> (consulted May 14, 2006).

(19) Farvar M. T., 2004. Ecoagriculture : A Trojan horse for agricultural multinational corporations to enter IUCN ? *CEESP Occasional Papers 3,* November 2004, 2-6.

(20) Scherr S. J., McNeely J. A., 2008. Biodiversity conservation and agricultural sustainability: towards a new paradigm of "ecoagriculture" landscape. *Phil. Trans. R. Soc. B 363,* 477-494.

(21) CIRAD, 2007. Le sens d'une évolution. <http://www.cirad.fr/fr/le_cirad/pdf/sens_evolution.pdf> (consulted May 5, 2007).

(22) IAASTD, 2008. Executive summary of the synthesis report of the international assessment of agricultural knowledge, science and technology for development. April 2008, Johannesburg, South Africa, <http://www.agassessment.org> (consulted May 21, 2008).

(23) The World Bank, 2007. Rapport sur le développement dans le monde 2008. L'agriculture au service du développement. Abrégé. 36 p. <http://www.worldbank.org> (consulted May 21, 2008).

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CHAPTER 2

Cotton, A Case Study

Grown essentially for its textile fibre, cotton is also a source of industrial oil and cooking oil extracted from the seed (Box 7). Cattle cake is made from the crushed seed and is used as animal feed. Cotton's popularity grew spectacularly due to a passion for cotton fabrics which appeared in the 18^{th} Century and persists today alongside the widespread use of synthetic fibres. As a renewable resource and now the subject of 'fair trade', cotton is undergoing a resurgence of interest, as evidenced by the animated debates on the cotton trade in the World Trade Organisation (WTO).

BOX 7 The origins of cotton (1)

Cotton belongs to the plant family Malvaceae, which also includes hollyhocks, mallow, hibiscus, squash and cocoa trees! Within this botanical family, the genus *Gossypium* includes 50 species of cotton, of which four have been domesticated for the fibres on their seeds. The other species have only very short fuzz on their seeds or no fibre at all.

Today, two species originating in the Americas produce the bulk of the cotton in the world: *Gossypium hirsutum,* which originated in Mexico, accounts for 90% of world production while *Gossypium barbadense,* which originated in South America, gives the best fibres (long and fine) and accounts for 5% of world production. The two other species, which originated in Africa *(Gossypium herbaceum)* and India *(Gossypium*

> *arboreum),* together account for the remaining 5%. Their fibres are shorter and coarser, and are most often used in local artisanal production, especially in the making of carpets and furniture covers.

Cotton is grown in a number of characteristic ways in contrasting socio-economic situations. It provides an illustration of current issues in crop protection as a whole, of recent developments in agronomic techniques and of the shift from agrochemistry to agroecology. Cotton has a global distribution, is produced in very diverse systems and is recognised for its over-consumption of pesticides, but is also enjoying current success due to the impact of genetically modified varieties, etc. (2). To help understand the examples used as illustrations in the following chapters, some general information is given below.

2.1 COTTON AND ITS CULTIVATION

Cotton is a perennial, woody plant exploited as an annual crop by 100 million farmers on 30-35 million hectares in 100 different countries, in tropical and sub-tropical areas characterised as hot/temperate. Today, production exceeds 25 million tonnes of cotton fibre, up from only 6 to 7 million tonnes in the 1950s from a roughly equal area. Sixty per cent of the total is produced in Asia, mainly in China, India, Pakistan, Uzbekistan and Turkey, 25% is produced in North and South America, especially the USA and Brazil and 10% in Africa, especially in Egypt, Mali, Côte d'Ivoire, Benin, Burkina Faso and Zimbabwe. The remaining 5% is divided between Oceania (Australia) and Europe (Greece and Spain) (Figures 1 and 2).

World cotton production has a number of characteristics:

- 80% of cotton is produced by seven states: in decreasing order of production China, USA, India, Pakistan, Uzbekistan, Turkey and Brazil.
- 80% of the cultivated area is located in 10 states: in decreasing order, India, USA, China, Pakistan, Uzbekistan, Brazil, Turkey, Turkmenistan, Mali and Benin.

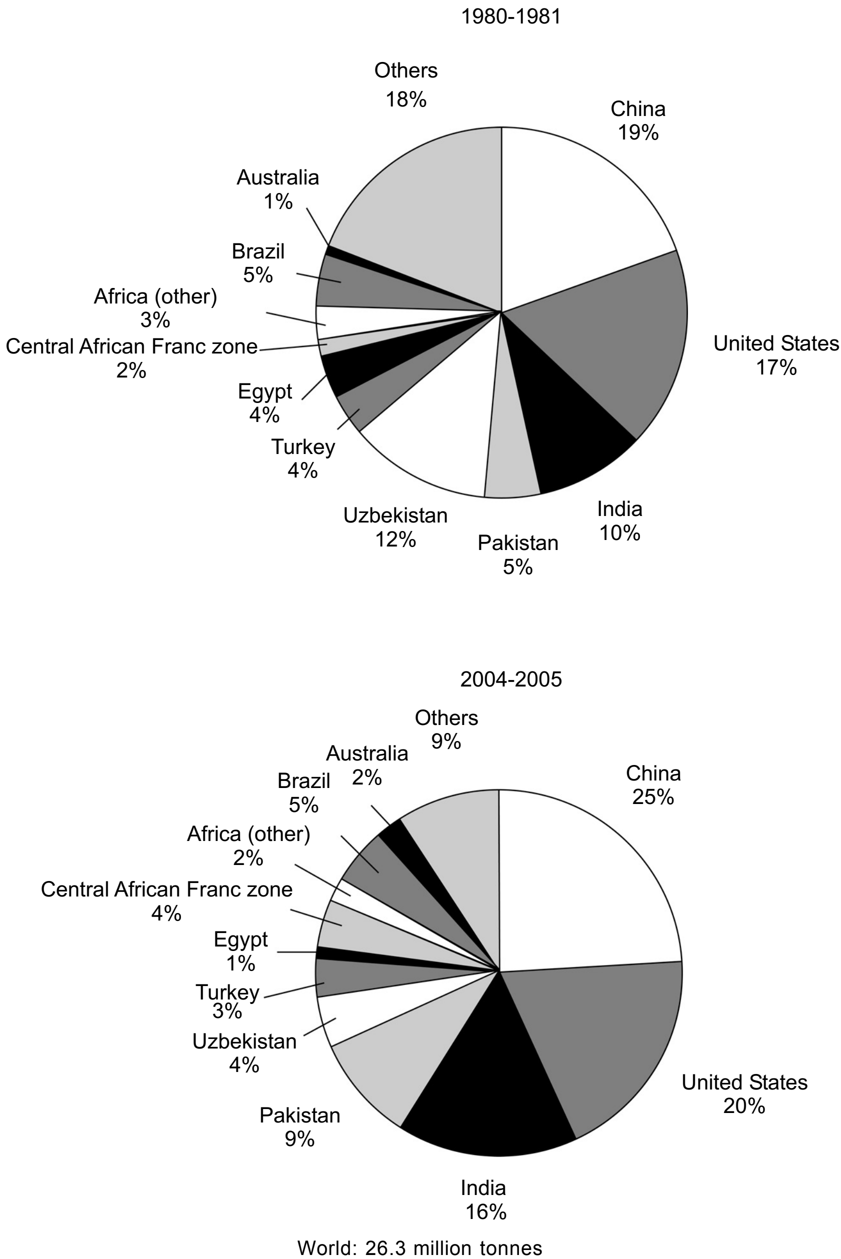

Figure 1 Comparison of national cotton fibre production between 1980-1981 and 2004-2005, expressed as a percentage of world production (3).

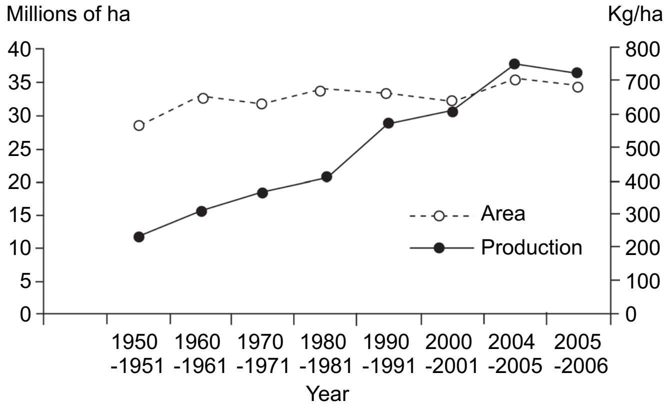

Figure 2 World cotton crop area and fibre production since 1950 (3).

- 80% of cotton is grown on small-scale farms in developing countries in fields often less than 1 ha in size (in China, the average field is 0.3 ha), while the remaining 20% is produced by large-scale, often very large-scale, producers (several hundreds or even thousands of hectares) in industrialised countries, such as Australia, Brazil and the USA.

Yields, with a global mean of over 600 kg of cotton fibre/ha, are also surprisingly variable: around 1,650 kg/ha in Australia, 1,000 kg/ha in Brazil, China, Greece, Mexico, Spain, Syria, Turkey and 730 kg/ha in the United States, compared with only 300 to 500 kg/ha in India before the arrival of Bt cotton, and the same in most African countries, with the exception of Egypt (Figure 3).

To this diversity of agrarian structures and yields is added the diversity of production systems, including both traditional and industrial agriculture. In developing countries in the tropics, production is essentially by small-scale farms, and is dominated by minimal use of inputs and by mixed cropping systems. By contrast, in industrialised countries, monoculture and recourse to intensive use of inputs is characteristic of a range of cropping systems which vary with the climatic conditions (either temperate or tropical) each of which may be arid, semi-arid or humid.

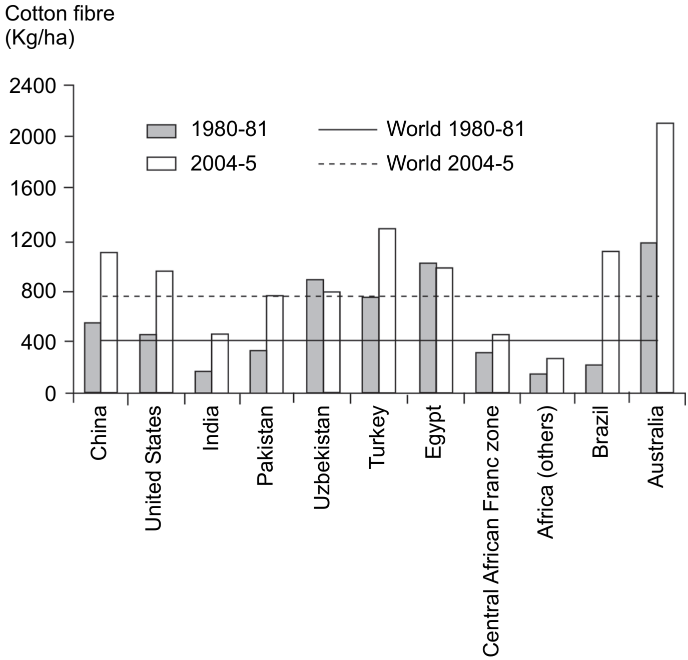

Figure 3 Comparative production of the main cotton producers expressed in kg of cotton fibre per ha, in 1980-81 and in 2004-5 (3).

In the USA, where large farms predominate, there are three growing systems in the southern cotton belt, each with its own pest complex:

1st system – in areas that are both temperate and arid, where the main crops are fruit and vegetables and involve the intensive utilisation of inputs including irrigation, for example in the San Joaquin valley in California or in the Salt River Valley in Arizona;

2nd system – in temperate, semi-arid areas, where cotton growing is predominant, usually rain-fed and involves limited use of inputs, for example in the central High Plains of Texas;

3rd system – in temperate, humid areas where soya and rice are the main crops, involving moderate use of inputs, for example in the Mississippi Delta and in the valleys in Arkansas, Louisiana and Mississippi (Table 2, § 2.2).

To cite an example from a small-farmer production system, the cotton zone of Cameroon in West Africa (4), three types of

TABLE 2 Major pests of three production systems with different climatic conditions in the American cotton belt (2)

Growing systems and major pests	*Climate: irrigated desert*	*Climate: semi-arid*	*Climate: humid*
Production zones	• *Far West* Arizona and California	• *Southwest* New Mexico, Oklahoma, Inland Texas	• *Southeast* Alabama, Florida, North and South Carolina • *Mid South Delta* Arkansas, Louisiana, Mississippi, Tennessee • *Coastal areas* Texas
Major crops	*fruits and vegetables* cotton, maize, sorghum, lucerne, wheat	*cotton* maize, sunflower, sorghum, soy, lucerne (alfalfa) and wheat	*soya and rice* cotton, maize, sorghum, sunflower, wheat and orchard crops
Major pests	*Pectinophora gossypiella* (Lepidoptera Gelechiidae), *Lygus hesperus* (Hemiptera Miridae)	*Pseudatomoscelis seriatus* (Hemiptera Miridae)	*Anthonomus grandis* (Coleoptera Curculionidae), *Helicoverpa zea, Heliothis virescens* (Lepidoptera Noctuidae)
Major weeds	*Cyperus* spp., *Ipomea* spp.	*Ipomea* spp. (Convolvulaceae), *Amaranthus* spp. (Amaranthaceae)	*Ipomea* spp. (Convolvulaceae) *Amaranthus* spp. (Amaranthaceae) *Senna obtusifolia* (Fabaceae)

growing systems are defined by the rainfall gradient (700 to 1,200 mm/yr), the population density (10 to 150 inhabitants/km^2), and by a wide range of soil types:

1st system – rain-fed systems without the use of fallows, generally comprising a cereal (sorghum or maize), cotton and vegetables (groundnuts or peanuts) and characterised by high maintenance of soil fertility (fertiliser, animal manure, treed parkland, tilling with animal traction);

2nd system – growing systems associated with irrigable areas (ridge and furrow, flood irrigation in the plains) and dominated by dry season crops such as transplanted sorghum or onions;

3rd system – rain-fed systems with fallow, confined to sparsely populated areas south of the main cotton area.

As the cotton plant depends on water availability at the beginning of vegetative growth, 55% of the total cotton area in the world is irrigated. Irrigated cotton is found in agroecosystems as different as those of the humid Mato Grosso and the deserts of Uzbekistan. Irrigated cotton provides three quarters of the world harvest. The production of rain-fed cotton is at the mercy of the weather.

This extreme diversity of growing conditions is reflected in the different crop protection strategies applied. Cotton is not only a plant with high nutrient requirements but is also exposed to large and varied pest complexes. Today, despite the powerful chemical control methods available, harvest losses due to pests and diseases are still in the order of 30% (12%, due to animal pests including insects, 10% to microorganisms and viruses, and 7% to weeds). As mentioned earlier (see § 1.1) there is considerable variation between countries. In the absence of any protection, losses can reach 82%, mostly due to animal pests including insects (37%) and weeds (34%), underlining the importance of the risks represented by the pest complex faced by cotton producers.

To these harvest losses must be added the significant depreciation in the market price of cotton lint caused by the exudates of sap-sucking insects, including whiteflies and aphids, or by fragments of weeds or other trash, whose presence complicates later industrial processing. Hand picking of cotton, which is practised by a huge number of small-scale producers, is thus a clear advantage and theoretically justifies a market premium for hand-picked cotton.

2.2 INSECTS AND WEEDS, MAJOR CONSTRAINTS TO COTTON PRODUCTION

The entomological fauna associated with cotton is rich and diverse (5, 6). However, although more than 1,000 species have been observed on cotton plants, only 10 to 15% are potential pests responsible for major harvest losses or the degradation of the quality of the lint. These are pests of the fruiting structures (fruit buds, normally called squares, and mature fruit, or bolls), leading to their early shedding by the plant, consuming the seeds, destroying or staining the lint fibres; leaf feeders; root feeders and sucking pests feeding on the tissue of young shoots or leaves. These pests include monophagous species, which are basically limited to the genus *Gossypium,* or to the Malvaceae and other closely related botanical families, and widely polyphagous pest species.

Two of the pests that are specific to cotton and very closely related plants have become extremely widespread and serious: the boll weevil *(Anthonomus grandis* Boh.) (Box 8), which originated in Mexico and is well on the way to colonising the whole American continent, and the pink bollworm *(Pectinophora gossypiella* Saund.), which most likely originated in Malaysia, Indonesia and the north of Australia and today is one of the major cotton pests across the globe.

BOX 8 A moment of glory for the boll weevil!

In 1919, the town of Enterprise (Alabama, United States) erected a monument to the glory of the boll weevil, the cause of the fortunate agricultural reconversion of the region to peanuts, following the economic disaster caused by the outbreaks of this insect in the cotton fields. Originating in Mexico, the boll weevil moved into Texas in 1892. Given the scale of the damage, an entomologist was hired in 1899 and a prize of 50,000 dollars offered for the discovery of a method of eradication. In vain! By 1904, the insect was observed in Louisiana, and crossed the Mississippi in 1908, and arrived south east of Alabama in Georgia. It was soon to become the most destructive insect pest in the whole of North America. In the 1920s, it affected all cotton production areas in the USA.

The caterpillars of noctuid moths, which belong to the genera *Heliothis* and *Helicoverpa,* are serious pests across the world: *Helicoverpa armigera* in Africa, Asia and Australia, *Helicoverpa zea* and *Heliothis virescens* in America and *Helicoverpa punctigera* in Australia. These species possess biological properties which are very favourable to the colonisation of crops: polyphagy, elevated fecundity, a short life cycle, arrests in development (hibernation and aestivation) allowing them to escape unfavourable conditions, and their migratory capacity, all of which favour a mix of generations on the same crop. Their vernacular names vary across the world, depending on the crop most threatened by them: tomato fruit worm, tobacco leaf worm, cotton boll worm, etc.

In cotton production, the relative economic importance of the different pest species varies with the agroecosystem and is a function of the selection pressure to which they have been subjected (Table 2). This phenomenon, which has been observed for many years in all the cotton regions of the world, is as much correlated with the general development of cropping systems as with the development of pest control techniques. Changes in the pest complexes are particularly significant in regions where a reduction in crop health treatments and a modification in growing systems have been made possible by the introduction of new agronomic techniques. The following observations, made in Arizona, show that the level of the populations of a specific cotton pest, such as the pink bollworm, can decline very significantly in regions where cotton that is genetically modified to express entomotoxins from the soil bacteria *Bacillus thuringiensis* (now called Bt cotton) is extensively cultivated. These observations support the hypothesis that these genetically modified plants, which cause increased mortality in a pest, can reduce its pest status before resistance develops. To cite another example, it is remarkable that the true bugs (Miridae and Pentatomidae) are now considered as the key pests in some areas of the cotton belt of the USA, although traditionally the boll weevil played this role. The success of the recent eradication campaigns directed against the boll weevil has enabled a reduction in the applications of broad-spectrum insecticides, which had eliminated not only the principal pest, the boll weevil, but also the true bugs, which were previously considered to be of only secondary importance. These changes in the pest complexes of cotton add further diversity to the cropping systems in the world, and prudence is advised in attempting to generalise recommendations.

Major insect pests: *Anthonomus grandis* (Coleoptera; Curculionidae), *Helicoverpa zea* and *Heliothis virescens* (Lepidoptera; Noctuidae), *Lygus hesperus* and *Pseudatomoscelis seriatus* (Hemiptera; Miridae), *Pectinophora gossypiella* (Lepidoptera; Gelechiidae).

Major weeds: *Amaranthus* spp. (Aramanthaceae), *Cyperus rotundus* and *Cyperus esculentus* (Cyperaceae), *Ipomea* spp. (Convolvulaceae), *Senna obtusifolia* (Fabaceae).

Early in its growth, the cotton plant is sensitive to competition with weeds, which may result not only in severe reductions in yield but also reduce the quality of the harvest. This is why manual weeding is one of the major constraints facing the small-scale farmer, whereas mechanised producers use herbicides. Seed producers have access to cotton varieties that are genetically modified for resistance to particular herbicides and many agronomists recommend sowing both these varieties and conventional varieties without tillage. For these reasons, the problem of weeds plays a particularly important role in cotton growing.

A hundred species of weeds have been recorded associated with the growing of cotton, but only a dozen are responsible for significant harvest losses. Introduced species are often the most numerous and the most dangerous, as in the absence of their natural enemies they are often more competitive than indigenous species.

In the particular case of the US cotton belt, the largest harvest losses are due to a few species whose relative economic importance varies with the climatic zone. Because of their great adaptability, weeds require constant attention. Quantitative and qualitative changes occur rapidly under the effects of selection pressure from the environment and agricultural techniques.

In addition, some weeds are hosts for fungal, bacterial or viral diseases of cotton; others provide alternative hosts for insect pests of cotton or for beneficial organisms. Consequently, the management of weed communities cannot be considered independently of overall crop health. For agronomists, the problem is developing growing systems that reduce competition from weeds while still favouring, as far as possible, the biological diversity of the associated entomofauna. This needs to be done in such a way that the pest populations do not exceed the intervention thresholds determined for each species in each given socio-economic context.

Cotton is sensitive to a range of plant diseases. The most serious and the most common are of fungal and bacterial origin. Sometimes they are associated with the presence of nematodes. The symptoms of these diseases are tightly linked with environmental conditions, and can therefore vary considerably from one year to another and from one field to another. For this reason, cultural practices have an important role to play in prevention, including the choice of resistant varieties. This was the case in Peru, where wilt caused by attacks of *Verticillium* could only be controlled by replacing the G. *hirsutum* cultivars by G. *barbadense* cultivars. Locally, as in certain areas of the American South West, the incidence of root rot caused by a fungus, *Phymatotrichum,* obliged producers to stop growing cotton and to switch to cereals and forage crops. The most severe and widespread diseases are due to the fungi *Rhizoctonia solani, Thielaviospsis basicola, Pythium* and *Fusarium* spp.

In tropical and subtropical regions, growers guard particularly against bacterial diseases, such as angular leaf-spot caused by *Xanthomonas campestris,* in addition to the diverse viruses responsible for leaf curling, mosaic diseases and blue disease. Bacterial wilt has spread considerably in the USA since 1950 and in India since 1970. Today it is present in all the world's cotton zones. Locally it can be the cause of significant harvest losses

(Sudan, Tanzania and many Asian countries). Its dissemination can sometimes be caused mechanically by insects which come into contact with the exudates of contaminated plants, particularly by sap-sucking insects. The recent increase in viral diseases is attributable to infestations of insect vectors, aphids and whiteflies particularly the whitefly *Bemisia tabaci,* which is a feared vector of cotton leaf curl virus in both India and Pakistan.

However, more generally speaking, the health profile of cotton is dominated by the use of insecticides, whereas in the majority of other crops, insecticides are usually of secondary importance (Table 4, Chapter 3). This is no doubt why cotton cultivation has particularly captured the attention of the initiators of Integrated Pest Management, most of whom are entomologists.

2.3 SENSITIVITY TO PESTS AND DAMAGE AND THE COMPENSATION CAPACITY OF COTTON

It is customary to distinguish three successive periods in each cotton growing season: the initial vegetative growth period, the flowering and fruit-set period, and the period of maturation of the bolls up to harvest. The length of each of these periods depends on the variety cultivated, and on climate and agronomic practices, but the periods are sufficiently predetermined to allow the establishment of a provisional calendar on the basis of mean values. In the American cotton belt for example, there are significant differences among the main cotton growing regions. The total cotton season (from planting to harvest) ranges from 140 days in the High Plains, 155 days in the southeast, to 195 days in the west.

It has been shown that the quality of growth in the first 30-40 days after sowing largely determines yield. Subsequent events, particularly pest management, can at best maintain the yield potential generated earlier. The quality of the seed thus underpins production, but this does not preclude the need for the careful choice of the field in terms of the physio-chemical characteristics of the soil or the need for crop rotations (particularly imposed by nematode infestations), or the preparation of the seed bed. The seed disease complex and a range of early season pests such as thrips, leaf miners and aphids, are also a major consideration. However it has been shown that the sometimes spectacular damage caused by these insects often has no real impact on the final harvest, because of cotton's capacity for compensation during the vegetative stage—if growing conditions are optimal (Table 3).

TABLE 3 Impacts on the yield and quality of cotton of damage caused by insects and mites in the American cotton belt (6, modified)

Major, secondary and occasional pests	*Quantity*						*Quality*	
	Shoots	*Terminal buds*	*Leaves*	*Flower buds*	*Flowers*	*Bolls*	*Fibre*	*Seeds*
a) Major pests								
Heliothis virescens		x		x	x	x	x	x
Helicoverpa zea		x		x	x	x	x	x
Anthonomus grandis		x		x	x	x	x	x
Lygus spp.		x		x	x	x		x
Pseudatomoscelis ser.		x		x	x	x		x
Pectinophora gossypiella						x	x	x
b) Secondary or occasional pests								
aphids			x				x	
whiteflies			x				x	
mites			x					
thrips		x	x		x			
mirids						x	x	x
looper caterpillars			x					
leaf-feeding caterpillars	x		x	x	x	x	x	x
nematode worms	x		x					

N.B. local infestations of the pests listed here as secodary or occasional can sometimes change category.

In the United States, the first flower buds appear five to eight weeks after planting, later in the West (60 days) than in the Delta (39 days) and in the High Plains (43 to 47 days), and the first flowers open three weeks later, i.e. 60 to 80 days after planting. At this stage, the above-mentioned compensation phenomenon may occur to compensate for damage caused to the terminal buds and to flower buds by major pests such as bollworms and bugs, and to leaf feeding damage caused by other species. In optimal growing conditions and during the initial growing period, simultaneous observations of the pest levels and the damage and compensation capacity of the plant enable adjustment of the pest thresholds generally used to decide whether crop protection will be necessary. This can lead to a significant reduction in plant protection treatments during the first two months of life of the cotton plant, which has favourable implications for beneficial fauna and consequently for pest control for the remainder of the season and for bio-diversity in general.

The majority of bolls (85% in the southeast and in the High Plains, 64% in California) set during the first three weeks of flowering. Their maturation therefore begins 65 to 95 days after planting and continues up to the latest dehiscence (boll opening), which can be as late as 140 to 200 days depending on the region. The bolls that set first have the shortest period to maturation, which — along with the other characteristics of 'earliness' mentioned above — argues in favour of the selection of early, or 'short-season' varieties, particularly as the insect pests of buds and bolls themselves have a long period of activity, between 50 and 110 days after planting.

In such a diversified agronomic context, it is important to be able to locally adapt the management of growing systems, for example by using a personalised management chart. This allows cross-referencing of the chronological development of the physiological stages of the cotton plant with those of the pests present in the area. This encourages field observations, which enable objective evaluation of the real risks. This is the first step towards an intervention strategy at the level of the individual field, but which can be scaled up within the framework of a spatial approach to the whole farm and its environment. This first step demonstrates the advantage of establishing a link between agricultural practices and crop damage, giving the producer a certain degree of autonomy in decision making. However, this obviously pre-supposes appropriate technical assistance, which is very often lacking in many developing countries.

In conclusion, cotton cannot escape the general rule requiring respect for good agricultural practices as a prerequisite for good crop health. These practices can be summarised as follows: planting and utilisation of early or short-season varieties, optimal fertilisation and irrigation, appropriate plant spacing, the use of trap crops and the destruction of crop resides. These are all excellent practices, known and adopted for a long time, for the reduction of the damage potential of insects and mites in cotton production (7). This chapter has deliberately focussed on the context of the American cotton belt to ensure coherence. In the course of the following chapters, other case studies will be used to flesh out this general information.

Bibliographic References in Chapter 2

(1) CIRAD, 2006. Cotton. What you need to know about cotton and cotton growing (botanical) http://www.cirad.fr/fr/regard_sur/coton/php (consulted August 18, 2008).

(2) Deguine J.-P., Ferron P., Russell D. A., 2008. Sustainable pest management for cotton production. A review. *Agron. Sustain. Dev.*, 28, 113-127.

(3) Berti F., Hofs J.-L., Zagbaï H. S., Lebailly P., 2006. Le coton dans le monde, place du coton africain et principaux enjeux. *Biotechnol. Agron. Soc. Environ.*, 10, 271-280.

(4) Dugue P., Vall E., Mathieu B., Sibelet N., Olina J.-P., Cathala M., Seuge C., 2006. Les paysans innovent, que font les agronomes? Le cas des systèmes de culture en zone cotonnière du Cameroun. In: *Agronomes et Innovations. Enjeux, outils et méthodes, perspectives* (Caneille J., ed.), Les Entretiens du Pradel, 8-10 septembre 2004. L'Harmattan, Paris, pp. 103-122.

(5) Leonard B. R., Graves J. B., Ellsworth P. C., 1999. Insect and Mite Pests of Cotton. *In: Cotton: History, Technology, and Production* (Smith W. C., Cothren J. T., eds.), John Wiley & Sons, Inc., New York, pp. 489-551.

(6) Matthews G. A., Tunstall J. P., 1994. *Insect Pests of Cotton.* CAB International, Wallingford, Oxon, UK, 593 p.

(7) Suguiyama L., Osteen C., 1996. The Economic Impact of Cotton Insects and Mites. *In: Cotton Insects and Mites: Characterization and Management* (King E. G., Phillips J. R., Coleman R. J., eds), The Cotton Foundation Publisher, Reference Book Series n° 3, Memphis, TE, pp. 755-780.

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CHAPTER 3

Stepping off the Pesticide Treadmill

With a value of 31.2 billion US dollars in 2005, the world market for plant protection products has been more or less stable since the beginning of the third millennium. However, locally there have been significant reductions in the tonnage of active ingredients sold. This is credited to the regulatory withdrawal of certain molecules and to the shift towards substances that require smaller doses in the field, and at the same time reduced pest pressure perhaps partly because of the growing success of the various forms of integrated or supervised control measures. National sales in the USA are worth US$6.5 billion with Brazil (4.4), Japan (3.1) and France (2.3) as the next highest users.

The agricultural use of plant protection products is certainly preponderant (88% of the total market). The world market for herbicides accounts for almost half (49% in 2006), with the remainder divided about equally between insecticides (27%) and fungicides (24%). Europe is the largest market in the world (31%), followed by North America and Asia (24% each) and South America (17%). The rest of the world, including Africa, accounts for only 4%.

The consumption of different types of products varies with the crop. Cereals, taken together, come at the head of the list, followed by fruits and vegetables (Table 4). Cotton growing—like fruit and vegetable production — differs from other crop systems in the importance of insecticides: nearly 20% of the global market for insecticides (18.3%) is applied in cotton fields, even though they represent only around 3% of the total cultivated area!

TABLE 4 World market for the different families of plant pesticides by crop as a percentage of the corresponding markets in millions of US$ for the year 2002 (1, modified)

Crop	*Herbicides*	*Insecticides*	*Fungicides*	*Others* *	*Total*
Long-straw cereals	17.3	3.6	21 .7	1 8.3	1 4.9
Maize	18.1	8.8	0.1	0.9	11.3
Rice	7.4	11.7	10.2	6.5	9.1
Soya	14.6	1.9	1.7	2.1	8.2
Rape	3.0	0.9	1.6	1.2	2.1
Sunflower	1.4	0.3	0.1	0.1	0.9
Cotton	3.7	18.3	0.7	23.6	7.6
Sugar beet	3.5	0.7	0.8	0.4	2.2
Sugar cane	2.1	1.2	0.0	1.0	1.4
Potatoes	1.5	3.7	8.6	3.8	3.7
Grapes	1.1	2.3	11.1	2.7	3.6
Pip fruit	0.8	4.1	6.2	2.6	2.9
Other fruits and vegetables	8.5	28.3	24.1	19.4	17.3
Other crops	16.4	13.3	12.3	16.8	14.8
Total %	100	100	100	100	100
Total in US$ mill	*12,490*	*6,363*	*5,425*	*872*	*25,150*

* these include plant growth regulators, molluscicides and nematicides

3.1 SUCCESS AND DISILLUSIONMENT, OR THE NEED FOR KNOW-HOW

The control of pests in crops and stored products increased spectacularly after the Second World War with the widespread use of toxic substances and synthetic pesticides. At one time it even looked as though such products would finally solve the never-ending problem of harvest losses and, by the same token, significantly contribute to satisfying the food needs of humanity.

Their remarkable efficacy, their ease of application with high capacity spray equipment and their relatively low cost when compared with their benefits, rapidly ensured their success. This was particularly apparent in intensive agriculture, to the extent that farmers progressively forgot about classical, proven, preventative techniques, such as crop rotations. The spectacular results that were very rapidly achieved allowed full advantage to be taken of the modern techniques of varietal selection, fertilisation and irrigation and enabled maximum yields to be obtained via the genetic potential of the selected crops varieties.

The continued improvement in the performance of insecticides through the synthesis of novel molecules, their formulation in the form of commercial products and the strict rules for their application, explains the continuing success of this technical solution which still dominates crop protection today. Sadly, the uptake of these new molecules, judged by some to be little short of miraculous, happened in a context that did not encourage a balanced assessment of their value. At the end of the 1940s most American farmers (pioneers of these techniques) quickly started using insecticides throughout the growing season, on a calendar treatment basis, without taking into account of the real risk to crop health in their fields. In practice, they were undertaking insurance treatments aimed at eliminating all risk, a solution that was quickly adopted to obtain the highest possible yields. At the time, the facts tended to support this view. For example, following the introduction of organochlorine insecticides in 1946, yields in the cotton belt increased by around 16%. In addition, their ease of application led farmers to abandon traditional ways of controlling boll weevil infestations, such as growing short-season varieties, destroying harvest residues or applying limited chemical treatments based on calcium arsenate. The technicians themselves encouraged farmers to use the new organochlorine insecticides regularly and even systematically – in some cases once a week – throughout the growing season, ignoring the risk of the selection of resistant pest populations. In the United States in 1964, more than half the annual consumption of insecticide was used for the control of cotton pests. However, as early as 1955, the boll weevil had become resistant to the active ingredients of organochlorines, *a* capacity soon acquired by all the other major insect pests of cotton. To overcome this difficulty, farmers were advised to use insecticides belonging to other chemical families, such as orgonophosphates and carbamates, until, in 1965, resistant populations were again discovered, first in *Helicoverpa zea* in Oklahoma, then in *Heliothis virescens* in Texas. The pesticide treadmill began to turn (Figure 4). At the beginning of the 1970s, it was the turn of organophosphates to be dethroned by pyrethroids, before they, in turn, were also threatened at the beginning of the 1980s by the appearance of resistance in *Helicoverpa armigera* in different parts of the world (Australia, Thailand, Turkey, etc.).

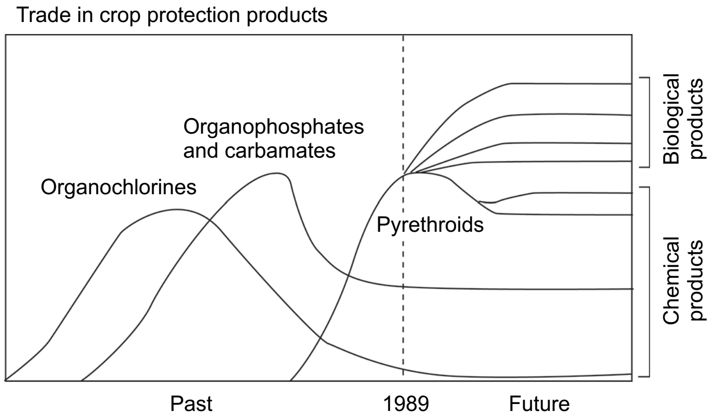

Figure 4 The agrochemical industry's vision of future of crop protection in 1989 before the introduction and spread of Bt cotton (2).

It was this same high-production strategy involving the massive use of inputs that was recommended at the time under the name of 'Green Revolution'. The aim was to improve agricultural productivity in developing countries, at the risk of aggravating the unintended effects mentioned above. Certain authors believe this policy was influenced by lobby groups from the plant protection industry who were keen to safeguard their return on the huge investments required to bring new molecules and formulations to market. Other authors explain this strategy by the particular political context of the Cold War, which led the Western powers to support the agricultural economies of countries suffering from chronic food deficits, a fertile environment for movements aimed at destabilising their political institutions.

In the 1950s, cereal production in Latin America became an experimental arena for the Green Revolution. The region was undergoing the conflicting effects of the promotion of chemical control of crop pests in general and of cotton pests in particular. The disastrous episode of cotton production in the Canete valley of Peru is a classic illustration of such disfunctionality. Up to the 1950s, the region had been mainly dedicated to sugar cane. From 1949 on it was almost entirely converted to cotton monoculture. After seven years of intensive use of organochlorine insecticides, it had undeniably become practically impossible to effectively control the pests by chemical means, despite the increase in the number of treatments (from 15 up to 25 per season in the broad-acre cotton plantations). Not only was the beneficial fauna destroyed, but the crop was also damaged by pests previously considered to be of secondary importance.

In the meantime, an original and surprisingly modern ecological study identified the scale of the imbalance within the closed ecosystem of an irrigated valley in a desert zone (3). The richness of the indigenous malvaceous flora (the botanical family to which cotton belongs), produced conditions that were favourable for the maintenance of a natural equilibrium between pests and their natural enemies, which migrated into the fields thereby contributing considerably to crop health. In 1956, faced with harvests reduced to 320 kg of lint/ha, the farmers finally adopted the recommendations originally formulated by local agronomic research services. They abandoned synthetic insecticides and returned to mineral or natural insecticides such as the arsenates and nicotine, plus biological control including introducing natural enemies of the pests, and to good management practices across the whole valley, in particular crop diversification. These were the strengths of the new strategy, which seven years later, in 1963, allowed the re-establishment of satisfactory crop health.

Similar situations were observed in the 1960s in Colombia and Venezuela, as well as in Central America (El Salvador, Guatemala, Mexico, Nicaragua, etc.), although such logical solutions were not always adopted. There are frequent references to 30 or more insecticide treatments in cotton fields over a period of 90 days, i.e. one application every three days! Subsequently similar cases were reported in other parts of the world, in particular in Australia, Asia and Egypt.

This was the problematic context in which a critical evaluation of the situation was conducted in 1972 (4). This assessment was so apt and visionary that many authors continue to refer to it today. According to its authors, the pesticide treadmill in cotton production follows five successive stages, often in a recurring cycle.

In the 'initial phase', cotton is one of several subsistence crops, does not benefit from any system of crop protection and produces very poor yields. This type of cotton cultivation in small, non-irrigated fields is characterized by a balance between the pest populations and indigenous beneficial insects, natural resistance of the cultivated varieties, manual removal of pests in the fields, and cultural techniques that are frequently traditional.

Where irrigation is possible, cotton is one of the first crops to benefit and thereby becomes a major resource which justifies protective measures. This is the 'exploitation phase', in which chemical control is calendar based, without taking into account the real risks involved. This approach characterised the period between the end of the 1940s and the early 1950s in most cotton producing countries. For the first time, highly effective insecticides were actually available to farmers. These were organochlorines (DDT, lindane, toxaphene, chlordane), which became available at the end of the Second World War and were sold from 1946 on. Thanks to their much broader spectrum of efficacy than that of previously used mineral insecticides, as well as to fertilisation and irrigation, yields increased significantly. At this time, new cotton varieties were being selected assuming a high level of chemical protection, with no research into pest resistance. As for the farmers, they very enthusiastically adopted these preventive treatments which ensured a quick return on their investments in agricultural equipment, ploughing and fertilisation. This attitude was defensible because the relative cost of systematic treatments was still low compared to other production costs. And their attitude was sadly encouraged by the providers of credit, who encouraged borrowers to take such preventive measures. This strategy soon spread to other crops, leading to a fundamental change in traditional crop protection.

After some years of this blind and often intensive chemical control, its efficacy decreased. It became necessary to start the treatments earlier in the season and to continue them up to harvest and often, after these interventions, the pest populations reappeared at higher levels than before. The substitution of one active ingredient for another most often had the same result. Occasional pests and pests of secondary importance became major and permanent. This was the 'crisis phase', which generally took the form of intensified chemical treatments and a significant increase in production costs. This new crop health situation was due to the appearance of pest populations which had become resistant to organochlorine insecticides, to the need to control pests which had previously been of minor economic importance, and to the effective disappearance of populations of natural enemies of the pests. Nevertheless optimism continued to reign, and farmers and agricultural technicians remained convinced that the agrochemical industry would rapidly solve the widely underestimated problem. And, in fact, manufacturers soon substituted other materials for organochlorines in the form of organophosphates (methylparathion, azinphosmethyl, malathion, etc.) and carbamates, which were very effective against the boll weevil, but less effective against the bollworms, especially since they severely damaged the beneficial fauna. It soon became necessary to resort to mixtures of organochlorines and organophosphates and then to increase the doses and the frequency of treatments, leading to a major increase in production costs. This was happening just as synthetic fibres were emerging to challenge the predominance of cotton.

The profitability of production was soon called into question, initially that of farms located on the least productive land, and then throughout whole agricultural regions. This has been described as the 'disaster phase', which was especially severe in a number of Central American countries where farms were abandoned and ginneries closed, resulting in the emigration of whole populations of smallholders. In the same way, in the USA, the end of the 1960s was characterized by disastrous harvests in the cotton regions of the lower valley of the Rio Grande in Texas as a result of the simultaneous development of resistance in the pink bollworm to organochlorines, organophosphates and carbamates. At the time, growers were applying 15 to 20 treatments, if not more, with high doses of extremely toxic active ingredients such as methylparathion, even at the risk of poisoning the agricultural workers. However, it is possible for this phase to be followed by a 'regeneration phase', provided the crop health strategy is changed and, more to the point, growers respect the principles of integrated pest management and integrated crop management which are discussed in Chapter 4.

The main conclusion of the evaluation was that the main blame for these disorders could be laid at the door of the exclusive and irrational use of highly toxic substances for the control of outbreaks of key cotton pests, including the boll weevil and the pink bollworm. The two major issues to resolve are conserving the beneficial role played by indigenous natural enemies in the regulation of pest populations and taking into account the capacity of living organisms to develop mechanisms of resistance to lethal threats. This leads us to a new pest management paradigm that modifies interactions between cultivated plants and their environment through the appropriate management of the crop systems and agrarian structures.

3.2 TOWARDS SUPERVISED CHEMICAL CONTROL

Preventative calendar-based treatments have been successfully used in French speaking Africa for the last 30 years. They take the form of supervised crop protection applied as a function of the physiological development of the cotton plant and of the dynamics of the pest populations.

When damage occurs early in the growing season, the sequence of treatments begins 45 days after seedling emergence; if there is no damage at this stage, then after 60, or even 75-85 days. The number of applications, which depends on the length of the reproductive period of the cotton, varies from three to nine depending on the region (on average four to six treatments). The interval between two applications depends on physiological factors (vegetative growth), biological factors (the length of the pest's development cycle), the chemicals used (the relative toxicity and persistence of the insecticide) and climatic factors, but cannot (according to the recommendations) exceed 14 to 15 days. This takes into account the total quantity of active ingredient applied per unit of the field surface area. Insecticides can be applied at shorter intervals, every seven days for example, as long as the calculations include the doses of the active ingredients applied throughout the pest management season.

The application of these principles obviously presupposes a system of technical training for small-scale farmers provided by the extension organisations responsible for the cotton chain, who themselves have links with national research institutes and extension services. Significant technical progress has been made with, for example, the appearance of ULV (Ultra Low Volume) rotating disc sprayers. These small, portable, machines require only one to three litres per hectare of oil-based insecticide formulations. The ease and speed of application of these treatments has enabled the most dangerous pests, bollworms, which are located in the upper part of the plants, to be controlled (5).

The new technique underwent significant improvement with the development of Very Low Volume (VLV) sprayers (eight to 10 l/ha). These enable the amount of active ingredient to be matched to the actual level of infestation. VLV sprayers have the added advantage of allowing the use of pesticides in the form of concentrated aqueous emulsions that are more widely available than the oil-based formulations required by Ultra Low Volume (ULV) sprayers.

In French speaking West Africa only, the spraying of these chemicals at reduced doses but at a higher frequency (changing from 14 days to seven days for example) has been attempted. The 'classic programme' was a calendar-based spraying programme with applications every 14 days at ultra low volume and at a rate of 1 l/ha of oil-based ready-to-apply formulations. This programme recommended four to six treatments, the first treatment 45 days after plant emergence, usually with a mixture of a pyrethroid and an organophosphate. Later, under the name 'dose-frequency' strategy, the doses were reduced and the frequency of application increased. Applications were made at very low volume (10 l/ha), i.e. a third of the dose recommended in the classic ULV programme (1 l/ha). The 'dose frequency' system took the form of eight to 12 applications, at 7-day intervals, the first 45 days after plant emergence, most frequently with a mixture of a pyrethroid and an organophosphate. In this situation, the reduction in the quantity of active ingredients enabled significant financial savings compared with a calendar-based programme with active ingredients and full doses chosen before the growing season.

A decisive innovation was with the introduction of 'staged control' under which treatments were determined as a function of observations in the field, allowing assessment of the real risks represented by the pests. The applications were made at VLV (10 l/ha) every 14 days, each of which was followed, seven days later, by an examination of the health of the crop. The types of active ingredient used were still determined in advance for each treatment. As a form of insurance, a reduced dose of insecticide was still systematically applied in four to six calendar-based treatments. The four to six 'insurance' treatments were made every two to three weeks, with an examination of the field and decision on whether or not to add a treatment being made in the intervening week.

A more elaborate form of this staged control strategy was named 'targeted staged control' *(lutte étagée ciblée* or LEC in French) (6). It always included a calendar-based protection programme, but the choice of the insecticide group and of the doses to be applied was only made after observations of the pests in the field (Figure 5).

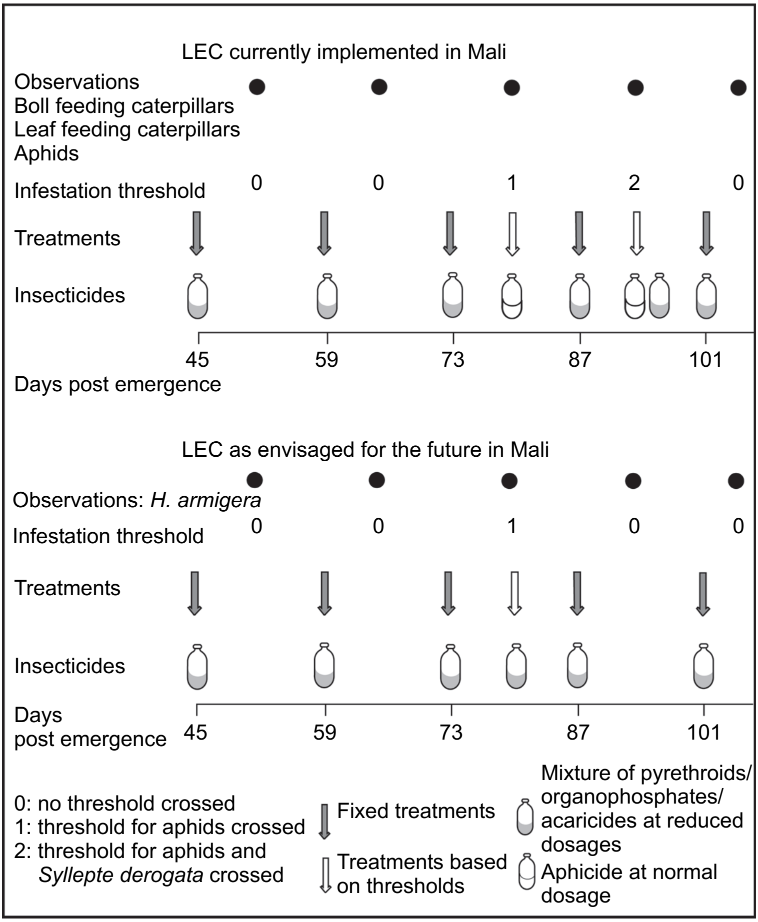

Figure 5 Application systems for staged targeted control (LEC is the French acronym) of cotton pests, the example of recommendations for Mali.

Two different procedures were followed. In the first, the observations were made the day before the calendar-based treatments which were applied at 14-day intervals from 45 days after plant emergence. The type of insecticide and its dose were then defined without changing the number of treatments with respect to the classical programme. In the second procedure, field observations were made six days after calendar-based treatments, which used half-doses of the insecticide compared with the classical programme. If necessary, a supplementary treatment was applied seven days after the preceding calendar-based treatment (also with half the dose of the insecticide). Thus the theoretical number of treatments varied from a minimum of four to six to a maximum of eight to 12 in extreme cases when all the intermediary applications were considered necessary.

The ease of use of the spraying equipment and the savings enabled by the reduction in the quantity of active ingredient (40-50%) ensured the success of this strategy, principally in Cameroon and Mali. However, the difficulties generated by the need for small-scale producers (who are very often semi-illiterate) to understand the pest scouting operations in the field, and the choice and dose of active ingredient, have not yet been solved. This is why the promoters of the programmes tried to amend them through simplified version of targeted control. In West Africa, for simplicity's sake, field observations only concerned the major bollworm pest *H. armigera.* Training workshops for these new techniques were organised in the villages. They included organising demonstrations of field scouting operations, coordinating planting dates, and the purchase and management of pesticide stocks.

This history of the use of supervised chemical control strategies has been recognised as one of the possible reasons for the different experience of the phenomenon of resistance to pyrethroids in bollworm populations in West Africa when compared with other parts of the world up to 1996-1998. The problem of resistance had appeared in the majority of cotton producing countries by the beginning of the 1980s. When resistance did start appearing in French speaking West Africa in the late 1990s, a mosaic of scheduled applications of new active ingredients (spinosad and indoxacarb) were tried with success, using a strategy comparable to one used earlier in Australia, in which 'time windows' are allocated to specific treatments in the spraying calendar (see § 3.3).

3.3 MANAGEMENT OF THE PHENOMENON OF RESISTANCE TO PESTICIDES

The development of resistance of pests to pesticides has been a very serious risk across the entire cotton growing world since the

1980s. It became vital for growers to be able to escape the vicious cycle of replacing one family of active ingredients with another, with the risk of one day being completely unable to defend the crop. As already mentioned, it was really this risk and not the risk of contaminating food chains or reducing biodiversity (although these are also important) that was behind recent changes in crop health strategies. Two risks were involved. The first was the potential consequences of spraying pesticides in repeated treatments in the 1980s. The second was repeatedly growing cotton which was genetically modified to express genes coding for the same insecticidal proteins at the end of the 1990s.

Given the scale of harvest losses caused by pest populations which have become resistant to a wide range of insecticide active ingredients in different cotton production areas of the world, and in order to ensure acceptable harvests, it was clearly necessary, even urgent, to develop strategies to manage resistance. This urgent constraint has had the beneficial effect of attracting the attention of cotton producers to the concept of integrated pest management described below. Here we use the example of Australia to illustrate this development, which is significant since it contributed to a global consideration of the sustainable management of cropping systems.

In 1983, the effectiveness of pyrethroid-based treatments against the bollworm *H. armigera* appeared to have failed in central Queensland, Australia. This was not only a problem for cotton producers but also for the majority of farmers in the region, because of the polyphagous nature of the pest and its capacity to resist most of the main insecticide groups (such as the organochlorine endosulfan) which were available as alternatives to pyrethroids. This led to a double requirement: to develop strategies applicable to all cases including a range of different approaches, and to ensure the involvement of all the farmers in a region and to obtain their voluntary acceptance of collective action. Scientifically, the idea of this new strategy, called the 'window strategy', benefited from the Australian concept of population management. The main innovation was alternating groups of active ingredients between one pest generation and the next (such as endosulfan and pyrethroids) while ensuring that the specific active ingredients used were appropriate for the pest complex at the particular time in the growing season.

To give an example of how the notion of economic thresholds can be applied to pest damage: for the control of *H. armigera,* a maximum of three successive applications of pyrethroids are authorised within a time window limited to 35 days during the crop growing period from September to the end of April. The 35 days correspond to the minimum development period of one generation of *H. armigera* in the field, which has an annual total of four or five generations on cotton.

The growing season was thus divided into three windows:

- in the first time window, from September to January (with cotton planted at the beginning of November), growers may only apply endosulfan (an organochlorine), or thiodicarb (a carbamate) or *B. thuringiensis,* with the later addition of an ovicide (methomyl or chlordimiform) to conserve beneficial fauna and avoid outbreaks of mites, whiteflies and aphids;
- in the second window, also 35 days long, from the beginning of January to the beginning of February, farmers can choose between endosulfan (if not used in window 1) or pyrethroids with a maximum of three applications;
- in the third window, from February to the end of April, farmers may no longer use endosulfan, which was permitted for cotton growers up to 1998/1999, and was then replaced by organophosphates.

These recommendations were included in an extended plan for integrated protection based on the spatial and temporal dimension of the resistance phenomenon. Today, the programme includes not three but five successive windows thanks to new information on population biology and to the recent products of biotechnology, such as Bt cotton.

In West Africa, where the emergence of pyrethroid resistance occurred much later than elsewhere most probably due to the use of insecticide mixtures (pyrethroids + organophosphates) and a well-organised programme encouraging a limited number of applications, a regional network for the prevention of resistance to pyrethroids by *H. armigera* was rapidly established based on the same principles. It should be noted, however, that the number of applications of insecticides in West Africa had been extremely low by world standards. Resistance began to emerge when significant numbers of growers began making several applications per season. The particular contribution of the PRPRAO (Regional Project for the Management of Pyrethroid Resistance in West Africa) recommended replacing early season spraying of mixtures of insecticides by endosulfan. It is not clear how widely this recommendation was actually followed. Nevertheless, the numbers of *H. armigera* fell dramatically right across the region in all crops, even though the endosulfan recommendation had only been followed in a limited area in one or two countries and only in cotton! India experienced a similar phenomenon when the number of *H. armigera* began to fall in 2001-2002, when Bt cotton was only just being introduced and the national insecticide resistance management (IRM) programme was affecting only a small percentage of the cotton area—although it was the most heavily sprayed districts. Across Asia *H. armigera* has become less of a problem in recent years, even in places like Pakistan which did not, officially, have access to Bt cotton. In India, where market access was limited to older chemical insecticides, since 1999 the national IRM programme has been recommending a 4-window strategy with applications based on the results of pest scouting. Treatments start with endosulfan at the beginning of the season for the control of sucking pests, then organophosphates and carbamates during the main bollworm season. For farmers who can afford it, this middle window is split into two, with the newer molecules, spinosad and indoxacarb as options in one half of the window. The use of pyrethroids (if still necessary) is reserved for the end of the season when the susceptible pink bollworm is a more serious pest than the largely resistant *H. armigera.* This strategy is now being used by a huge number of growers, greatly improving the profitability of cotton production.

In the case of the herbicides, the emergence of resistance in weeds was not really a serious problem for agriculture until the mid 1970s with the introduction of triazine, but has become a major issue since then.

In addition to the classical reaction of changing from one group of active ingredients to another, the emergence of resistance triggered a long-awaited appreciation of the IPM principles developed many years ago by entomologists, despite the biological and ecological obstacles which had to be overcome. Promoters of IPM underlined the importance of developing a strategy to account for the whole cropping system at the level of the whole ecosystem. In Australia, the objective was to introduce a management system that progressively reduces the stock of weed seeds in the soil while minimising surface ploughing. Again, recommendations mainly focussed on local actions by individual farmers and aimed to reduce the use of herbicides and to slow down the emergence of resistance to them. Nevertheless, a strong research programme in weed science is indispensable. To develop a genuine synergy around the concepts of IPM, such a programme would need to account for the biological and ecological particularities of the weeds concerned.

It is important to emphasise that the success of the different strategies developed in different parts of the world is always subject to their acceptance by the actors concerned and, more generally, to acceptance of the fact that mankind is only one component of ecosystems among many others. This implies a social dimension, which is often underestimated but which is the key to success in applying the concepts of sustainable development.

3.4 CROP PROTECTION AT THE CROSSROADS

There is only a limited range of novel active ingredients which can be used in cotton production to replace those whose efficacy is compromised by resistance. It thus makes sense to consider alternative solutions, including those offered by biotechnologists, or by the development of new cropping systems and techniques. The era when growers had access to an apparently endless array of new active molecules seems to have come to an end (7).

Besides indoxacarb already mentioned the most important new insecticide molecules are probably methoxyfenocide and imidacloprid. Methoxyfenocide is a lepidpoteran moulting hormone antagonist which disrupts insect growth. Imidacloprid is particularly used to prevent attacks of aphids, jassids and whiteflies during seedbed preparation. Amongst active ingredients of biological origin, in addition to spinosad, which is a metabolic product of a soil actinomycete fungus and particularly recommended against bollworms, considerable interest has been shown in the new avermectin derivatives such as chlorfenapyr, isolated from a strain of *Streptomyces.* This limited range of insecticides is not specific to cotton production. The situation with respect to the availability of alternative chemicals is worsened by the increasingly stringent regulation of the use of all pesticides resulting from awareness of the need to preserve the health of the environment, of farmers, and of consumers.

Among new techniques, those concerning so-called 'precision agriculture' are often proposed as a way of responding to the economic and environmental constraints of 'supervised agriculture' ('*agriculture raisonnée*' in French). For the moment, their use for crop protection is largely limited to the domain of research. They involve improved use of crop protection products as a function of the characteristics of the crop, such as its growth stage and its actual level of infestation. The optimisation of classical spraying techniques has already resulted in significant progress. A new stage was reached recently by the ability to take into account variability within individual fields. Thanks to the possibility of capturing data on the growing crop and on the harvest in individual areas of the field using remote sensing and global positioning systems, and to decision support models, it is now possible to adjust the delivery of crop development compounds such as growth regulators or defoliants in particular areas of single fields. As far as crop protection in cotton is concerned, the results of preliminary experiments in the USA are revealing both the potential and the limits of these highly complex techniques. It has been shown that it is possible to significantly reduce the consumption of insecticides through localised applications. However, at present remote sensing only enables indirect assessment of the risk represented by the pest in the field through differential measurements of the vigour of plant growth, and not direct detection of the presence of the pests themselves. The debatable working hypothesis is that the density of pest populations is significantly higher when the plants are growing vigorously (which can be detected and captured in automatic systems). Direct measurement of risk is the object of current investigations and initial results are promising. Future applications of this technique may enable a spatial approach to crop health problems at the level of groups of farms or even entire regions.

Between 1960 and 1980, biotechnologies made the phasing out of older insecticides for reasons of efficacy and environmental concerns appear possible. Much was expected of biopesticides, i.e. preparations based on microorganisms, or the use of mass-reared beneficial organisms. However, their specificity of action, their variable efficacy, the cost of producing them and particularly the difficulty of preparing sprayable formulations all placed significant limits on their development. In addition, their biological origin does not guarantee their safety for human and environmental health.

In the 1990s, the application of molecular biology to the genetic transformation of cultivated plants was an area which attracted both funding and the interest of researchers. Unexpectedly, this placed crop protection at the centre of a societal debate. Unexpectedly, because for almost a century we have known about the insecticidal properties and good environmental profile of a common soil bacterium, *Bacillus thuringiensis,* which has been considerably exploited as a biopesticide in powder and sprayable forms. The relative simplicity of expressing the bacterial genetic code for this insecticidal protein in plants such as soya, maize, oilseed rape, potato and cotton has given rise to encouraging but controversial prospects that may get around the need for more complicated strategies. At the same time, realisation of the need to ensure the sustainable functioning of ecosystems has drawn attention to the need to preserve biological diversity, which has clearly been endangered by the successes of industrial agricultural production.

Over the last 20 years, a number of industrialised countries have introduced national measures aimed at reducing pollution caused by the use of pesticides. In these countries, for example, in the USA, the strategy has been to better inform users of pesticides and the general public of their drawbacks, and then to tighten up environmental regulations imposed on crop health products available on the market. In the United Kingdom, the Pesticide Forum brings together representatives of industry, users, agricultural advisors and consumer associations as defenders of the environment to facilitate the promotion of new agronomic practices. In addition, the British Ministry of Agriculture has introduced a code of good practice which requires the users of pesticides to obtain a certificate of competence in the area concerned. At the same time, agricultural organisations and the government approved a voluntary code of practice concerning the use of insecticides. In Denmark, a plan of action banning the most dangerous pesticides and limiting the use of others has been in place since 1986. This plan brought together researchers and extension staff and made training obligatory for pesticide users and also introduced a tax on the sale of pesticides. A review in 1997 showed that it is possible to reduce the number of treatments by 30 to 40% without any major restructuring of the agricultural sector. The programme was prolonged up to 2009, including the promotion of on-farm demonstrations, warning systems and decision aids. In the Netherlands, an ambitious plan to reduce the consumption of pesticides by half was launched in 1991. Positive results were obtained, particularly in reducing the quantities of soil fumigants used in market gardening and floriculture. Efforts are now focussed on limiting toxic residues in water through regulations which will oblige market gardeners and farmers to implement new control methods and formal crop protection plans.

In France, the strategy is based on the use of decision aid tools for farmers in the form of 'Agricultural Warnings' by the Plant Protection Service, technical institutes, Chambers of Agriculture, and distributors of plant protection products. This will enable rational decisions to be made about treatments, though certainly more with an eye to optimal production than to the preservation of the environment. However, the part played by individual contractual crop protection requirements in France appears to be significant, if modest when compared with the investments made by the other European countries. At the level of the European Union, a review of all the active ingredients on the market was launched in 1991 and continued up to 2008.

In this context, a group of French experts from a wide range of institutions was mandated by the Ministries of Agriculture and of the Environment to assess the state of knowledge on the conditions of use of pesticides in agriculture, to find ways to reduce their use, and ways to limit environmental impacts. This group produced a report that included reservations about prospects for the development of agrochemistry (8). Amongst the arguments advanced, the increasing costs of the development of new molecules and the limited opportunities for novelty appear to be the most significant. The number of companies which undertake research and development of new molecules has dropped from over 20 to only six over the last 25 years.

In October 2007, a summary report published at the end of the Grenelle Environment Forum by representatives of the state and of civil society outlined the conditions which would allow France to move towards sustainable agricultural production (9):

- programmed withdrawal of the 53 most dangerous crop health chemicals, of which 30 were part of more than 1,500 commercial formulations available at the end of 2008,
- implementation of a plan (ECOPHYTO 2018) to reduce the use of pesticides by 50%, if possible within the next 10 years,
- tripling the land area dedicated to organic agriculture by 2012, following a 5-year action plan allowing the gap between intensive and organic agriculture to be closed through the reorganisation of the business chains, improved access to modern techniques, innovations by the farmers concerned, and the development of production in the framework of a revision of the Common Agriculture Policy (CAP).

More broadly, the federation of existing structures in France under the umbrella of a single national agency for biodiversity is intended to ensure the coherence of actions undertaken in all the areas concerned.

This plan of action supports the role of research and training to facilitate the development of organic agriculture. Since the management of crop health constraints is decisive in this particular sector, investments in agroecological research are much more important for the eventual profitability of the sector. Adoption and application of the results obtained should be much simpler given that organic agriculture is already largely inspired by the ecological principles of crop protection and the preservation of the environment (Box 9).

BOX 9 Crop protection in organic agriculture

Organic agriculture has advanced considerably in recent decade as actors in the agro-alimentary chain became aware of the risks for the environment and for human health caused by the practices and products associated with intensive agriculture. However, despite the recent increase in interest, the cropping areas under organic agriculture are still limited (less than 1% of the cultivated surface area). It has been suggested that organic agriculture alone could suffice to feed the planet, but this view is not given credence by the FAO either for the present or for the future. At a national level, organic agriculture is proposed as an overall solution for agriculture in certain countries, such as Sweden and more recently, France. For these countries, organic agriculture is a mode of production that would provide the consumer with high-quality food products that are also safe. In many developing countries, this method of production is most often practised at the family level with traditional agricultural practices, because of the high cost and poor availability of synthetic inputs and because of the availability of manual labour required for this technique. Villagers' tiny plots are miniature historical models for a special version of organic agriculture developed to fit local situations.

It has been shown that crop pests, especially insects, are one of the main difficulties faced by organic agriculture. This is particularly true in the hot tropics where the rate of reproduction and the number of pest generations is much higher than in temperate areas. Several authors have proposed approaches for crop protection in organic agriculture. Wyss et al. (10) proposed a conceptual framework within which preventative and indirect measures are given priority, direct or curative measures are envisaged only as a last resort. Zehnder et al. (11) described a framework organised around four strategic axes:

- enabling the crop to avoid attacks by pests (in time and space), based on the understanding of the bio-ecology of the pests. For example: selection of the location of the field, crop rotation and positioning, management of the calendar of cultural practices, preventive measures aimed at destroying both crop residues and diapausing insects in the soil;
- reducing host crop attractivity to the pests by modifying their behaviour (egg laying, host plant acceptance, or positioning of the plant host). For example: companion planting and the use of trap crops;
- stabilising arthropod communities in favour of useful species to the detriment of pest species. For example: increasing plant diversity in the agroecosystem by habitat management;
- reducing the sensitivity of the crop to the pests. For example: use of resistant or tolerant varieties (excluding GMOs), improving soil quality and fertility.

These principles of crop protection in organic agriculture are consistent with agroecological approaches to pest management such as those described in the present work. Crop protection in organic agriculture rejects all use of synthetic inputs (particularly chemical pesticides) for agroecological crop protection.

Bibliographic References in Chapter 3

(1) Bocquet J.-C., My J., Michel P., 2005. Données économiques sur le marché des produits phytosanitaires. *In: Enjeux phytosanitaires pour l'agriculture et l'environnement* (Regnault-Roger C., ed.), Tec & Doc, Lavoisier, Paris, 40, pp. 835-848.

(2) Morton N., Collins M. D., 1989. Managing the pyrethroid revolution in cotton. *In: Pest Management in Cotton* (Green M. B., de B. Lyon D. J., eds.), Elis Horwood, Chichester, England, pp. 153-165.

(3) Barducci T. B., 1972. Ecological consequences of pesticides used for the control of cotton insects in Canete Valley, Peru. *In: The Careless Technology. Ecology and International Development* (Farvar M. T., Milton J. P., eds.), The Natural History Press, Garden City, NY, pp. 422-438.

(4) Smith R. F., Reynolds H. T., 1972. Effects of manipulation of cotton agro-ecosystems on insect pest populations. *In: The Careless Technology. Ecology and International Development* (Farvar M. T., Milton J. P., eds.), The Natural History Press, Garden City, NY, pp. 373-406.

(5) Smith R. K., 1989. The "Electrodyn" sprayer as a tool for rational pesticide management. *In: Pest Management in Cotton* (Green M. B., de B. Lyon D. J., eds), Elis Horwood, Chichester, England, pp. 227-246.

(6) Deguine J.-P., Ekukole G., Amiot E., 1993. La lutte étagée ciblée: un nouveau programme de protection insecticide en culture cotonniére au Cameroun. *Coton et Fibres Trop.* 48, 99-119.

(7) Benbrook C. M., Groth E., Holloran J. M., Hansen M. K., Marquardt S., 1996. *Pest Management at the Crossroads.* Consumers Union, Yonkers, NY, 272 p.

(8) Aubertot J. N., Barbier J. M., Carpentier A., Gril J. J., Guichard L., Lucas P., Savary S., Savini I., Voltz M., 2007. *Pesticides, agriculture et environnement. Réduire l'utilisation des pesticides et en limiter les impacts environnementaux. Rapport d'expertise collective* 2005. QUAE, Collection Expertises collectives, Versailles, France, 119 p.

(9) Tuot T., 2007. Grenelle de l'environnement: rapport général. Ministére de l'écologie, du développement et de l'aménagement durables, France. Secrétariat d'Etat à l'écologie, 39 p. <http://lesrapports.ladocumentationfrançaise.fr/BRP/074000693/0000.pdf> (consulted August 18, 2008).

(10) Wyss E., Luka H., Pfiffner L., Schlater C., Uelinger G., Daniel C., 2005. Approaches to pest management in organic agriculture: a case study in European apple orchards. *Organic Research,* May, 33-36.

(11) Zehnder G., Gurr G.M., Kühne S., Wade M.R., Wratten S.D., Wyss E., 2007. Arthropod pest management in organic crops. *Annual Review of Entomology,* 52, 57-80.

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CHAPTER 4

The Concept of Integrated Control

The goal of integrated pest management (IPM) is to find alternative solutions to chemical control (although in association with chemicals if need be), in a coherent strategy that ensures the expected efficacy is achieved while reducing negative effects on the environment. This concept has engendered enthusiasm for 50 years but has never reached the desired level of application. This is not only because of the often limited effectiveness of alternative solutions but also because of the difficulties involved in applying and disseminating them and the difficulty in understanding the principles of this new strategy which involves a coherent vision of the functioning of a pest and its natural enemies. In a constantly changing context, in which interpretations of IPM also vary and are often used inappropriately, it is not easy to be sure what IPM really means. Alternative 'IPM' solutions are frequently believed to be of biological origin. The main problem with the concept in scientific, technical and socio-economic domains is the difficulty of finding rational ways to manipulate and manage living organisms.

4.1 CONTROL, SUPPRESSION, ERADICATION, MANAGEMENT OR PROTECTION?

There has been active public debate between those who push for suppression and even eradication of certain major pests, particularly by chemical means, and those who believe in rational management of pest populations, in particular through appropriate cultural practices. The USA has been the theatre of operations, above all in revealing the differences in points of view between Federal institutions and the Californian school of thought, which has been highly respected for its advanced ideas. Each party based its conclusions on experiments or observations in the field and made proposals for actions that may initially appear to be very different, but in fact ultimately converge.

In the 1960s, each side had blind confidence in its own techniques, whether these were chemical or biological. The spectacular success of programmes for the eradication of migrant populations of the screwworm fly (a livestock parasite) by releases of sterile males, and the immediate effectiveness of synthetic pesticides before the development of resistance, encouraged Edward Knipling, head of the Entomology Division of the Agronomic Research Service of the federal Ministry of Agriculture in the USA, to recommend the combined application of these two approaches for pest control. The originality of associating two such different techniques lay in exploiting their complimentarity. Chemical control was said to be most effective in the presence of outbreaks of pests while autocidal control was best when populations were low.

The screwworm is a pest of farm animals, mainly cattle, sheep and goats. Originating in Mexico, it attacked cattle herds in the south of the United States and caused significant economic damage over a long period. The screwworm lays its eggs in the wounds that animals raised in the open often have. As the larvae, or maggots, develop in the animal's flesh, they cause abscesses. These are sources of infection and of unthriftiness which is most often fatal to the animal. During winter, the flies hibernate in central Texas and Florida. From spring to autumn, they infest

Oklahoma, Kansas, Missouri, Georgia and Alabama (and sometimes North and South Carolina). Co-ordinated control programmes were set up just before the Second World War. Around this time, Knipling devised a hypothetical process for control in which competition for mating of the wild female flies by previously sterilised male flies (which were simple to rear in an insectary) would prevent the laying of fertile eggs. This was an elegant solution to the problem, but there was a long way to go before it could be achieved. First, the taxonomic identity of the pest had to be confirmed and its biology fully understood, then a laboratory mass-rearing technique using an artificial rearing medium was required. Then a method of successfully sterlising the male flies without compromising their ability to mate with wild females needed to be developed, followed by an effective release system. Observations in the field revealed that wild populations were very thinly dispersed, a situation judged to be favourable for the success of mating competition with mass-reared flies. Nevertheless, it was necessary to understand the flux of migrant populations and to incorporate them in mathematical models. It was not until the 1950s, after publication of the sterilising effects of X-rays on vinegar flies (*Drosophila* species), that a practical method was developed for sterilisation, which was needed for mating competition to work. The initial irradiation experiments carried out in a medical centre in San Antonio seemed promising: the irradiated male flies remained viable, effectively sterile and competitive in the mating of wild females, whose eggs, as expected, were therefore sterile. Later, costs were substantially reduced by replacing X-rays with gamma rays from cobalt 60. In 1951-1952, the first experimental releases were made on the island of Sanibel off the coast of Florida. The experiment was beset by difficulties, but was later successfully repeated at Curaçao in 1954-1955, in the most favourable, geographically isolated, conditions. Very large scale operations were then undertaken in Florida in 1958-1959, and from 1962 on in Texas.

During the same period (1959), the concept of integrated pest management was being formalised following experiments in California on lucerne (alfalfa), which was under serious attack from caterpillars, aphids and bugs. Before systematic treatments based on DDT started in 1945, it was understood that the caterpillar populations could be regulated naturally by local indigenous beneficial fauna. It therefore seemed judicious to limit the use of chemical products especially mineral insecticides, which were already being recommended at the time, in order to enable and encourage the expression of this natural regulation. At the request of lucerne growers, an entomologist was appointed to survey crop health and recommend chemical interventions only when the beneficial impact of the indigenous natural enemies proved to be insufficient. Fifteen years later, in spite of the spectacular success of treatments based on DDT, the formerly used strategy was sufficiently effective to once again become normal practice when the lucerne growers were invaded by aphids, which had rapidly become resistant to the organophosphate insecticides (1956). Once again, the rationale for chemical control changed, this time in the choice of active ingredients. This type of work provided the experimental bases of the concept of integrated pest management. This is characterised by considering the agroecosystem in its entirety, the idea of an economic threshold of pest damage, the preservation of natural enemies, the choice of selective insecticides and the tracking of the populations of pests and of their natural enemies in the field. More recently, the importance of the impact of cultural techniques on pest populations has been emphasised and promoted as examples of good management practices, for example for cotton as an associated crop in a larger system.

Given the gravity of crop health problems encountered in apple orchards across the world after the Second World War, in 1967 the FAO mandated a committee of experts to elaborate on the new concept of integrated control (Box 10). The definition is rarely cited in its original form and the exact wording has been changed many times. The most general version accepted today, proposed by the International Organisation for Biological and Integrated Control of Noxious Animals and Plants (IOBC), is that of integrated management or integrated protection, emphasising the fact that all the populations of an ecosystem must be taken into consideration at the same time and not only the key species (Table 5). In fact the original definition by the FAO suffices, as it provides an explicit base for modern approaches to problems of crop protection.

BOX 10 Definition of integrated control (1)

A system for managing populations of pests in the context of the surrounding environment and of the population dynamics of populations of pest species, using all appropriate techniques in the most compatible manner possible to maintain pest populations at levels lower than those causing significant economic damage. In its narrowest sense, this applies to the management of a single pest species in a particular crop or place. In its broadest sense, it applies to the harmonious management of all the populations of pest species in their agricultural or forest environment. It is not the simple juxtaposition or superimposition of two control techniques (e.g. chemical control and biological control) but the integration of all appropriate management techniques in tune with natural regulation and with limiting factors in the environment.

TABLE 5 Differences in language and/or culture (2, modified)

Expressions in the English speaking world	*Expressions in the French speaking world*
chemical control	*lutte chimique*
supervised control	*lutte raisonnée, lutte dirigée (C, CH)*
biological control	*lutte biologique*
integrated control, integrated pest control	*lutte integree*
integrated pest management or IPM integrated plant protection, integrated crop protection (GB)	*protection intégrée*
ecologically-based pest management or bio-intensive IPM (USA) area-wide integrated pest management	*gestion spatio-temporelle des populations*
farmscaping (USA) integrated farming (GB)	*production intégrée*

C: Canada, CH: Switzerland, GB: Great Britain, USA: United States of America

Only five years after the adoption of the definition of integrated pest control in 1967, it was the expression '*protection intégrée*' that progressively imposed itself in the French speaking world, a translation of the North American expression 'integrated pest management' (IPM). It is doubtless no coincidence that the origins of the rapid adoption of the principles of IPM were political, following a speech made in 1972 by US President Richard Nixon before the US Congress on the subject of environmental protection. In the same period (1987), the first United Nations Conference on the Environment was held in Stockholm, from which emerged the concept of ecodevelopment. This was defined as a mode of harmonious development in a given environment, taking into account nature as well as human needs and introducing the idea of sustainable development which guarantees the needs of the current generation will be met without jeopardising the needs of future generations. In this way environmental issues were officially associated with agronomic and toxicicological constraints in crop protection. What is more, the American Federal Administration received the mandate to make this integrated plant protection the spearhead of its environmental policy, a role reiterated by successive presidents with the goal — which proved to be utopian — of reducing the consumption of pesticides by 50%! One the earliest measures was banning the use of DDT as an agricultural insecticide.

A recent global analysis concluded that the application of the principles of integrated crop protection have been very patchy, varying with the country and the crop concerned (3). In most cases, it has enabled a certain reduction in the number of treatments and better use of pesticides in the form of 'intelligent pesticide management'. In a few cases, it has enabled sustainable impacts of biological control, the primary objective of true integrated pest management. However, most often these new approaches to crop protection have not been implemented in the context of the total pest complex in the truly integrated manner originally sought, but against pests taken out of the context of their biological environment. This is why, 40 years after its adoption by the FAO, the concept of integrated plant protection is still frequently the subject of critical evaluation, even by its defenders. Nonetheless it is still considered as the unquestionable basis of modern agriculture, being both sustainable and respectful of the environment. Clearly there is a mismatch between the results that were expected and those that were actually obtained.

Three categories of constraints explain this situation. The application of the techniques of integrated crop protection is considered — quite correctly — to be laborious and difficult by the farmers themselves. In particular, the need to simultaneously take several techniques into account to manage the different populations of pests in the same place is often rendered impossible by the different demands on their time and resources which farmers have to face daily. What is more, the specialist consultants, with whom the final responsibility lies in many industrialised countries, do not always have the time to undertake a detailed analysis of the local crop health situation, which may be complex. Often these consultants are also employees of the agrochemical firms, which does not guarantee that their advice will be objective. Finally, even the researchers rarely have the necessary multidisciplinary competence and thus prefer to limit themselves to their special fields, in which they consider that they are most likely to obtain original results rapidly. The result is a lack of management programmes which take into account the spatio-temporal dimensions of the phenomena involved. These difficulties explain why the total consumption of pesticides has not declined as much as expected. This conclusion is confirmed by the detailed information collected on the subject in California, a state recognised to be one of the promoters of integrated crop protection.

These setbacks may also be attributed to the inadequacy of the idea of an intervention threshold for particular types of pests, in addition to the inadequate performance of the alternative solutions proposed to farmers. A recent review presented the state of the art in this area, including forecasts of its future applications (4). The idea of an intervention threshold, i.e. a trigger for action, usually a number of pests counted or level of symptoms observed above which significant economic damage would be caused by the pest, is the mainstay of integrated pest control. This concept was introduced by entomologists, who in most cases were able to establish a causal relation between visual counts of insect pests on plants and the magnitude of the damage subsequently encountered (5). The situation proved to be more complex for other types of pests, and for weeds and diseases. For example, when symptoms of diseases caused by micro-organisms or viruses are visible on plants, infestation is frequently already too advanced for preventative solutions to be effective. For other reasons related to the aetiology of the infestations, the idea of a threshold is equally difficult to put into effect in the control of weeds or rodents. These constraints partly explain the reluctance of some scientific disciplines to fully adopt the concept of integrated crop protection. As for alternative solutions, which are most often of biological origin, their implementation requires strategies that differ from those recommended for chemical pesticides. This implies, for example, interventions when the visible populations of the problem organisms are still very limited, with much lower impacts than those used to establish economic thresholds for damage caused by pests. This adds to the difficulties mentioned above. It should be recalled that effective reduction of harvest losses usually initially requires the use of cultural techniques to ensure vigorous plant growth, the maintenance of biological diversity through crop rotation and intercropping, the use of clean healthy seeds, and the choice of planting dates to avoid the worst infestations of the pests.

Given that beneficial organisms are often recognised as key factors in the population dynamics of pests, it seems reasonable to consider them as a determining element in integrated crop protection. Until recently, recommended biological control strategies envisaged either the introduction/ acclimatisation of exotic species under 'classical' biological control, or repeated bio-control treatments using mass-reared beneficial organisms, a technique known as 'inundative biological control'. Recently, growing importance has been given to preserving the role of indigenous natural enemies, which leads not only to a reduction in treatments — which they render unnecessary — but also to integrated agronomic practices within farming systems so that the natural enemies find favourable conditions for their multiplication. This is then called 'conservation biological control'. This strategy focuses on the role of indigenous natural enemies and emphasises the importance of the spatio-temporal dimensions of biological phenomena well known to epidemiologists. In an unexpected way, the popularisation of genetically modified plants represents a positive contribution, not only thanks to the reduction in chemical treatments they allow, but also to the creation of unsprayed refuges designed to delay the development of resistance. This is why today some authors suggest that appropriate cultural practices are in fact a springboard for effective integrated pest control.

For other authors, the application of applied genetics to plant improvement represents the major advance. Starting in the 1970s, understanding and being able to manipulate the genome were rapidly acknowledged to be ideal contributions to the development of plant protection. Through transgenesis, cultivated plants could be protected from serious viral diseases. By successive hybridisation followed by backcrossing with wild-type lines, many varieties have been made resistant to insects and to bacterial and fungal diseases. Similar genetic engineering techniques now enable early detection and identification of pathogens in the field, even before the crop is planted. Easy-to-use diagnostic kits are now available to farmers. In the case of insects, the benefits of genetic engineering are well illustrated by the expression of genes coding for the expression of the different entomotoxins of *Bacillus thuringiensis*. The transformation of cotton is a good example. However, despite the precautions taken, we should be aware of the development of resistance to these toxins which has recently been observed in the polyphagous (cotton, maize, tomato) noctuid moth *Helicoverpa zea* in the USA (6). It is difficult to predict which solution will be the most appropriate in the face of this new development. A number of potential solutions are now under study including perturbation of the metabolism of ecdysone, the moulting hormone of insects by modifying the sterolic fraction of plants by genetic engineering, alteration of the digestion of insects with lectins, and expression by the transformed host plant of allelochemic substances attractive to natural enemies. A review of the characters introduced by genetic engineering and field experiments in recent years showed that resistance to insects and tolerance to herbicides are now the most desirable traits. However, this trend is likely to change in the future because second generation GMOs have other agronomic objectives than just the quantitative improvement of production performance, for example, drought and salinity tolerance or the improvement of the nutritional characteristics of the crop.

Chemical ecology is also a very promising field. Plants contain many secondary chemicals, or allelochemical molecules. These have the unique property of interfering in the relations between individuals of different species, in this case between cultivated plants and their pests. Two strategies are envisaged: one by spraying the leaves with products which are toxic, anti-feedant or anti-metabolic, the other by enhancing the biosynthesis of allelochemic factors within the plant itself. The use of elicitors, or chemical warning signals perceived by the plant, triggers defence reactions including the reinforcement of mechanical barriers, the stimulation of enzymes and the production of defence proteins.

Other volatile chemicals or pheromones interfere in communications between individuals of the same species. Many complex molecules with these properties have been identified in the last 40 years in Lepidoptera in particular. For example, sex pheromones emitted by the females are the signal perceived by the males in which it triggers searching behaviour leading to a sexual partner. These pheromones could thus be used to prevent reproduction based on a method known as sexual confusion, by which farmers can prevent infestation in a field by placing pheromone emitting dispensers throughout the field, effectively 'confusing' males who are attempting to follow scent trails to individual females. As there is no mating, no fertile eggs of the pest species are laid in the crop. Alternatively, traps baited with synthetic pheromones can be used. This technique, known as mass trapping, is recommended in certain cases, for example for fruit flies (Diptera: Tephritidae). Several companies produce synthetic pheromones and have developed pheromone diffusers for this purpose.

4.2 ERADICATION OF COTTON PESTS

Encouraged by his success against the screwworm, in the 1960s E. Knipling recommended research aimed at the possible eradication of boll weevil populations, which had become suddenly (to the amazement of many) resistant to DDT. These studies focussed primarily on the factors that determine the weevil's life cycle and particularly the phenomenon of diapause, a period of physiologically enforced dormancy which allows adults present in the cotton fields in autumn to survive the winter in the soil or in surface plant trash left around the fields, ready to infest the young crop the following spring.

These observations led to an entirely new control strategy in which chemical treatments against diapausing adults were recommended in the autumn, during or even after harvest. This strategy was subsequently refined by recommending earlier chemical interventions, i.e. that targeted the generation preceding that of the diapausing weevils, to further reduce their numbers and effectively put the population in optimal condition for autocidal control by releases of sterile males. The challenge was to develop an artificial diet to mass rear sterile male boll weevils. When this obstacle was finally overcome, the first attempts at sterilisation by gamma rays sadly turned out to be ineffective, as the insects did not survive irradiation. Thousands of potentially sterilising chemical compounds were then screened before discovering something which finally worked satisfactorily at the end of the 1960s. Preliminary field trials began and were then presented by Knipling as a model of integrated crop protection, a harmonious combination of chemical and autocidal control. However, this approach initially required an increase in the usual chemical treatments in order to reduce populations to the level at which eradication became possible. And this was judged to be contrary to the principles of integrated control as elaborated by the Californian school.

Three pilot eradication attempts were made, one in Louisiana and Alabama (1971-1973), another in North Carolina and Virginia (1980-1982), with a simultaneous intervention over a vast area in Mississippi. These trials were allowed in order to test the validity of the proposed protocols and techniques. Despite the sometimes debatable results, from 1983 on, the strategy was progressively successfully applied in the majority of states in the US cotton belt, finally allowing a reduction in pesticide use of around 50% compared to the quantity traditionally used, while increasing the harvest by around 10%. This twin benefit is attributed to the positive role played by beneficial organisms which had survived thanks to the reduction in chemical treatments, and to the reduction in harvest losses caused by the boll weevil itself. However, in a few specific cases, increased infestations of secondary pests were attributed to the reduction in chemical treatments which triggered unfavourable reactions to the programme. Today, around 98% of the US cotton belt use such operations, 38% having achieved the final goal of eradication/ suppression.

The eradication/ suppression programme comprises successive phases over a period of three to four years. The location of the cotton fields is mapped by GPS. The pest populations are mapped with the help of species-specific pheromone traps. Control is based on a combination of cultural, mechanical and chemical techniques. Cultural techniques include using uniform planting and harvesting dates to create a plant host free period unfavourable for the development of the pest. It addition to their role in detection, mass capture in pheromone traps also mechanically removes a fraction of the male population. During the growing period, chemical treatments are typically reduced to a single application of insecticide (Malathion), which is only applied if the damage threshold is exceeded. However, in most regions, the programme begins with an average of seven aerial chemical applications in the preceding autumn in infested fields only. The following spring, during the vegetative phase and the fruiting period right up to harvest, treatments are based on the results of pest scouting. In each succeeding year, the number of fields requiring treatment is considerably reduced. A system of surveillance for possible re-infestation is then implemented, mainly through a network of dedicated pheromone traps. The key to success in such operations is the farmers' willingness to work together, to make decisions concerning treatments by popular vote, and also their willingness to intensify insecticide treatments if necessary. Success also depends on cooperation between federal and state agencies on one hand and the cotton industry on the other. The involvement of local technical staff in the implementation of the operations is also important. Recent technical innovations are also improving the performance of trapping techniques. In sub-tropical countries in South America where the boll weevil does not enter diapause/hibernation, a new type of trap, called a 'bait-stick' which lures the insects with pheromone and then kills them with malathion, is distributed around fields in spring and autumn when the weevils move in and out of the field. It can be used on its own as a successful means of control. However, co-financing such eradication/suppression operations is still a source of preoccupation in the United States and elsewhere, despite the reduction in the costs of production which has benefited producers. In practice, in the regions where the threat posed by the boll weevil is usually slight, cotton growers are reluctant to pay an increased share of the cost of collective operations at a time when the federal contribution is being reduced.

Since the end of the 1960s, a programme for the autocidal eradication of the pink bollworm has been implemented as a way of managing infestations in the San Joaquin valley in California. It is still operational today in the context of a wider strategy of integrated control. The biological characteristics of this insect (the adult moth's mobility, their great reproductive potential, the fact the caterpillars feed inside the cotton bolls, which reduces the efficacy of chemical treatments) led producers to exploit all available control methods, including the use of genetically modified cotton. In 2001, a bilateral Mexican-American programme was adopted based on four types of intervention: widespread pest scouting, sowing of Bt cotton, the use of pheromones to disrupt the mating of moths, and the release of sterile males. Federal participation in the funding was intended to cover 20% of the total cost. Producers had to purchase the transgenic seeds themselves. The US National Cotton Council favours the strategy of eradication/suppression for economic reasons. The Council is currently trying to maintain programmes that have been operational in California for many years, and at the same time to start new programmes in Texas, New Mexico, and Arizona for a period of four to five years. In this particular case, chemical insecticides will not be used to reduce the populations of the pink bollworm, instead only Bt cotton will be planted. Sterile males will not be released until pest populations have been sufficiently reduced.

These experiments are a rich source of information, even if they only concern pests that are more or less limited to cotton, a biological characteristic that makes them suited to the management of their populations. The operations are original for two reasons: first they underline the importance of the spatio-temporal dimension of the problems and second, the entire producer community is involved in the decision-making process, despite the fact that integrated control generally recommends a localised and personalised approach. The two populations of insects concerned (the boll weevil and the pink bollworm) are capable of moving considerable distances each year, which means, at best, we can only expect a reduction in populations but not complete eradication. This basic issue is currently being debated within the American scientific community. It may be that the term 'eradication' in the programme title was retained because of its possible impact not only on producers but equally and perhaps to an even greater extent on political decision makers. The involvement of policy makers in the project is indispensable to ensure that part of the cost is covered by public funds, that local regulations are followed and that the relevant crop health directives are respected by the grower community.

4.3 CONSIDERATIONS FOR IPM IN COTTON CULTIVATION

In 1967, after having brought together a panel of experts for the purpose of defining the concept of integrated control, the FAO turned its attention to writing directives for major crops. As mentioned above, the strategy had rapidly changed from a combination of chemical and biological control to the management of communities within the same ecosystem. The ecological bases of this new concept, with its three levels of complexity — population, community and ecosystem — were later reinforced by the conclusions of the UN Conference on the Environment and Development (Rio de Janeiro, 1992), which gave the concept of IPM a central role in agriculture within its Agenda 21. This is why the FAO directives give priority to understanding the functioning of the cotton agro ecosystems and their biodiversity, which is considered to be a guarantee of their long-term sustainability.

Bearing in mind the need to exploit the natural factors in population regulation and to find alternative biological solutions, the first priority was to limit the use of chemical insecticides which were the source of the development of resistance and also had unintended effects on the indigenous flora and fauna. Innovative control programmes for cotton pests used at that time in the Californian San Joaquin valley were again the exception. The Californians developed practices that took the new factors into consideration (Box 11).

BOX 11 The cotton IPM strategy adopted in California (7)

The strategy was based the following actions:

- scouting pest populations and the use of infestation prediction models,
- using economic damage thresholds,
- recognising the role of indigenous beneficials in the regulation of pest populations,
- evaluating the impact of agricultural practices on the populations of beneficial organisms,
- implementing control measures based on the relationship between the sensitive stages of the crop and the actual presence of pests,
- exploiting general cultural and agronomic practices to facilitate pest management,
- implementing alternative, ecologically selective, chemical and microbiological control.

The Californians were thus pioneers in the application of novel techniques in cotton production. They were certainly the first to exploit a two-level strategy. There was a collective effort to prevent the migration of the pink bollworm through autocidal control, and at the same time, there were individual efforts to control infestations of indigenous pests. Elsewhere, only elementary attempts at integrated control have been made based (more on the principles of supervised chemical control than true integrated control) such as pest scouting, the use of pest thresholds and the application of selective insecticides. These components of IPM practices were still being used in the United States well into the 1980s in four major crops (lucerne [alfalfa], apple, cotton and soya), showing just how slow the adoption of a fuller IPM has been.

With the passage of time and as a result of the recent success of Bt cotton (Chapter 5), the question arises as to whether the order in which the actions were implemented was ideal. While it was certainly aimed at ending what had often become unreasonable overuse of pesticides, it is important not to underestimate the reluctance of farmers to change their behaviour when they are accustomed to the ease of application and the efficacy of pesticides. The best way to proceed would doubtless have been to encourage farmers who applied pesticides to change their practices by offering them an effective alternative as rapidly as possible. However the choices of those who direct research channelled funding for scientific research into understanding and modelling of populations, and significantly into targeted biopesticides (the results of the first generation of biotechnologies), as an alternative to synthetic pesticides. These were longer term solutions.

The Huffaker project in the United States (Box 12) entitled "Principles, strategies and tactics for the regulation and control of pest populations in the major agro ecosystems" (1972-1978) is a good example of the role of political choices in the financing and orienting of applied research, which is as important as the influence of the conceptual conflicts between schools of thought. The Huffaker project was launched as a major thrust of environmental policy following the adoption of the concept of IPM in the United States. Priority was given to pest scouting, a technique for forecasting crop health risks which had been known for many years in forms that were clearly empirical, but became the key to all economic decisions in pest management. Today, the elements that underpin modern pest scouting are the detection of pests in the field, their accurate identification, evaluation of their population levels in relation to potential economic damage,

BOX 12 The Huffaker project (1972-1978)

Financed by the National Science Foundation (NSF) and the Environmental Protection Agency (EPA) under the Nixon administration, this was a programme which brought together the services of the federal department of agriculture and forests, extension services, 19 universities and private industry. It was undertaken in the United States over a period of six years with the aim of encouraging an ecological approach to the control of insects and mites in six production systems (cotton, citrus, pine forests, pip fruit, lucerne [alfalfa] and soya) with a view to significantly reducing the use of pesticides which had undesirable environmental repercussions. Management of the project was given to Carl Barton Huffaker, Professor of Entomology at the University of California, who was a specialist in biological control, the author of more than 250 scientific publications (8, 9) and who mobilised more than 300 researchers.

Despite its imperfections, this project is considered as the prototype of international IPM programmes. The American Federal Administration showed remarkable political continuity in continuing to promote this control strategy from President Carter to President Clinton. Expanded to include the whole insect, disease and weed complex and once again integrating environmental constraints, it is planned that this strategy will be used in around 75% of the total cultivated area in the USA by 2020.

application of the appropriate plant protection recommendations, and implementation of an appropriate management practice, followed by monitoring of its effectiveness.

Producers were soon faced with the difficulties of implementing pest scouting and diagnosis, which were preconditions for decision making, when they had previously been accustomed to applying precautionary calendar-based treatments. In the countries where cotton is grown intensively, today it is not unusual for these new activities to be undertaken by professionals. Data is often captured and entered directly into a portable computer and analysis is done by programs that are a cross between a cotton growth model and a population dynamics model of major pests. This computerised technique enables the definition of threshold levels that vary according to the weather and are adjusted in real time to the development stage of the crop.

However, this help does not solve all the problems, as was shown by a recent survey of cotton producers in South Carolina which showed that the majority were not very receptive to the required changes in their cultural practices. In southern countries, where most small-scale farmers are semi-illiterate and can only depend on themselves due to the lack of adequate technical training, the FAO, in collaboration with local institutions, was obliged to organize mass-education programmes, not in the use of portable computers but in the use of an ingenious peg-board which allows farmers to manually record their observations. The cotton growers learned to practice a form of sequential sampling and decision making (Box 13). These efforts might seem derisory in the face of the magnitude of the task: there are around 10 farmers per 1,000 ha in the United States, as opposed to more than 2,350 per 1,000 ha in Bangladesh. Nevertheless, the impacts have been considerable.

BOX 13 The pegboard, a simple aid to scouting pest populations in cotton fields

A wooden board, often roughly made, approximately seven to eight cm wide and 15 cm long and around one cm thick is the main component. It is pierced with holes with the diameter of a matchstick spaced 15 to 20 mm apart and arranged in parallel columns down the long axis of the board. Each column is marked with the local name or a rough drawing of the major cotton pest species in the area. Normally three columns are sufficient for the key pests, which limits the risk of confusion by the farmer/ pest scout. The board is supplied with small wooden pegs made to fit tightly in the holes, but these are usually lost, and so fragments of twig or pieces of grass stem or matchsticks are used instead. Armed with the pegboard, which is rudimentary but simple to use, the team of pest scouts divides up the field between them and proceeds to make observations on a predefined number of plants (the number of holes in each column) selected within the field following a rough randomisation procedure organised by the group leader. Each time one of the major pests is seen to be present on a cotton plant, the scout places a peg in a hole on the pegboard in the column belonging to the pest concerned. The group leader then uses the data to calculate the percentage of infested plants and to compare this percentage with the local intervention threshold. In some countries, for example Uganda, where individual farmers scout in their own field, each column is marked with a red line part way down based on the number of plants infected with this pest out of the 25 plants to be scouted, which indicates that the pest threshold has been crossed. If the farmer finds he has crossed any of the red lines, then he needs to take action (normally with an insecticide spray). A simple sticker on the back of the pegboard tells him how to scout and what to spray if a threshold for a particular pest has been crossed. This is a simple form of sequential sampling and can greatly reduce the labour of scouting if the field is heavily infested, as it is only necessary to examine plants up to the point at which a threshold is crossed.

Bibliographic References in Chapter 4

(1) FAO, 1967. Report of the first session of the FAO panel of experts on integrated pest control. Meet Rep PL/1967/M/7, September 18-22 1967, Rome, 19 p.

(2) Milaire H., 1995. A propos de quelques définitions. *Phytoma - La Défense des Végétaux,* 474, 7-9.

(3) Ehler L. E., 2006. Integrated pest management (IPM): definition, historical development and implementation, and the other IPM. Pest *Manag. Sci.,* 62, 787-789.

(4) Stejskal V., 2003. "Economic Injury Level" and preventive pest control. *J. Pest Science,* 76, 170-172.

(5) Higley L. G., Pedigo L. P., eds. 1997. *Economic Thresholds for Integrated Pest Management.* Univ. Nebraska Press, Lincoln, NE, 327 p.

(6) Tabashnik B. E., Gassmann A. J., Crowder D. W., Carriére Y., 2008. Insect resistance to Bt crops: evidence versus theory. *Nature Biotechnology,* 26 (2), 199-202.

(7) Flint M. L., van den Bosch R., 1981. *Introduction to Integrated Pest Management.* Plenum Press, New York and London, 240 p.

(8) Perkins J. H., 1982. *Insects, Experts, and the Insecticide Crisis. The quest for new pest management strategies.* Plenum Press, New York, N. Y., 304 p.

(9) Jacobsen B. J., 1997. Role of Plant Pathology in Integrated Pest Management. *Annu. Rev. Phytopathol.,* 35, 373-391.

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CHAPTER 5

Harmonising Control Methods: Mirage and Reality

Long before the discovery of synthetic pesticides, crop protection was based on three pillars: good agricultural practice, selection of appropriate crop varieties, and respect for natural balance. Today we recognise that one of the main obstacles to the development of alternative strategies is our lack of understanding of the molecular mechanisms which determine the interactions between a plant and its pests. Through the new discipline of genomics, a comprehensive approach to the genetic study of pest-plant interactions has now been developed, thanks to the characterisation of their genomes. Although we are still far from our final goal, we can already identify resistance genes and accelerate the process of crop varietal selection using molecular markers. At the same time, the prospect of stimulating the plant's natural defences by biological or biochemical means opens new perspectives.

The first example of transgenesis in plants was made public in 1985 with the expression of an insecticidal protein from the soil bacteria, *Bacillus thuringiensis,* in tobacco. This was the starting point for a genuine technological revolution. This pioneering work came to fruition 10 years later with the sale of crop varieties transformed to express genes with similar insecticidal properties and others with genes conferring resistance to a herbicide, glyphosate. New varieties of maize, soya, canola, potato and cotton have since been grown on a total of more than 100 million hectares by more than 10 million farmers! It is too early for a balanced assessment of the positive and negative consequences of this revolution, since the manipulation of living organisms can have unforeseen long-term effects. Even so, this discovery has many other potential applications beyond the field of crop protection.

5.1 OPTIMISING VARIETAL SELECTION AND TRANSFORMING LIVING ORGANISMS

Since the end of the 19th Century, the growing of 'early' cotton varieties (also called 'short-season varieties') has been recommended in Texas as a means of limiting damage caused by the boll weevil. The selection of short-season varieties with a limited vegetative phase and a short, synchronised fruiting period was the main aim of cotton breeding for plant protection. Today there are many examples of plant resistance to bacterial, fungal, and viral diseases thanks to varietal selection. Up to the middle of the 1960s, selection programmes focussed on adding to the earliness trait combinations of resistance to pests and to different stresses which affected cotton productivity and the quality of the cotton fibres. Minimising the period between planting and harvest is still the order of the day in the southern USA, since it limits the impact of the pests and consequentially the use of broad spectrum chemical treatments based on expensive active ingredients for the control of autumn populations of boll weevils and bollworms. Given the global stagnation in harvests in the 1990s and early 2000s, current research is focussed on the creation of cultivars suited to particular growing systems, drawing on research into the interactions between genotypes and cropping systems. It also makes sense to simultaneously apply appropriate agronomic techniques, such as adjusting planting dates, irrigation practices, fertilisation, and the use of plant growth regulators and pre-harvest desiccants.

Plant architecture is another adaptive factor which is taken into consideration, the aim being to increase plant density, particularly in Argentina, Australia, China and the USA. Covering the soil with plastic film allows early germination of the seeds as the soil warms under the plastic and also reduces weeds by cutting out light and reducing soil borne diseases thanks to high temperatures. The total growth period is reduced by two or three weeks, and yields are increased provided the increased level of technology required by these plants is respected, including the application of growth regulators at the appropriate time and the use of appropriate harvesting equipment. The consequences of such practices for crop health are still poorly understood, and there is a risk that the increased root volume resulting from the increase in plant density may favour underground pests (nematodes, bacteria, fungi and viruses).

Conventional methods (for example genealogical selection by stabilising favourable characters over several generations of inbreeding) are now becoming more effective thanks to new tools such as marker-assisted selection and genetic transformation. Molecular markers are short sequences of DNA which are linked to the presence of a particular property of the overall plant, such as tolerance to a disease (usually because their location on the chromosome is close to that of the genes which control the trait of interest). These sequences are valuable because they allow researchers to rapidly characterise genetic diversity and thus to speed up hybridisation programmes. The objective of selection is to combine in the same plant all the sequences that appear to carry favourable genes. Unlike conventional selection, it is enough to make breeding selections on the basis of the presence of particular genotypes and no longer on the phenotype, where gene expression is modified by the plant's environment. In addition to its relative rapidity, this biotechnological advance thus has the advantage of allowing us to ignore the influence of the environment when selecting plant lines. Many traits for pest tolerance or resistance have been identified in the diploid species of the genus *Gossypium* and are now available for transfer into cultivated (tetraploid) cottons (Table 6).

TABLE 6 Traits of interest for crop protection transferred into *Gossypium hirsutum* from the diploid cotton species (1, modified)

Introgressable traits	*Phytosanitary interest*	*Origin*
Resistance to *Xanthomonas malvacearum*		*Gossypium herbaceum*
	Improvement of cotton productivity in infested areas	
Resistance to *Puccinia cacabata*		*Gossypium arboreum* *Gossypium anomalum*
Glabrous leaves		*Gossypium armourianum*
	Improvement of resistance to bollworm	
High gossypol levels in the tissues		*Gossypium raimondii* *Gossypium thurberi*

Given the possible use of cotton seeds in the food sector, the selection of varieties with low gossypol levels is also attracting the attention of breeders. Gossypol adds a yellow phenolic pigment to different vegetative parts of the cotton and to its seeds. It also has the disadvantage of not being digestible by monogastric animals – particularly humans – and of having negative effects on fertility and blood constituents due to hypocalcemia. In the 1970s in China and Brazil, the possibility was discussed of whether it could be used a contraceptive! On the crop health side, this molecule is known for its nematicidal properties as well as its ability to repel insects. Experiments have been undertaken in West Africa aimed at producing lines without gossypol glands (glandless varieties). These experiments were most strongly pursued in the 1970s. However, in the Mbikou region of Chad, experimental plantings of these new varieties suffered from rats, which ate the seeds, and from monkeys, which ate the developing bolls, as well as from insects, which attacked all the vegetative stages of the plant. However, when production was undertaken on a large scale, these problems proved to be less severe than initially feared as evidenced by observations in Chad, Côte d'Ivoire and in the United States. At the same time, breeders improved the technological performance of glandless varieties, particularly the characteristics of their fibre and oil, while nutritionalists recommended the use of the oils, flours and seed cake produced from the reduced gossypol varieties for feed for polygastric animals and finally even for humans. However, the growing of such varieties was abandoned in the 1990s. One reason was insufficient investment in the adaptation of industrial extraction technologies to meet the norms for the production of a food product. Another reason was that the usual varieties, which contain gossypol and are more appropriate for field cultivation, displayed the same technological properties as those of glandless cottons. Geneticists nevertheless continued to aim at selecting varieties whose seeds would not contain gossypol but in which the pigment would continue to be secreted in the vegetative parts of the plant so as to retain its pest repellent properties.

Twelve years after the sale of the first transgenic seeds, the scientific community is still divided over the future of this technological innovation. The different interpretations of what in some areas — such as crop protection and the preservation of biodiversity — is still preliminary data, partially explain these differences of opinion. For some, this technological step is decisive and finally opens the way to the long awaited generalisation of IPM based on a spectacular reduction in the use of synthetic insecticides. For others, the proclaimed benefits should not be too hastily generalised given the diversity of crop health situations, the increasing risk of the development of pest resistance resulting from higher selection pressure, and the risk of genetic contamination of other plants by the genes concerned.

After 1996, the sale of cotton varieties genetically modified for the expression of one or more genes coding for entomopathogenic proteins from the bacteria *Bacillus thuringiensis,* reduced the number of insecticide treatments against the caterpillars of the most dangerous Lepidoptera by 50 to 80% (Box 14). However, the gains in yield varied depending on the local technical level, and in fact the results, which were often described as miraculous, are still the subject of debate. It is recognised that the most impressive results were obtained in the first years following the introduction of the Bt seeds in regions where intensive chemical control of bollworms had previously been the rule. Questions remain on how justifiable the use of Bt-cotton is in small-scale agriculture. In practice, Bt varieties do not always live up to their promise unless optimal fertilisation and pest management is available, as the plant needs to be physiologically capable of carrying the extra

BOX 14 The surprising fate of the bacteria from Thuringia, *Bacillus thuringiensis* (2, 3)

- 1901: S. Ishiwata discovered that a disease of silk worms was caused by an unknown bacterium,
- 1911: E. Berliner came to the same conclusion with the Indian meal moth and identified the causal agent of the disease as the bacterium *Bacillus thuringiensis* (Bt),
- 1938: In France the first insecticide formulations based on Bt were sold,
- 1954: T. A. Angus demonstrated that the crystal protein produced during sporulation of the bacteria is responsible for the insecticidal properties,
- 1983: Researchers showed that plants can be genetically modified,
- 1987: Confirmation of resistance to insects in tobacco plants genetically modified for the expression of Bt entomotoxins,
- 1996: Sale of genetically modified cotton (Bt cotton),
- 2007: 114.3 million hectares of genetically modified plants were being grown all over the world, of which 40.4 million (35.3%) expressed Bt genes on their own or associated with genes for resistance to a herbicide (maize 28.1 million ha and cotton 12.3 million ha).

(undestroyed) bolls through to harvest, which is often not the case especially where irrigation is not available. In practice then, the problems of under-performance of Bt cottons in many areas have now been shown to be due to the choice of agronomically inappropriate varieties into which the trait was introduced. However, even in the most favourable conditions, stopping chemical control of bollworms may favour outbreaks of secondary pests, obliging the farmer to undertake supplementary chemical treatments. Because of the rushed and illegal sale of hybrid genetically modified varieties which were poorly adapted to local conditions, spectacular harvest losses were observed in some parts of India, which were exploited by the detractors of the technology. *Heliothis virescens* and *Pectinophora gossypiella* were the first pests targeted by the original Bt varieties. Others, such as *H. armigera* in the Old World, are also affected despite their lower sensitivity and a certain variability in the tissue concentration of the entomotoxin produced by Cry1Ac (which has been the active material in most Bt varieties), particularly at the end of the growing season. It thus makes sense to conduct economic and environmental analyses based on local conditions before deciding to use transgenic seeds (4, 5).

Broadly speaking, we are only now beginning to analyse the first results of studies to evaluate the direct and indirect impacts of Bt plants on associated fauna and on the environment (6, 7). Our limited understanding of the functioning of ecosystems and the use of investigation methods that are too often still elementary, explain this delay, when it is not simply due to a lack of interest on the part of researchers who are attracted by what they judge to be the most immediately profitable fields of study. Changes have already been observed in the relative importance of the different pest species, in direct relation with the specificity of action of the different Bt toxins. On-going studies suggest an apparently limited impact on the diversity of non-target arthropod communities within cotton fields, while other investigations have focussed on the impact (also limited so far) of the entomotoxins on soil biology.

In addition to genetic transformation for the expression of genes coding for entomotoxins, other transformations enable the expression of genes conferring tolerance to a range of herbicide molecules (glyphosate, glufosinate, bromoxynil). These are also increasingly successful (Box 15). The two properties (herbicide tolerance and insecticidal action) are now available in combination in the same plant. The total areas sown in 2007 (5) were 10.8 million ha of Bt cotton, 1.5 million ha of Bt cotton tolerant to the herbicide glyphosate, and 1.1 million ha of cotton resistant to glyphosate alone. The breakdown for maize in the same year was 9.3 million ha of Bt maize, 18.8 million ha of Bt maize tolerant to herbicide, and 7 million ha of maize tolerant to a herbicide alone. However, the global market for genetically modified crops is dominated by herbicide tolerant soya, which in 2007 accounted for 58.6 million ha. Herbicide tolerant soya alone represent 51.2% of the total area of all transgenic crops. In all, 80.9% of the area under GMOs (92.5 million ha), was planted with crops that are tolerant to the same herbicide – glyphosate – a situation which, perhaps

BOX 15 Glyphosate explained (8)

Glyphosate is an analogue of a natural amino acid, glycine, which inhibits an enzyme required for the synthesis of aromatic amino acids involved in the synthesis of vitamins in many secondary metabolites.

Glyphosate is a systemic herbicide that is only active against plants, but has been described as non-selective and as presenting risks for the health and biodiversity of aquatic animals (including amphibians). Beyond its agricultural uses, aerial applications have been used to destroy cocaine plantations in Columbia, and it was in 'agent orange' the defoliant used during the Vietnam War. Since the cultivation of glyphosate-resistant GMOs and particularly of glyphosate-resistant soya, the consumption of glyphosate has risen significantly and it has largely replaced other available herbicide active ingredients. However, following the use of transgenic herbicide-tolerant soya, a range of weed species has already become resistant to glyphosate, for example *Ambroisia trifida* in the United States (Indiana, Ohio). Herbicide applications on GM crops have recently led to the localised appearance of resistant strains of *Lolium rigidum* in asparagus crops, orchards and vineyards.

unwisely, creates particularly favourable conditions for the emergence of resistance to the herbicide, and for the development of changes in the composition of the weed flora. In Australia, the seriousness of these risks has led to recommendations for the development of integrated weed management systems within an overall strategy of integrated protection.

Given likely impacts on crop health and on the environment, and the current state of knowledge of cotton growing, the future of existing GMOs may be threatened by the development of resistance by pests and weeds. The rational use of GMOs in the context of an integrated control strategy is therefore crucial if they are to continue to be useful. The spectacular reduction in the applications of traditional insecticides made possible by Bt cotton has freed us partially—but significantly—from a constraint which up to then had prevented the development of more bioecological solutions. Resistance management programmes encourage us to take into account the spatio-temporal dimension of the biological and genetic mechanisms involved to the benefit of an agroecological approach to plant protection.

5.2 FORESEEING THE DEVELOPMENT OF RESISTANCE

Awareness of the risk of the development of resistance is reflected in the legal obligation of cotton growers in the USA to set aside areas without Bt cotton, called refuge areas. The aim of these areas is to favour dilution of resistance genes in pest insects by enabling genetic exchange between populations that are under selection pressure from Bt proteins and those that are not. Since the earliest sales of the GM cotton variety Bollgard® in the USA, the American Environmental Protection Agency (EPA) had two requirements: first, guaranteed high-level expression of the entomotoxin *CrylAc* to ensure that practically all individuals of the target pest species are destroyed. Second, producers' compliance with the requirement for 'refuge' crop areas, sown with non-transgenic cotton seeds. There were two options: dedicating 4% of the total surface area of the farm's cotton crop to non-Bt cotton on which no insecticides were applied, or 20% of the same total cotton area (also in non-Bt cotton) in which insecticide applications could be used on the condition that they did not include applications of sprayable Bt formulations. Annual monitoring of the frequency of resistance alleles in the pink bollworm populations in Arizona since 1997 appears to confirm that this strategy was well founded. We should note, however, that this strategy requires particular genetic characteristics of the resistance gene (recessive, low initial frequency) which are not necessarily met for all Bt susceptible pests in all areas.

These regulatory measures have undergone modifications since 1995 to take into account both their suitability for local cropping systems and the reluctance of producers to respect them, as well as advances in our understanding of the distribution of lepidopterous pests among fields. Today, different options are available in the USA. One option under study, which is likely to be attractive to groups of producers, as opposed to individual growers, is based on one of the two options mentioned above, but facilitates the concentration of the refugia (Figure 6).

These arrangements are also applicable to more recent types of Bt cotton sold. Further slight modifications may be advisable as

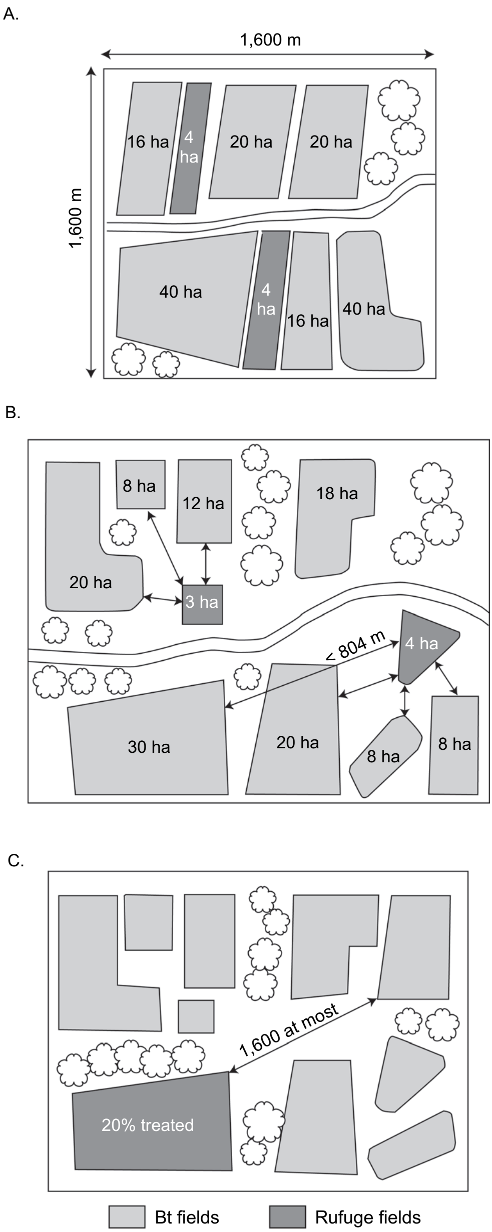

Figure 6 Towards concerted planning of refuge areas (9,10)

A concerted approach is recommended to facilitate the collective management of potential problems of resistance. Rather than imposing a refuge zone in each field within a production area, it is proposed that a number of whole fields should be kept as refuge areas, provided this is accepted by the producers concerned. All the cropped fields within a square of side 1,600 m (around 1 square mile) are then considered as part of the same resistance management unit. In each case, the refuge areas are sown with a non-Bt variety of cotton whose agronomic characteristics are as close as possible to those of the Bt variety sown in other parts of the management area. All producers need to use the same agronomic practices in a homogeneous and synchronised way. Three options are available:

- Option A (non-Bt refuge areas located within the Bt fields): parts of the cropping area are by communal agreement designated as refuge areas on the basis of 5% of the total area of the cotton crop in the management area concerned; these areas must remain free of all treatments based on Bt;
- Option B (refuge areas located outside fields planted with Bt cotton and not treated): in this option whole fields are designated as refuge zones, separated from the Bt fields and given over entirely to their function as refuges. They need to be located less than 400 m from the Bt crop fields and to be free of insecticidal treatments of all kinds;
- Option C (refuge located outside the Bt fields and treated with pesticides): these are whole fields as in option B, but they can receive insecticidal treatments of any type, provided that the cumulative refuge area represents at least 20% of the total cotton area in the region concerned. They need to be located less than 1,600 m from the areas planted with Bt cotton.

our knowledge increases on the mode of action of the entomotoxins or on the genetic basis of resistance in the pest species concerned.

An exception to these general rules can be observed in areas where the pink bollworm is the major pest, since it is the target of specific control measures, either by the release of sterile males or by pheromone trapping (as is the case in California, Arizona and New Mexico). In this particular case, it is acceptable to practice intercalated sowings of Bt and non-Bt varieties, for example one row of non-Bt cotton for every six to 10 rows of Bt cotton. It is worth emphasising that both in the case of refuges and of no refuges, the pest manager needs to be aware of the importance of the spatial dimension of crop protection. In areas where cotton is associated with maize, there is a risk involved in planting the two crops side by side if both are genetically modified for the expression of the same or very similar toxins as the two crops share key pests. In this case, it is recommended that at least 50% of the total cultivated areas be set aside as refuge areas.

Other strategies have already been envisaged in addition to the expression of several toxins in the same plant: rotation of crops expressing different entomotoxins or increases or reductions in the levels of toxins expressed. These emphasise the fact that it would be wise to undertake preliminary studies on a case by case basis. There are also agronomic particularities which may require local adaptation because of the composition of a particular pest complex, or because of cropping systems that combine transformed maize and cotton, for example. In certain situations taking into account the combination of crops that can host the same polyphagous lepidoptera allows more flexibility in meeting the requirements of the regulations when designing refuge areas.

In Australia, in comparable industrial growing conditions but where the pest complex is dominated by *H. armigera,* priority has been given to good agricultural practices, in the first tier of which is limiting the total area sown with Bt cotton. Initially the farmers were not allowed to grow Bt cotton on more than 30% of their land. This precaution took account of the inadequate expression of the Cry1Ac protein at the end of the growing season, a possible factor in the emergence of resistance. Complimentary chemical treatments were therefore recommended to reduce this risk in the framework of an overall management plan like the one detailed below.

In China and India, cotton is grown on very small-scale farms which practice mixed cropping. For example, in China, cotton is grown with wheat, soya and peanuts. In India, the cropping associations include pigeonpeas, chickpeas, sunflowers, okra and red peppers. In these conditions, the creation of planted refugia is considered unnecessary at least for the control of the polyphagous *H. armigera.* Although a GM field border of five rows of non-GM cotton is the official recommendation in India, in practice few farmers comply. The polyphagous nature of *H. armigera* allows for natural dilution of resistance genes as a variable proportion of the insects feed on non-transgenic hosts. Various weed species also contribute to the natural refuge for polyphagous lepidoptera. However, in the particular case of the pink bollworm, the fact that it is monophagous on plants in the order Malvaceae, including cotton, hibiscus and okra, but on few other cultivated plants, increases the importance of planted refugia.

The second generation of transformed varieties, which express two or more entomotoxins simultaneously, has recently increased the spectrum of activity of Bt cotton (Table 7). A wider range of lepidoptera, including *Spodoptera frugiperda, S. exigua, S. litura* and *Pseudoplusia includens,* are controlled in addition to *H. armigera, H. zea, Heliothis virescens* and *Pectinophora gossypiella.* Measures to prevent the development of resistance can then be modified to account for the fact that resistance in the key species would require the simultaneous development of separate resistance mutations to both insecticidal proteins. In Australia, the sale of second generation Bt cotton (Bollgard II)® expressing two different Cry proteins, enabled an increase in the proportion of the total cotton area that can be planted with Bt cotton from 30% with the first generation variety (Ingard)® to 70%.

The genetic determination of insect resistance to these entomotoxins now appears to be more complex than initially believed. By analogy to the resistance observed with synthetic

TABLE 7 Characteristics of commercial varieties of Bt cotton (11)

Trade name	*Firm (or institution)*	*Genes coding for Bt proteins*	*Activity spectrum*
		First generation varieties	
Bollgard®	Monsanto (United States)	*cry1Ac*	*Heliothis virescens, Helicoverpa zea, H. armigera, Pectinophora gossypiella*
Guokang	Chinese Academy of Sciences	*cry1Ac/1Ab* fusion gene +/- CpTi	*Helicoverpa armigera, Pectinophora gossypiella*
		Second generation varieties	
Bollgard II®	Monsanto (United States)	*cry1Ac* and *cry2Ab*	*Heliothis virescens, Helicoverpa zea, H. armigera, Pectinophora gossypiella, Spodoptera frugiperda, S. exigua, Trichoplusia ni, Pseudoplusia includens*
WideStrike®	Dow AgroSciences LLC (United States)	*cry1Ac* and *cry1F*	*Heliothis virescens, Helicoverpa zea, H. armigera, Pectinophora gossypiella, Spodoptera frugiperda, S. exigua, S. litura, Trichoplusia ni, Pseudoplusia includens, Estigmene acrea*

pesticides, it was thought that resistance to the Bt delta-endotoxin would be semi-recessive, and that the expression of resistance would vary depending on whether the insect carried one or two copies of the resistance gene (semi-recessiveness could also be a function of the dose expressed in the plant). Recent investigations showed that resistance to Bt entomotoxins is more complex, frequently being at least semi-dominant, allowing an insect carrying only one resistance allele to display high tolerance to a toxin. In such conditions, the expected efficacy of the resistance prevention measures mentioned above is significantly compromised. Seed producers are now stacking an ever-increasing number of entomotoxins within the same cultivated plants, partly to prevent the risk of resistance and partly to increase the spectrum of pests against which the plants are active, raising the spectre of a new resistance treadmill comparable with the one observed earlier with synthetic insecticides. Although these developments doubtless have their benefits, the promoters of genetically modified plants constantly emphasise the importance of appropriate agronomic practices for the management of the populations concerned if the advances are to be sustainable.

To date, the major stacking of entomotoxic genes has used multiple proteins from the same bacterial species *B. thuringiensis.* Along with the Cry (crystal proteins or delta-endotoxins) already expressed in earlier transformed varieties and also used in the form of liquid and granular formulations, the more recently discovered Vip (vegetative insecticidal protein) exotoxins (also from Bt) are now available. A third generation Bt cotton variety, combining different types of toxins (Cry1Ab and Vip3A) which has an enlarged spectrum of action against pests, is registered in the United States by Syngenta under the name VipCot™. Chinese varieties containing Cry1Ac plus a Cowpea trypsin inhibitor (CpTi) have been available for years – the cowpea trypsin inhibitor is essentially an antifeedant and it is not clear how important its role is.

5.3 EXPLOITING NATURAL PLANT DEFENCES AND PROMOTING BIOLOGICAL CONTROL

Exploiting the natural defence reactions of plants is a new area of investigation for crop protection. The use of plant defensive reactions has been known for almost a century but is still not well understood. It is known that plants have the ability to recognise certain phytopathogenic agents and to develop their own defence reactions to prevent the disease developing. Recognition involves chemical components in the pathogen and/or in the plant itself. The recognition factors are able to elicit, induce, activate, or stimulate responses. The binding of an elicitor with a plant cell receptor triggers a succession of events resulting in the production of the defence response. The molecules whose synthesis is induced in the plant in response to biological, physical, or chemical stress factors, are called phytotalexins.

A range of studies has shown that applying biological elicitors to a plant increases its resistance to diseases by prophylactically activating its defence reactions. A new pest control strategy is currently being developed based on the stimulation of natural defences in this way. To clarify the principles of the strategy, some authors have drawn an analogy with the immune reactions of vertebrates triggered by vaccination.

Laminarin, an elicitor extracted from brown algae, has just been approved by the French Ministry of Agriculture as a molecule of interest for the control of early cryptogamic diseases of wheat and barley. It comprises an unremarkable 'reserve' polysaccharide, an analogue of starch in higher plants, whose application on a plant induces a range of defence responses. Other compounds with similar properties are extracts or secretions from a range of fungi and bacteria. Elicitins, for example, are small eliciting proteins produced by fungi of the pathogenic genera *Phytophthora* and *Pythium.* They trigger defence reactions in certain plants through mechanisms which are not yet understood. Harpins, small proteins of bacterial origin, have similar properties and are the basis of a range of formulations in the United States, especially for use against cotton diseases. For the moment, the cost of the formulation of these molecules, along with their very specific requirements for extraction and preservation, limit their application to high value-added markets such as market gardening, tree crops, and horticulture. Laboratory studies recently showed that cottons that are genetically transformed to express these harpins are resistant to nematode attacks.

As indicated above, the application of autocidal control techniques implies perfecting industrial scale mass rearing of the target insects, and mastering their handling and dispersal in the environment after sterilisation. With beneficial entomophagous fauna, these difficulties are compounded as their multiplication also requires the mass rearing of their insect hosts. One of the most common examples is the ladybird, which is sold today in garden centres. Ladybirds are produced in insectaria on reared aphids, themselves raised on appropriate plants, or alternatively in industrial multiplication units where they are reared on the eggs of lepidopterans such as the Indian meal moth. As can be imagined, the problems involved in the storage and transport of these living organisms are quite different from those of inert substances which can be placed on the shelf of the shop without any special precautions. A specialised market has consequently emerged to meet the specific needs of the growers of vegetables and ornamentals under glass or in the open field, and for fruit growers and producers of cereals such as maize.

In the case of microbial biopesticides (Box 16), the technical difficulties to be overcome are theoretically simpler to the extent that bacteria and fungi can be multiplied on—or in—culture mediums. The industrial techniques of deep liquid fermentation or semi-solid fermentation are fairly simple whereas the multiplication of viruses is necessarily intracellular. This requires either mass rearing of the insect host or cell culture in fomenters.

BOX 16 Biopesticides, agents of biological control or biological means of control?

As for IPM, opinions differ on the definition of the term 'biopesticide'. Some limit it to living pesticides while others extend it to include all products of natural origin which have biocidal properties, whether living or inert.

- The latter definition appears to be prevailing today among legislators, and was also recently adopted by the US-EPA. According to this definition, biopesticides fall into three categories of substances of natural origin which share the ability to control crop pests:
  - Biochemical pesticides originating from substances of natural origin, for example sex pheromones which disrupt the mating behaviour of Lepidoptera and certain Diptera;
  - Microbial biopesticides, comprising micro-organisms (bacteria, fungi, viruses) and protozoans, such as *Cryptonectria (Endothia) parasitica* hyper-virulent strains of which are used to control chestnut canker;
  - Plant protection compounds or pesticidal substances synthesised by plants which are genetically modified for the purpose, like the entomotoxins from *Bacillus thuringiensis* synthesised in the tissues of maize, soya, cotton and potato.
- In Europe, only two categories of crop protection products are officially accepted: chemical substances (including those of natural origin) and micro-organisms. There is no identification of a specific category of biopesticides. In its *Index Phytosanitaire 2008,* the French *Association de Coordination Technique Agricole* (ACTA) advises against the use of the term 'biopesticides' and recommends the term 'biological product' or better 'biological tool' to designate all organisms, substances or preparations for the control of pest organisms for which the active ingredient is produced by living organisms or is a product of their metabolism. Taken out of their context, these expressions may be disconnected from the specific properties of the living world that can be exploited and with the characteristics of the products or techniques concerned (mode of action, mass rearing, formulation, homologation, processing, storage, conditions of use, etc.).
- For this reason, in this work, we use the distinction adopted by most biologists:
  - 'Biological control agents' is used to describe biopesticides produced from living organisms, parasites, pathogens, antagonists or competitors,
  - 'Biological control methods' is used to describe control techniques based on natural biological substances such as the pheromones described above.

In any event, the multiplication of living organisms poses specific problems, including the precise biological characterisation of the organisms, the preservation of their specific properties during multiplication, their formulation, concentration and storage, not to mention their cost. Because of the regulations applicable to their status as living things, the difficulties encountered in the course of their formulation into products have usually discouraged investors. Finally, the users themselves have often been discouraged by the constraints they involve and by the particularities of their modes of action. For these reasons, biopesticides based on living organisms—biological control agents—represent less than 2% of the pesticides sold today.

Cotton has not been the subject of spectacularly successful classical biological control based on the introduction of beneficial organisms. This is because of its annual growth habit, and the wide diversity of its pests (which are often polyphagous), and also because, very early on, priority was given to the use of very non-specific insecticides. However, inundative biological control (meaning the release of large numbers of beneficial organisms, which may or may not survive to breed, into a system as a sort of biopesticide) has inspired many research and development programmes.

Pest control using parasitoids such as trichogrammatid egg parasitoids, or baculoviruses has targeted boll-feeding caterpillars. Trichogrammatids are minute hymenopteran insects whose females lay their eggs in the eggs of various lepidopteran crop pests and other insects. They are used particularly in China and in the ex-USSR, but were promoted in a way that did not allow a clear assessment of their individual efficacy rather than the efficacy of other changes in techniques applied simultaneously, such as the reduction in the use of broad spectrum insecticides. Trichogrammatids were produced in bulk in the area in which they were to be used, i.e in the *kolkhozes* or communes, thus avoiding problems of storage and transport. In retrospect, quality control at the level of such small production units was often inadequate, and consequently applications were probably often ineffective. Today, modern production procedures are used in automated pilot factories which operate all year round, and utilise the control of developmental arrest in these insects, which is specific to certain strains. In France, the firm BIOTOP (which belongs the co-operative group IN VIVO) produces and sells trichogrammatids for use against the maize stem borer (86,000 ha treated in 2006), but also, under the brand name TRICHOTOP E®, against the polyphagous noctuid moth *H. armigera,* well known to cotton producers. In developing countries particularly, however, problems of quality control and the difficulties of proving timely delivery of the parasitoids to the field continue to bedevil the use of the technique.

Baculovirus is currently produced from mass-bred infected insects, which is less costly than production by cell culture. In certain cases, such as that of the velvet bean caterpillar, *Anticarsia gemmatalis* in Brazil, it is even profitable to manually collect infected caterpillars from fields naturally infected early in the season in sufficient quantities to enable the extraction of useful quantities of the virus. Of course the cost of production depends on the quantity produced and the use of cell cultures in simple nutritive mediums may be possible one day. This may be vital if resistance to genetically modified cotton compromises the future of existing control strategies. The product GEMSTAR®, a formulation based on a baculovirus of *H. zea,* is registered in the United States, Mexico and Australia.

In several areas of the world—including the Middle East where pressure from pests is locally low—biological control plays a major role in protecting cotton crops. The most distinctive example is undoubtedly that of Syria, where, over a period of about 25 years (1979-2004), the percentage of the cotton crop area (203,000 ha in 2003/2004) treated with insecticides dropped from 25% to around 0.5%. This drop was due to an intentional change in crop health strategy within the framework of strictly planned production, which was adopted more for economic than environmental reasons. The pest thresholds for the major pests, such as *H. armigera,* were considerably lowered in order to reduce the consumption of insecticides and as a result, the demand for insecticides decreased to the benefit of populations of indigenous beneficial organisms. Early sowing of short-stemmed varieties of cotton (less than 90 cm), with smaller leaves had the consequence of improving overall crop health thanks to better exposure of the leaves to sunlight, better ventilation within the canopy and to the plant reaching an advanced stage of vegetative development before the major pests appeared. Biological control is practiced, in strictly controlled circumstances, by inundative releases of trichogrammatids multiplied in state laboratories. Other beneficial species are recommended against outbreaks of whitefly. Varieties that are resistant to verticillium wilt and the use of appropriate cultural control techniques (planting density, irrigation management, hand weeding) prevent the appearance of bacterial diseases. Herbicide treatments are approved alongside hand and mechanical weeding. In these particular conditions, the yields obtained are amongst the highest in the world (around 1,300 kg/ha of cotton fibre).

Comparable results have been obtained locally in Turkey in conditions which are ecologically similar but economically different. The high yields obtained have been credited to the beneficial role of the indigenous predator fauna maintained by the use of an IPM strategy. In Egypt, in a biological control programme, trichogrammatids were released, *B. thuringiensis* was sprayed and, if needed, insect growth regulators were used. The results were equivalent to those obtained with chemical treatments. Australia has a recommended management strategy for indigenous beneficial insects. In addition to specifying the appropriate techniques described below, this strategy is notable for taking into account a predator/pest threshold ratio before launching specific actions, with a view to maintaining populations of predators. The same strategy was tested in Texas without the same success, but in an agronomic and pest context that was significantly different.

In general, in growing systems based on classical IPM techniques or which promote the use of genetically modified cotton, the significant reductions in insecticide treatments have enhanced the beneficial role of the indigenous beneficial predator fauna, which was usually insufficient on its own and had been little exploited up to then. Here we see a new biological control strategy in the process of development, particularly through the appropriate management of the habitats required for conservation biology. This has been called 'conservation biological control'.

In the past decade, a transition programme from conventional agriculture towards organic production has been implemented in the San Joaquin Valley (California) under the name of BASIC — *Biological Agriculture Systems In Cotton.* Located on the fringe of the American cotton belt and protected from invasion by the boll weevil, farmers in this programme can use planned crop protection practices which have enabled spectacular reductions in the quantities of pesticide used, on condition that growers strictly respect the complex IPM advice, which largely draws on biological control techniques (Box 17).

BOX 17 Principles of the BASIC programme used in California (12)

- Sow the cotton in April, at the optimal date determined by a decision tool based on measurements of soil temperature,
- plant the cotton field adjacent to lucerne (alfalfa) fields, which creates a border of plant habitats favourable to beneficial organisms,
- intensively scout populations of pests and natural enemies,
- release beneficials organisms in the cotton fields early,
- reduce, or if possible eliminate, spring pesticide treatments, or, if not, then use active ingredients which have limited effects on beneficial fauna,
- balance fertiliser applications to meet requirements.

At the end of the 1980s, cotton production trials following the principles of organic production were first undertaken in Turkey, and later in India, Peru, Egypt and the United States. In all cases, this involved diversifying the systems of low input 'organic' agriculture already in place, and combining them with no use of synthetic inputs, selection of locally adapted varieties, use of local organic fertilisers and green mulching, crop rotation and mechanical or hand weeding. In this crop protection system, the objective is to re-establish the natural equilibrium to avoid pest outbreaks through the creation of habitats appropriate to the maintenance of beneficial populations, growing plants that favour their multiplication or which attract the pests out of the crop to be protected, synchronous seeding and the destruction of crop residues after harvest. If necessary, disruption of mating with artificial pheromones or biological control is undertaken. The financial consequences of using organic practices are decisive for the farmers, as the production cost is significantly higher than in traditional cotton mainly because of increased labour requirements and reduced yields. The demand from the fashion industry, responding to a public demand for fairer trade, is the reason for the successful economic returns on investments in organic agriculture in many African countries—Benin, Burkina Faso, Mozambique, Senegal, Tanzania and Zimbabwe. However, the world market for organic cotton represents less than 1% of the total market and appears to be stagnating, although this does not seem to be discouraging the promoters of organic cotton. Taken together, the outcomes of these practices are a source of precious information for the development of new growing systems (13).

Bibliographic References in Chapter 5

(1) Mergeai G., 2006. Introgressions interspécifiques chez le cotonnier. *Cahiers Agricultures,* 15 (1), 135-143.

(2) Hofs J.-L., Berti F., 2006. Les cotonniers *(Gossypium hirsutum* L.) génétiquement modifies, Bt: quel avenir pour la petite agriculture familiale en Afrique francophone? *Biotechnol. Agron. Soc. Environ.,* 10(4), 335-343.

(3) Abou Abba A., Hofs J.-L., Mergeai G., 2006. Relever les défis environnementaux pour les filiéres cotonniéres d'Afrique de l'Ouest et du Centre. *Biotechnol. Agron. Soc. Environ.,* 10(4), 351-359.

(4) Nester E. W., Thomashow L. S., Metz M., Gordon M., 2002. *100 years of Bacillus thuringiensis. A Critical Scientific Assessment.* American Academy of Microbiology, Washington D.C., 18 pp., <http://www.asm.org/academy/index.asp?bid=54424> (consulted August 19, 2008).

(5) James C., 2007. Global Status of Commercialized Biotech/GM Crops: 2007. ISAAA Brief n° 37, ISAAA, Ithaca, NY.

(6) Hofs J.-L., Schoeman A., Mellet M., Vaissayre M., 2005. Impact des cotonniers génétiquement modifiés sur la biodiversité de la faune entomologique: Le cas du coton Bt en Afrique du Sud. *Int. J. Trop. Insect Sci.* 25(2), 63-72.

(7) Wolfenbarger L. L., Naranjo S. E., Lundgreen J. G., Bitzer R. J., Watrud L. S., 2008. Bt crop effects on functional guilds of non-target arthropods: A meta-analysis. PloS ONE 3(5): e2118.doi :10.1371/journal.pone.0002118.

(8) Vandelac L., 2005. OGM, la filiére pesticide et l'herbicide Roundup. Quelles leçons pour une agriculture durable et viable? Forum annuel de

l'IAC : A la recherche de stratégies de soutien de l'agriculture durable au Canada; 6-9 novembre 2005, Québec. <http://www.aic.ca/conferences/pdf/2005/Louise_Vandelac_FRA.pdf> (consulted August 19, 2008).

(9) Monsanto 2005. 2005 Bollgard and Bollgard II Insect resistance Management (IRM) Guide. 10 pp., <http://www.monsanto.com/monsanto/ag_products :pdf/stewardship/bollgard.pdf (consulted April 15, 2006).

(10) Monsanto 2008. Cotton 2008 IRM Guide, a) Eastern Region b) Western Region. <http://monsanto.com/monsanto/ag_products/stewardship/irm.asp> (consulted August 20, 2008).

(11) Deguine J.-P., Ferron P., Russell D.A., 2008. (see reference n° 2 of Chapter 2).

(12) Gibbs M., Dufour R., Guerena M., 2005. BASIC Cotton Manual. Practical Lessons Learned from the Sustainable Cotton Project's Biological Agricultural Systems In Cotton (BASIC) Program. Sustainable Cotton Project, San Joaquin Valley, California, 2001 to 2004, 54 pp., <http://www.caff.org/programs/farmscaping/Cotton%20Manual.pdf> (consulted June 18, 2006).

(13) Haynes I., 2006. Le coton bio et/ou equitable: réel avenir ou effet de mode? *Biotechnol. Agron. Soc. Environ.*, 10(4), 361-371.

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CHAPTER 6

Ecological Bases of the Management of Populations

The United Nations Conference on the Protection of the Environment, 'We have only one World' (Stockholm, 1972), was the occasion for publicly expressing the growing preoccupation with the overall management of the planet. The conference saw the adoption of the principles of ecodevelopment, forerunner of the current concept of sustainable development, which proved ephemeral because of the economic consequences of the subsequent oil crises. According to this new principle, it was recognised that it was not only necessary but also possible to design and implement socio-economic development strategies which are equitable and respectful of the environment. This was a positive response to the Malthusian conclusions of the report of the Club of Rome ('Limits to Growth', 1972), the publication of which understandably alarmed the governments of developing countries (1).

More generally, the conclusions of the Stockholm conference underlined the fact that the problems of the environment and those of development need to be treated together. Ecology, the science of interactions between living things and their environments, thus made its entrance on the political stage

(Figure 7). At the same time (1971), a Secretariat for the Environment was created by the French government. In the same year, the United Nations Organisation for Education, Science and Culture (UNESCO) launched the 'Man and Biosphere' (MAB) programme, whose objective was combining concerns for the protection of nature with those for the development of populations and of local economies in a concerted approach. Its originality lay in its interdisciplinarity, particularly in bringing together biological and human sciences to achieve its objective of demonstrating—and providing training in—the rational use of natural resources for the benefit of human populations. Its activities were concentrated in demonstration sites, called Biosphere Reserves (482 reserves in 102 countries were inventoried in 2005 including the Camargue and Mont Ventoux in Provence, and the archipelago of Guadeloupe). Today, several West African states are requesting that these biosphere reserves be used as demonstration sites for sustainable development. As a matter of fact, cotton plays a determining economic role in several of these sites, including the Pendjari Reserve in Benin, the mouth of the Baoulé River in Mali and the vast cross-border regional park of Benin—Burkina Faso — Niger.

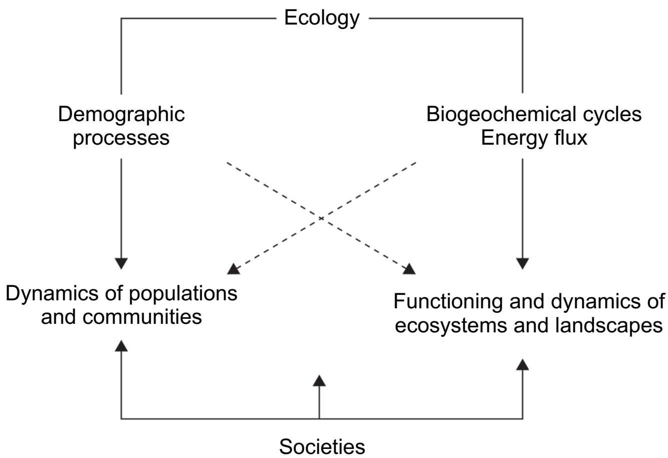


Figure 7 Ecology, the science of nature (2)

It is in this context that the biology of conservation, (or the ecology of conservation according to Robert Barbault, Professor at the University of Paris VI (2)), was born in a scientific milieu favourable to the protection of nature and preoccupied by the accelerating reduction of biodiversity. The biology of conservation recently addressed itself to the field of agronomy and more specifically to the problems of preserving biological diversity, which is considered to be a determining factor in the ongoing functioning of ecosystems. Conservation biology comprises the study of the effects of human activities on species and ecosystems, and the design of appropriate solutions to prevent the extinction of the species most at risk. At least initially it has been primarily concerned with emblematic species, such as the giant panda, to the detriment of the too-often anonymous key species that ensure the proper functioning of ecosystems, e.g. pollinators and decomposers of organic matter. Methodologically, it relies mainly on the analysis of the processes which maintain biodiversity at different spatio-temporal and ecosystem levels, and its aim is to provide concrete proposals for the sustainable conservation of species, communities, ecosystems and landscapes. It gives priority to the concept of ecosystems and it thus makes sense to reposition agriculture within this conceptual approach and break with the traditional vision of 'the environment', which is all too often reduced to its physio-chemical constituents and frequently limited to the scale of a single field.

For C. Dupraz (3) this implies a radical change of perspective, moving away from an increasingly specialised approach to agricultural production at the level of the single field to the 'management of cultivated ecosystems' based on concepts of innovative growing systems inspired by the ways in which natural ecosystems function. In crop protection, this also implies a fundamental review not only of our objectives but also of our way of thinking. In this view, crop protection must also play a role in ensuring the conservation of the biological diversity of the biosphere.

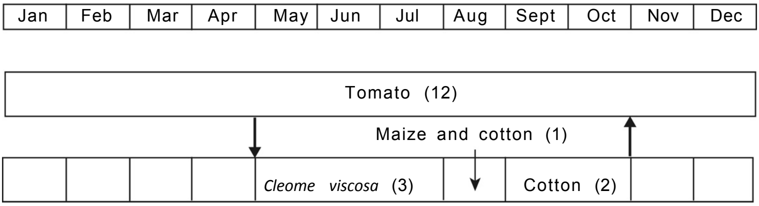
6.1 "THINK GLOBALLY, ACT LOCALLY"

Although this maxim, which was coined by Rene Dubos, is frequently cited today, its ecological context is rarely acknowledged. According to the author, "the management of the future may be summarised as follows: '*think globally, act locally*'" (4). However, if this recommendation is to be followed correctly, understanding ecological systems is an essential prerequisite.

Thinking about ecology, we immediately come up against the complexity of the living world, despite undeniable avances in our understanding over the last 20 years. The complexity is due to the variety of actors concerned and their interactions in a changing world. These are not ideal conditions for finding sustainable solutions to the problems of crop protection which concern us here. Nevertheless, this is the direction that reason compels us to take, bearing in mind the limits and the drawbacks of the methods and techniques now available to us, and given the urgent need to change the way we exploit the resources of the biosphere.

To understand the complexity, we cannot limit ourselves to Cartesian methods that directly link causes to their effects and vice versa, which would perhaps be useful in the context of stable systems with a limited number of components. In this context, systems approaches have had considerably more success (5). A systems approach is based on a representation of reality that integrates aspects which are difficult to understand due to the lack of appropriate information, and which is more focused on finality than on causality. Such an approach uses innovative techniques like simulating complex phenomena. In the field of crop protection, simulation models can account for the dynamics of a pest population including variations in age structure over time and in changing environments. These approaches have largely replaced the simpler risk assessment models traditionally used as decision-aid tools in crop protection (6).

One example of the use of such an approach in cotton production is the simulation of the population dynamics of the polyphagous noctuid moth, *Helicoverpa armigera,* in the growing conditions of small-scale farmers in West Africa (Figure 8). The



Numbers in parenthesis are the number of generations affected by *H. armigera* in African cotton-based ecosystems (6, 7). Arrows indicate the movements of *H. armigera* between plants or crops.

Figure 8 Dynamic of attacks of *Helicoverpa armigera* in African cotton-based ecosystems (6, 7).

caterpillars of this pest attack both irrigated vegetables in peri-urban areas and rain-fed crops in rural areas. The climatic conditions of these regions, which are characterised by a long dry season from November to April, oblige H. *armigera* populations to migrate from one area to another to survive. During the unfavourable season, the insect multiplies on irrigated tomatoes with up to a dozen successive generations. With the arrival of the rainy season, and given the increased scarcity of vegetable production, the moths migrate towards rain-fed maize and cotton fields and use common weeds, such as *Cleome viscosa* (Capparidaceae), as temporary plant hosts. At the end of October, after three successive generations on cotton, the moths move back to the market gardens.

This example shows that the functioning and kinetics of a population of pests cannot be understood without taking their environment into account, what R. Barbault called the 'population-environment' (2). A population can be considered as a system because of the multiple interactions between the individuals which comprise it and those with which they are associated in the same biological community. Characterised by multiple state variables (numbers, age structure, genetic structure, spatial distribution etc.), which themselves are affected by demographic processes (birth, mortality, emigration, immigration), which in turn, are affected by other biotic and abiotic factors in the environment, the population acquires a kinetic that we need to understand if we are to be capable of managing it. This may give rise to an overarching intervention system capable of limiting harvest losses, accounting for both spatial and temporal scales, as already suggested by plant disease epidemiologists (8). Such a system has been used to validate the 'refugia strategy' in the case of the increasing number of insect-resistant GMOs, comprising a range of actions such as those described earlier for Bt cotton (Figure 6, Chapter 5).

Using such approaches means we need to understand the different trophic levels of the ecosystems concerned, from photosynthesising plants (the primary producers) to the different consumers and decomposers (Figure 9). These transfers have simultaneous effects at different spatio-temporal levels. The maxim laid down by Rene Dubos during the 1972 Stockholm conference cited above '*think globally, act locally*', needs to be adapted to the scale of the activity. It is often necessary to think and act globally and locally at the same time to ensure the preservation of biodiversity, since the data and results are relevant at a local scale (plant, field), while their integration feeds decision making at a larger scale (region, landscape).

Given the gaps in our knowledge of the determinants of the population dynamics of the different organisms involved, we usually have to limit ourselves to local targeted actions. In the

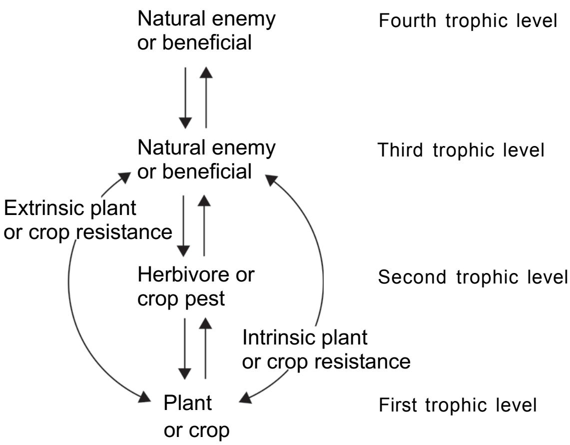


Figure 9 Diagram of the interactions between the different trophic levels of ecosystems (9).

absence of an overarching strategy which requires a complete review of agrarian structures. As was the case during land reorganisation in the 1960s in France, such actions often concern the organisation of field borders. In France, reorganisation was undertaken in response to the need for the mechanisation of agriculture, which implied rethinking the geometry and distribution of fields, even though their secondary effects on soil erosion, water dynamics, biodiversity, etc., were poorly understood or even ignored at the time. This plan led to the destruction of around 70% of the two million kilometres of hedgerows that existed in France at the beginning of the 20th Century, the peak period for farmland criss-crossed by hedges and trees (10). Today, before it is too late — as for example in Brittany—we are forced to recover ancestral knowledge on the maintenance and management of hedgerows, with the twin goals of reversing the degradation of the traditional wooded countryside and of restoring practices which ensured sustainability and resilience. We are moving towards the re-invention of traditional agrarian structures, like those still found in vast areas of Central and Eastern Europe which have medium or low agronomic potential and are still characterised by scattered very small fields, and by layouts which—intentionally or not — include ecological compensation 'set-aside' areas. The Council of Europe has instigated a European-wide movement in this direction, partly inspired by the planning of rural areas in the Middle Alps in Switzerland (11). According to this functional approach, natural or ecological infrastructures fulfil the function of allowing animal and/or plant species to move around, feed, exchange genes, and colonise new territory. They are therefore vital for all the species in a biological community while providing for the specific needs of each. Overall, this approach seeks to re-establish the bioecological balance required for the sustainable functioning of cultivated ecosystems which were upset by the intensification of production.

It is easy to imagine the difficulty faced by farmers confronted with the need to reconcile the requirements of a production system which must achieve optimum quantity and quality to survive in competitive markets, with the conservation of the totality of biodiversity. As regards crop protection, a farmer using this approach has to make choices, initially on general functional ecological bases which favour populations of pollinators, parasites and predators, for example, and then as a function of the specific constraints related to the particular pests whose outbreaks he wishes to avoid.

The following are three areas of preventative agroecological interventions which are appropriate for this process:

- the adaptation of cultural practices and the adoption of innovative systems,
- the inclusion of non-cultivated areas within the farm to form these new ecological infrastructures,
- the creation and maintenance of corridors of natural perennial vegetation to favour the movement of vertebrates.

Here we are a long way from the traditional (limited) strategy of crop rotation in which the individual field was the only centre of interest.

These necessary alterations in scale certainly imply improved dialogue between farmers and planners. This broader approach to the management of plant populations based on local actions is supplemented by recently acquired knowledge in landscape ecology. For example, it has been demonstrated that the colonisation plots of fragmented populations can occupy large areas (up to several hectares) and that their distribution is linked to the nature of the agrarian structures themselves (12). We believe this change in mentality and in strategies and practices may finally enable the preservation of biodiversity to the benefit of truly sustainable development of the biosphere.

6.2 COMBINING PRODUCTIVITY AND THE PROVISION OF ECOLOGICAL SERVICES

The basic difference between a cultivated ecosystem and a natural ecosystem is the role played by people, since they exploit the resources of the first and benefit from the services provided by the second (Box 18). We can now complete the earlier schematic diagram (Figure 9) illustrating the interactions between the different trophic levels of ecosystems by taking into account the physio-chemical, biological, and socio-economic services provided by the ecosystem and the impacts of human activity.

BOX 18 Ecological services ensured by the proper functioning of ecosystems (14)

- Regulation of the chemical composition of the atmosphere, regulation of climate,
- regulation of environmental perturbations (floods, droughts, storms)
- regulation of the water cycle, control of erosion,
- soil formation, storage and recycling of nutrients, waste treatment, pollination, biological control of populations across trophic chains,
- refugia for resident or migratory populations,
- production of materials, sources of biological material and of natural substances,
- ecotourism, outdoor activities, aesthetic, educational and scientific values.

This gives a central role to biodiversity as a concept applied to the different forms of variation in living things: genetic diversity at the level of the species, the diversity of species within the different taxonomic groups and the diversity of ecosystems. We are currently experiencing erosion of these different forms of biodiversity including the eutrophication, destruction and fragmentation of natural habitats, and the introduction of exotic species which are sometimes invasive. At the 2005 International Conference in Paris, 'Biodiversity: Science and Governance', David Tilman (14), Professor at the University of Minnesota, reported the convergent results of five major experiments on several continents: "the erosion of plant diversity provokes a reduction of productivity and of the absorption and fixation of carbon dioxide, and an increase in the loss of nutrients, of the frequency of diseases and of the sensitivity of systems to invasion by new species...and (very likely) a reduction in the stability of ecosystems". In fact, the richer an ecosystem is in species, the greater the diversity of functional systems within that ecosystem will be, which appears to be the key to the eventual outcomes. In the absence of incontestable experimental demonstrations of the impact of the partial loss of biodiversity, ecologists agree on the need to preserve in their entirety all the species that exist in ecosystems. Following the international conference in 2005, a global scientific evaluation was launched on the theme of biodiversity to better grasp the risks to which we are exposed. In Europe, concerted action has been proposed to measure the scale of the reduction in biodiversity and particularly to identify its causes. This is currently underway as part of the programme ALARM (Assessing Large-scale Environmental Risks for Biodiversity with Tested Methods), one of whose modules is dedicated to pollinators (Box 19).

BOX 19 Pollinators: Threatened providers of a major and often underestimated ecological service (15, 16)

The United Nations Conference on Biological Diversity (1992) underlined the crucial importance of pollinators in ensuring the survival or the evolution of more than 80% of plant species. Pollinators are mainly insects, frequently vectors of pollen in the course of their plundering activity as they move from flower to flower. Bees are the best known representatives of this group worldwide, with more than 20,000 wild and domestic species. Other insects such as flies, wasps, certain beetles and butterflies play the same role. This activity is as beneficial for wild flora as it is for cultivated plants, assuring their sexual reproduction while reducing the risk of degeneration through consanguinity.

Among the roughly 100 cultivated plant species which provide 90% of our food requirements, 71% are pollinated by bees, mainly by wild species. In practice, most fruit (Rosaceae), legumes (Cucurbitaceae, Solanaceae), oil seeds (rape, sunflower), proteinaceous plants (field beans) and forage plants (lucerne [alfalfa], clover), spices and stimulants such as cocoa and coffee, depend on insect pollination (cereals are wind pollinated and other crop plants, such as the grapevine and the olive can be self-fertilised). Many wild plants are equally dependent on pollinators: to cite some Mediterranean examples: forest tree species (maple, wild cherry, rowans, service trees, etc.), woody species (brooms, rock roses, etc.), ericaceous plants (cranberries, heathers, etc.), labiates (rosemary, thyme) (17).

Convergent observations made in different areas of the world show significant reductions in populations of pollinators. The media frequently draws attention to the concerns of beekeepers faced with the disappearance of their livestock, which may be explained by health factors, or by toxicological or ecological problems. We know that the disappearance of hedgerows which served as nesting sites, the increasing rarity of wild plants which provided nectar and pollen, applications of chemicals against pests, and the negative effects of certain invasive species, are the main causes of the reduction in wild bee populations.

This leads to the need to manage bee populations through the planning of agrarian structures and cropping systems, following a similar pathway to that described earlier for the auxiliary fauna which benefit crops.

The principal causes of the loss of biodiversity have been identified. Climate change is becoming a disturbing reality, but major recent factors are the destruction and fragmentation of habitats, overexploitation and the introduction of new species, together with the lack of understanding of the functional value of biodiversity for the sustainable exploitation of the biosphere. Given the current state of knowledge, research programmes in functional ecology are mainly centred on the analysis of population dynamics and communities or on measuring the impact of the fragmentation of ecosystems on the evolution of their biological characteristics. In practice, these are the forerunners of management studies for plant and animal communities in cultivated ecosystems and, more generally, for planning on a landscape scale.

The agronomist is one of the main actors concerned because of the size of the areas dedicated to agriculture over the centuries. Natural habitats, which are heterogeneous, continuous, and function according to the rhythm of the seasons, are disappearing and being replaced by artificial habitats, most often homogeneous, discontinuous and temporary in accordance with the economics of today, especially in the case of monocultures. Today agriculturalists exploit a very small number of cultivated species: 12 species of cereals, 23 species of beans/peas, 35 species of tree fruits etc., in all, a total of around 100 species for all the cultivated land on the planet, whereas in a single hectare of a humid tropical forest there are at least this many species of trees. It has even been estimated that around 90% of human food requirements are basically satisfied by 15 plant species and eight animal species.

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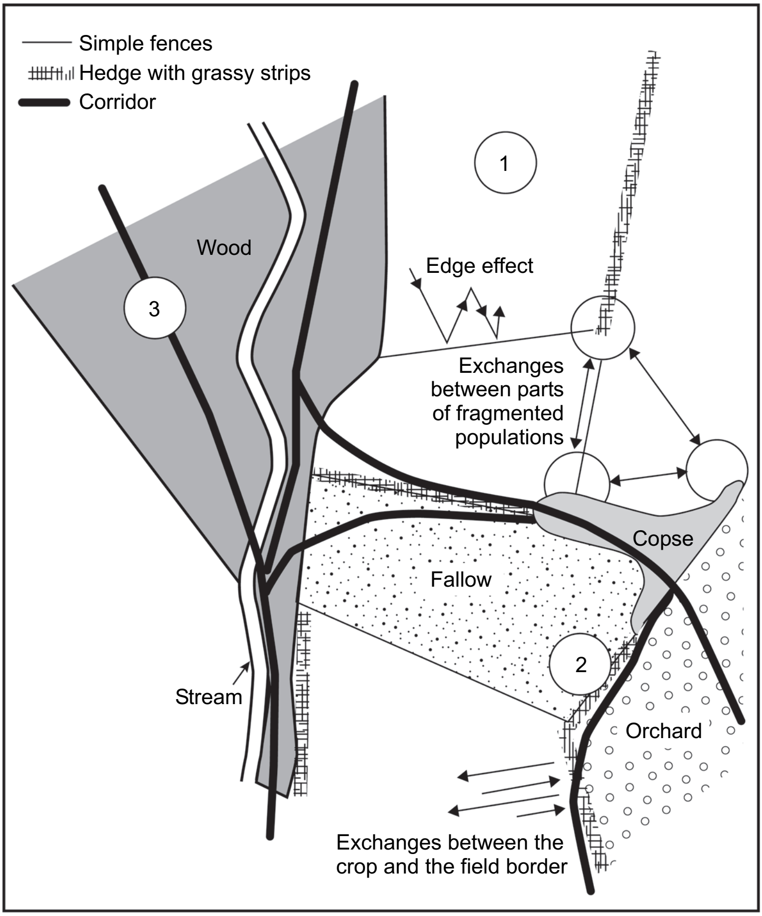

(1) Crop: planning of cultural practices, introduction of innovative cropping systems.

(2) Field borders: layout of ecological infrastructures such as hedges, turning areas, grassy margins

(3) Corridor: layout of perennial ecological infrastructures such as woods, copses, streams, orchards, vineyards, etc.

Figure 10 Schematic representation of some of the ecological functions of field margins (18, modified)

recourse to inputs (fertilisers, pesticides, energy) and to conserve biodiversity (see Box 5). It is thus a matter of reproducing natural ecological processes, but not simply by copying them, as we must take into account the impacts of human activities. In pursuing this goal, we need to keep in mind the basic concept of the trophic

BOX 20 The message from Ovronnaz (19)

As reported by M. Baggiolini, in 1976 a group of five entomologists from the IOBC assembled around H. Steiner in Ovronnaz (a small village in Valais, Switzerland). Inspired by the experience acquired through over 30 years of research and practical experimentation dedicated to integrated control, these researchers attempted to sketch the basis of a new conception of agricultural production. In 1977, a year later, the manifesto 'Towards integrated agricultural production, through integrated control' was published in the IOBC/SROP 1977/4 Bulletin.

Their message is summarised in the history of the conception of plant protection since the arrival of synthetic pesticides:

1. Blind chemical control	• widespread scheduled routine use of the most effective pesticides; advice provided by industry;
2. Recommended chemical control	• the use of broad spectrum insecticides following advice from an advisory or warning service;
3. Supervised chemical control	• the introduction of the concept of a threshold of economic tolerance, the use of pesticides without damaging secondary effects to protect beneficial organisms;
4. Integrated control	• in addition to the preceding recommendations concerning supervised chemical control, inclusion of techniques of biological control or of biotechnical advances resulting in good agronomic practices; strict limitation of chemical control;
5. Integrated farming	• in addition to the preceding recommendations concerning integrated control, respect for, and integration and development of all the positive factors in the agroecosystem, respecting ecological principles.

structure of ecosystems. The two fundamental components were summarised by R. Barbault (Figure 11). The first, concerning herbivory, is characterised by photosynthesising organisms or primary producers capable of fixing solar energy and of

BOX 21 Definition of integrated production updated by the International Organisation for Biological Control (20)

Integrated production is a system of production of high quality foods and other products through the utilisation of natural resources and balances, which allows the replacement of polluting inputs while ensuring the sustainability of the farming system. Attention is drawn particularly to a) a systematic overall approach considering the whole farm as the basic unit, b) the central role of the agroecosystem, c) the balances of material and energy, d) the well-being of livestock.

The essential components are the preservation and improvement of soil fertility, a diversified environment, and respect for ethical and social criteria. Biological, technical and chemical methods are carefully balanced taking into consideration environmental protection along with social and economic requirements.

synthesising their own tissues including the incorporation of mineral elements, and then by a succession of primary consumers (phytophages), and secondary consumers (carnivores). The second

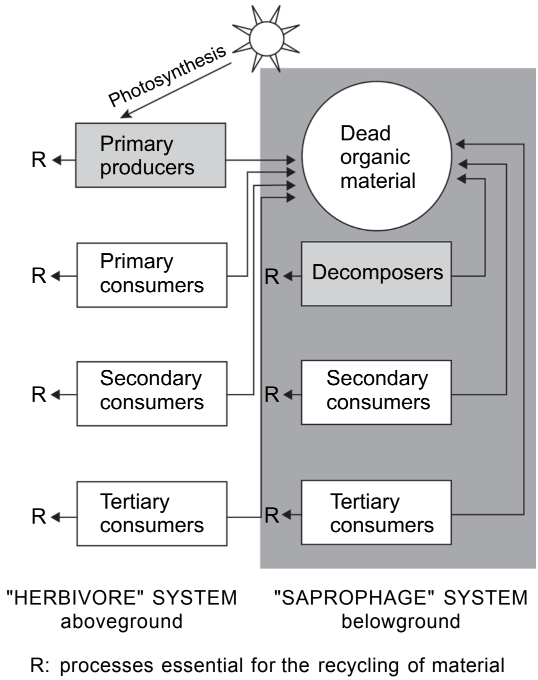

Figure 11 Schematic representation of the trophic structure of an ecosystem (2).

is composed of saprophages which ensure the recycling of organic matter and includes coprophages, saprophages, microorganisms and invertebrate decomposers, which are the functional equivalents of the primary consumers in the herbivory component. Within this sub-system, we also find the classic pyramid of secondary and tertiary consumers.

What is important to remember is that the two sub-systems are interdependent, which implies that all agroecological solutions proposed should take this association into account. Comparative analysis of the ecological processes in different types of growing systems shows us the areas in which we have to intervene to ensure the conversion of traditional systems to more sustainable management systems (Table 8). For this to happen, the following principles need to be respected: reducing the use of inputs, changing conventional practices and designing new production systems.

TABLE 8 Major ecological differences between natural and cultivated ecosystems (21)

	Natural ecosystem	*Cultivated ecosystem*	
		Sustainable	*Intensive*
Net productivity	average	average	high
Trophic interactions	complex	intermediate	simple, linear
Species diversity	high	high	low
Structural diversity	high	moderate	low
Genetic diversity	high	high	low
Resilience	high	high	low
Durability	long	long	short
Habitat heterogeneity	complex	intermediate	simple

Examples of production systems that are economical in inputs, through imitation of the functional processes of natural ecosystems ('mimicing natural ecosystems' or the 'Rule of 5 Ms' (see below)) were described by C. Dupraz (3). He identified four types of incorporation of species diversity into production systems at the field level: species associations (crop associations, mixed fodder plants, agroforestry, etc.), plant mosaics around crop fields (hedgerows, copses, riparian woodlands, banks, grassy strips, etc.), relay cropping (sowing under the cover of the previous crops), and traditional rotations. The solutions proposed are relevant to mimetic agriculture, a variant of the concept of biomimetism, which is characterised by cultivated systems inspired by the functioning of natural multispecies ecosystems, which are stable and sustainable. The 'Rule of 5 Ms' — Making Mimics Means Managing Mixtures—illustrates the central role of species diversity in ensuring the stability and permanence of these natural ecosystems in this concept. The stated objective is therefore to manipulate interspecific relationships to limit stresses. These stresses may be abiotic (water, light, nutrients) or biotic (competition and predation/parasitism). Attention is drawn to the need to demonstrate the productivity and durability of ecosytems cultivated with many different species, since up to now there have been only a few examples of real agronomic applications. The guiding idea (which is a little disturbing as it is contrary to established principles), is to grow mixtures of perennial plant varieties. In this way, not only do we avoid disturbing natural cycles, which is particularly unfavourable to the stability of cultivated ecosystems, but we also encourage competition, thereby helping to ensure diversified exploitation of resources through adaptive processes. This school of thought is thus the opposite of the productivist attitude. The former seeks to select annual varieties from wild perennial species. Mimetic agriculture resorts in particular to traditional practices used for thousands of years in the agricultural landscapes of the south. For example, many farmers in the Sudano-Sahelian countries of Africa sow several varieties of sorghum in the same field, each differing from the other by the length of their vegetative growth period, their sensitivity to pests (notably birds), their processing ability and in their taste.

It is easy to understand that the spatial heterogeneity within such fields could be difficult to manage, so much so that farmers are generally not prepared to adopt this technique, with the exception of some mixed cropping, forage mixtures, grassing of orchards and vineyards, and intercropping in agroforestry systems. Under this paradigm, the diversification of crops and their environment is generally considered to be favourable to the natural regulation of populations and to sustainable agriculture. Figure 12 is a schematic illustration of the importance for crop protection of three main components of the management of populations of pests and their natural enemies: a) prophylactic measures ensuring the use of healthy plant material which, if possible, is resistant to pests, b) the management of habitats in such a way as to limit the levels of pest populations while increasing the abundance and efficacy of beneficial organisms, c) optimisation of the potential of indigenous beneficial insects through conservation and biological control.

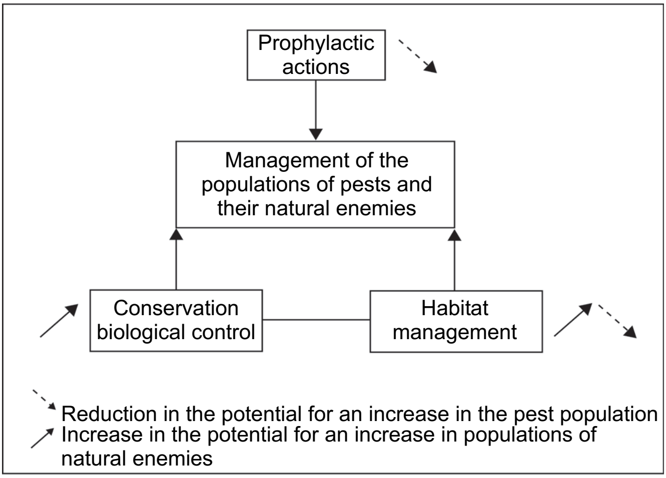

Figure 12 Main components of preventive management of populations applied to agroecological crop protection.

These agroecological concepts are based on the hypothesis that the diversity of habitats favours the multiplication of potential prey species and thus the abundance of beneficial organisms. For example, it has been shown that populations of the sunflower moth *Homeosoma electellum* are more abundant and less parasitised in cultivated areas than in natural areas where the ancestral parents of the cultivated varieties are still found (22). Most often, however, experiences with polyculture, such as those reported earlier for the Canate Valley of Peru for the re-establishment of the threatened cotton economy (see Chapter 3, § 3.1), do not enable us to draw conclusions in such a simple way. No doubt the reduction in the applications of pesticides is also involved.

These ideas explain why crop protection has been included in the global agroecological movement, as summarised below by M. Altieri and C. Nicholls (23):

- increasing the recycling of biomass, optimising the availability of nutrients, balancing nutrient flows,
- protecting soil conditions favourable to the growth of plants, particularly by the management of organic material and the stimulation of soil microbial activity,
- reducing losses due to certain physio-chemical factors in the environment (sunshine, water regime, etc.) with the help of microclimatic planning, optimisation of water use and soil protection through the use of plant cover,
- increasing the biodiversity of agroecosystems, in time and in space,
- increasing favourable biological interactions and synergies in such a way as to favour ecological processes and services.

Bibliographic References in Chapter 6

(1) Meadows D., Randers J., Meadows D., 2004. *Limits to Growth. The 30-Year Update.* Chelsea Green Publishing, White River Jct, VT, 338 p.

(2) Barbault R., 1997. Ecologie générale. Structure et fonctionnement de la biosphére. Collection Enseignement des Sciences de la Vie, Masson, Paris, 4éme édition, 285 p.

(3) Dupraz C., 2006. Entre agronomie et écologie : vers la gestion d'écosystémes cultivés. *Déméter 2006 Economie et stratégies agricoles.* Club Déméter, Paris, 73-89.

(4) Dubos R., 1980. *Courtisons la terre.* Stock, Paris, collection Laurence Pernoud, 243 p.

(5) Durand D., 2006. *La systémique.* PUF, Paris, collection Que sais-je ? 128 p.

(6) Nibouche S., Beyo J., Brevault T., Cretenet M., Gozé E., Jallas E., Martin P., Moussa A. A., 2004. Cotton bollworm economic injury levels based on crop model predictions: another use of the COTONS model. Another use of the Cotons® model. *In: Proceedings of the World Cotton Conference-3: Cotton Production for the New Millenium.* 9-13 March 2003, Cape Town, South Africa, ARC, Institute for Industrial Crops, pp. 1353-1358, Swanepoel A. ed., Pretoria, RSA.

(7) Nibouche S., Guerard N., Martin P., Vaissayre M., 2007. Modelling the role of refuges for sustainable management of dual-gene Bt Cotton in West African smallholder farming systems. *Crop Protection* 26(6), 828-836.

(8) Savary S., 1995. Systémé, modéle, simulation: applications des concepts de l'analyse des systémes en protection des cultures. *In: Modélisation en protection des cultures* (Savary S. ed.), Colloques et séminaires, 1994, Montpellier, Orstom, Paris, pp. 141-146.

(9) Verkerk R. H. J., 2004. Manipulation of tritrophic interactions for IPM. *In: Integrated Pest Management: Potential, constraints and challenges* (Koul O., Dhaliwal G. S., Cuperus G. W. eds), CAB International, Wallingford, Oxon, UK, pp. 55-71.

(10) Pointereau P., 2002. Les haies, évolution du linéaire en France depuis quarante ans. *Courrier de l'environnement de l'INRA,* 46, 69-73.

(11) Jongman R. H. G., Kristiansen I., 2001. Approches nationales et régionales pour les réseaux écologiques en Europe. *Sauvegarde de la nature,* 110, 96 p.

(12) Thies C., Steffan-Dewenter I., Tscharntke T., 2003. Effects of landscape context on herbivory and parasitism at different spatial scales. *Oikos,* 101, 18-25.

(13) Lévêque C., Mounolou J.-C., 2001. *Biodiversité. Dynamique biologique et conservation.* Dunod, Paris, collection Sciences de la Vie, 248 p.

(14) Tilman D., 2005. Biodiversité et services écosystémiques: Faut-il se préoccuper de l'érosion de la biodiversité? *Actes de la Conférence internationale : Biodiversité, Science et Gouvernance,* 24-28 janvier 2005, Paris, J.-P. Le Duc coord., pp. 102-110, MNHN, Paris.

(15) Klein A.-M., Vaissiére B. E., Cane J. H., Steffan-Dewenter I., Cunningham S. A., Kremen C., Tscharntke T., 2007. Importance of pollinators in changing landscapes for world crops. *Proc. R. Soc.* B 274, 303-313.

(16) Gallai N., Salles J.-M., Settele J., Vaissiére B., 2008. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. *Ecological Economics* <doi :10.1016/j.ecolecon.2008.06.014> (consulted August 20, 2008).

(17) INRA, 2005. Biodiversité des pollinisateurs et agriculture. Fiche de dossier de presse, 01.02.05. < http://www.inra.fr > (consulted April 10, 2007).

(18) Fry G. L., 1994. The role of field margins in the landscape. *In: Field Margins: Integrating Agriculture and Conservation* (Boztman N. ed.), British Crop Protection Council Monograph 58, pp. 31-40.

(19) Baggiolini M., 1998. La production intégrée en Europe: 20 ans aprés le message d'Ovronnaz. 2.1. Historique : 50 ans de souvenirs. *Bull. OILB srop-IOBC wprs Bull.,* 21(1), 3-7.

(20) Boller E. F., Avilla J., Jörg E., Malavolta C., Wijnands F., Esbjerg P., 2004. Integrated production: Principles and technical guidelines. 3rd ed., *Bull. OILB srop-IOBC wprs Bull.* 27(2), 50 p.

(21) Gliessman S. R., 2004. (see reference n° 16 of Chapter 1).

(22) Chen Y.-h, Welter S. C., 2002. Abundance of a native moth *Homeosoma electellum* (Lepidoptera: Pyralidae) and activity of indigenous parasitoids

in native and agricultural sunflower habitats. *Environ. Entomol.,* 31, 626-636.

(23) Altieri M. A., Nicholls C., 2004. Effects of agroforestry systems on the ecology and management of insect pest populations. In: *Ecological Engineering for Pest Management. Advances in Habitat Manipulation for Arthropods* (Gurr G. M., Wratten S. D., Altieri M. A. eds.), CSIRO Publishing, Collingwood, VIC, Australia, and CABI Publishing, Wallingford, Oxon, UK, pp. 143-154.

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CHAPTER 7

Habitat Management: The Factor Uniting Agronomy and Ecology

In the preface to a work by F. Burel and J. Baudry dedicated to landscape ecology, R. Forman (1), Professor at Harvard University, reviewed the structural conditions needed to ensure the ecological integrity of an agroecosystem without compromising its ability to produce food resources: "the fields, the network of hedgerows, some larger plots of natural vegetation, small pieces of natural habitat, watersheds with their diversified riverine corridors, lanes and roads, farms and their buildings, housing areas, etc." Elsewhere, Forman drew attention to the organisation of agricultural landscape structures, based on the logic of a scientific discipline dating from the early 1980s — landscape ecology.

Situated at the interface of ecology and biogeography, landscape ecology studies the flux of living things in a specified area, with its connections, its corridors, and the genetic exchange between populations. J-C. Lefeuvre (1), Professor at the Museum of Natural History in Paris, pointed out that this discipline "has had the great merit of assisting the reunification of natural sciences and social sciences, in considering man as an integral component of the ecosystems that make up the biosphere" *(translated from the French).* Addressing the research community, B. Chevassus-au-Louis (2), the French Inspector General for Agriculture, described the necessary conditions: "the challenge of agronomic research is (therefore) to pass from a linear and sequential vision to a vision of a system in which the three aspects — description, understanding, and management — develop simultaneously in an interactive manner, in such a way that each activity benefits, as rapidly as possible, from the results of the others" (*translated from the French*).

The development of landscape ecology has enabled us to recognise that spatial and temporal heterogeneity is an organising factor in ecological systems, although ecosystems are classically defined as localised, homogenus groupings such as a forest, a meadow, or a marsh. For Burel and Baudry (1), the landscape constitutes "a level of organisation of ecological systems above an ecosystem, which is essentially characterised by its heterogeneity and by its dynamics, and which is partly governed by human activity" (*translated from the French*). Landscape ecology can be understood in different ways. Scientists always give it a functional significance to the exclusion of an aesthetic dimension, which may be more relevant to non-scientists.

This implies that agronomists have an important role to play in terms of the population dynamics of the organisms in cultivated areas. The choice of crops and cropping systems interacts with the larger landscape mosaic. In addition to implementing agronomic practices which combine optimal production conditions by the judicious choice of growing systems and technical itineraries, the agronomist is also involved in the planning of the agrarian structures described below, and is consequently one of the main actors in a possible second Green Revolution (§ 1.2).

Landscape ecology aims to mobilise all the farmer's practical knowledge in order to obtain the best qualitative and quantitative harvest, by ensuring the best vegetative and fruiting development of the crop and by avoiding or reducing the negative impact of pests, while preserving the biodiversity of the farming environment. Intensive agricultural practices have been responsible for a significant impoverishment of biodiversity and a significant reduction in ecological services. The goal is thus to enable 21st Century agriculture to recover past biodiversity (3).

The practical modalities of the reconversion of intensive cropping systems have been the subject of few studies to date. Such studies entail the following three phases of action: first, increasing the efficacy of existing inputs hence reducing the quantity required, which implies optimising existing techniques; second, replacing these inputs and the corresponding practices by modes of intervention which are less damaging to the environment (reduced tilling, planting nitrogen-fixing crops, using biological control); third, considering the farming system in its entirety, identifying local factors which limit harvests, and applying preventative measures using ecological processes that are specific to the crops concerned (rotation, companion planting, agroforestry). A conversion of this type requires evaluation criteria to design and monitor a farm-level, multi-year plan of action based on an initial diagnosis.

The most recent guides to good agronomic practice are still far from achieving such goals even when they are inspired by the principles of truly integrated crop management (Box 22). The techniques of crop protection are linked to other agronomic practices like fertilisation or irrigation. These guides strongly encourage producers to opt for joint action at a regional level. They support a move away from traditional attitudes and practices by demonstrating the advantages of a change in the spatio-temporal scale in the search for solutions to agri-environmental problems.

BOX 22 Integrated crop management (4)

Integrated crop management implies using systems of production for cultivated plants which are the best suited to local agroeconomic conditions and to the plant's environment. All procedures that are appropriate for the agronomy, nutrition and protection of plants are used as harmoniously as possible, taking advantage of technical progress, of current biological understanding and of natural regulating factors for pests, in such a way as to provide a long-term guarantee of yields and economic returns.

7.1 AGRONOMIC AND AGROECOLOGICAL INNOVATIONS IN COTTON PRODUCTION

One of the most complete guides to good agronomic practices in the cotton sector today is undoubtedly Australian (5). This guide assembles inputs from companies, researchers and technicians, and defines a common strategy largely based on the most recent data (Table 9). There is no gap before the new cotton growing season which immediately follows harvesting of the preceding crop, as was the case in the calendar-based system previously used in the San Joaquin Valley, California for successive annual intervention programmes (6).

Both these systems recommend minimising the crop health risk by destroying as far as possible residual pest populations which survive the non-crop season thanks to diapause. An example can be found in Australia, where cotton growers try to mechanically destroy the subterranean pupae of *Helicoverpa armigera* by ploughing the soil in the beds of trap crops specifically planted for the purpose. Cotton regrowth and certain weeds may serve as refuge plants and consequently have to be destroyed. Cotton producers need a crop rotation plan to reduce the potential development of soil-borne infections, particularly plant pathogenic nematodes. They also need to plan the spring planting of the fields, whether with cotton or with a rotation crop, including planted refugia for Bt cotton or trap crops.

From planting to harvest, the crop should be continuously monitored for the presence of pests using scouting practices. These practices should vary with the growth stage of the cotton to enable the choice of the most appropriate pest management actions should the need arise. Scouting applies equally to beneficial organisms and especially to generalist predators. Some treatments may not be advisable when beneficials are present in large numbers and may be able to regulate the pest populations by themselves. This implies that the producer should not limit observations to a single crop or field, but rather examine wild and cultivated plants in the area surrounding the field. Government services may also provide information of regional importance.

TABLE 9 Annual guide to integrated control in cotton production in Australia (5, modified)

			Annual stages in cotton production		
Objectives	*After harvest*	*Before sowing*	*From sowing to one flower per linear metre*	*From one flower to one open boll per linear metre*	*Between one open boll per linear metre and harvest*
1. Growing a healthy plant	- choose crop rotation, determine fertiliser needs and the risk of disease	- prepare the seed-bed, choose the cotton variety, - decide on the irrigation programme	- respect the sowing window, - apply planned treatments, - manage irrigation	- monitor crop development, - manage water and pests	- stop irrigating, use defoliants, - control pests
2. Scouting for insects and damage	- check for the presence of *H. armigera* pupae in the soil	- decide on the choice of seed treatments, apply insecticide in the form of granules	- count pests and beneficials in the crop and in the trap crop	- check threshold levels, and the ratio of pests to beneficials	- stop all treatments when 30-40% of the bolls are open
3. Appropriate use of beneficials	- sow lucerne (alfalfa) in the autumn, - establish a collective treatment plan	- lay out diversified habitats, in particular other crops such as sorghum if the employment of egg parasitoids is envisaged	- if treatments are needed, refer to the list of recommended substances	- release trichogrammatid egg parasitoids in sorghum, - apply food additives for the beneficials, - harvest lucerne	- enhance the action of beneficials on resistant pests still present at the end of the season
4. Preventing the emergence of resistance	- destroy *H. armigera* pupae by ploughing, - sow spring trap crops, - stay informed about the risk of resistance	- lay out the refugia linked to the sowing of Bollgard II®, - select the crop protection products to use at planting	- refer to the threshold values, follow regional directives concerning resistance and for treatments of Bollgard II®	- refer to the threshold values, follow regional directives concerning resistance and for treatments of Bollgard II®	- refer to the threshold values, follow regional directives concerning resistance and for treatments of Bollgard II®
5. Managing weeds	- destroy weeds and cotton regrowth	- check summer crop rotations	- destroy weeds	- destroy weeds	- prepare winter rotations - destroy weeds
6. Using trap crops	- time sowing for the desired flowering date	- prepare for summer trap crops	prepare for late trap crops	- manage *H. armigera* populations in the summer trap crops	- use biological means to destroy eggs and caterpillars in trap crops
7. Using integrated control	- join information groups, - take part in training seminars	- implement the treatment programme with neighbours and consultants, - take part in training seminars	- meet crop health consultant, - discuss with neighbours, - attend local meetings	- meet crop health consultant, - discuss with neighbours, - attend local meetings	- meet crop health consultant, - discuss with neighbours, - attend local meetings

In some countries, programmes for the eradication of pink bollworm by the release of sterile males have been tried. In most areas, all the crop residues and weeds have to be destroyed in autumn to prevent the survival of pink bollworm and whiteflies, and in the Americas of overwintering boll weevils.

These guides to good practice are subject to constant revision as they progressively incorporate new agronomic and agroecological knowledge: genetically transformed varieties or the results of classical selection, improved cultural practices, new crop protection techniques, etc. We illustrate some of these 'good practices' below and then move on to look at the particular case of sucking insect pests of cotton.

- The genetic transformation of cotton for the expression of genes coding for the synthesis of materials of interest for crop health (Bt entomotoxin, glyphosate herbicide tolerance) is no doubt the most spectacular innovation of the last ten years. Its direct and indirect impacts on crop protection are discussed at length above (see § 5.1 and § 5.2).
- High density sowing is practised today in China, Argentina, Australia, Brazil and the United States thanks to the application of herbicides on genetically tolerant varieties. This production technique is based on high plant density (ultra narrow row cotton). Thanks to early leaf coverage of the soil, photosynthetic assimilation is optimised allowing the total crop season to be reduced by two or three weeks while at the same time ensuring higher yields. However, the constraints of these growing technologies need to be acknowledged. They require the use of growth regulators and of appropriate harvesting equipment. Manual harvesting, as practised in most of China, is not feasible in industrial agricultural systems. The consequences of these practices for plant health are not yet clear, but the increase in total root volume, following the increase in seeding density, favours soil pests (nematodes and fungal and bacterial diseases).

- Minimum tillage is often associated with high density seeding. The physio-chemical and biological conditions of the cotton environment are very significantly modified by this practice. In addition to an improvement in the structure and porosity of the soil, there is an increase in the diversity and abundance of the populations of living organisms — both invertebrates and vertebrates — connected with the crop. Results of studies undertaken in different parts of the American cotton belt do not suggest that populations of major pests are particularly encouraged by these practices. For this reason, no special plant heath recommendations have yet been made in connection with the extension of high-density planting.
- Direct seeding under plant cover has also been the subject growing interest in the last 20 years. Direct seeding is generally used in growing systems in which the soil cover is maintained throughout the year. Since the 1980s, these growing systems, which comprise the main crops and the crops to be used as ground cover, have been used in tropical regions where loss of soil fertility due to erosion and heavy competition from weeds is the major constraint. Direct seeding takes different forms depending on local socio-economic conditions: seeding without ploughing in the residues of the previous crop, sowing in cover-plant mulch, sowing in a living cover crop, etc.

In the Cerrados region in the humid tropics (Mato Grosso) in Brazil, there has been a spectacular recent expansion of growing systems based on an appropriate crop rotation, direct seeding under ground cover plants and appropriate selection of varieties. Two annual crops, soya and rain-fed rice, are the main crops. Maize, sorghum and millet are grown as secondary crops, locally called *safrinhas.* Cotton is included in the rotation as a secondary crop, either after soya and rain-fed rice, or after the cover plants (*Brachiaria ruziziensis, Eleusine coracana)* have produced abundant biomass (Figure 13). Studies are underway to evaluate the plant health risks associated with the presence of the cover plants, which may favour the development of pests such as *Spodoptera frugiperda.*

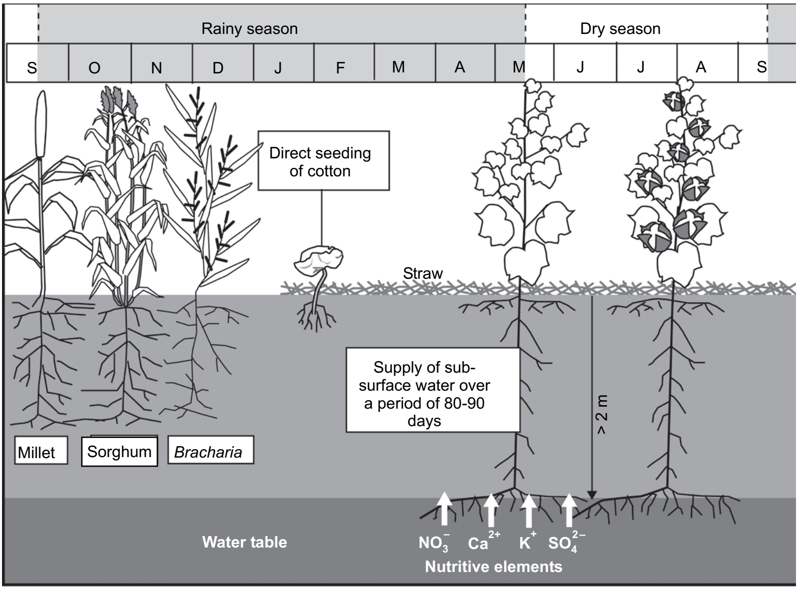

Figure 13 Cotton growing system under plant cover in Brazil (7).

A comparable technique is currently the subject of experimentation in the cotton systems of West and Central Africa, especially in Mali/Burkina-Faso and in Cameroon/Chad. The goal of these systems, in which cotton is sowed under plant cover, is to prevent production losses due to climatic risks, which are high in the case of iron-rich soils of limited fertility that are very sensitive to water and wind erosion. Thus, in North Cameroon, where a cotton-cereal rotation is common, two types of crop system are under study. In the first type, the production of plant biomass plays the role of mulch one year out of two. In the first year, sorghum, maize or millet is cultivated in association with a plant cover suited to local conditions (*Brachiaria ruziziensis, Mucuna pruriens, Dolichos lablab, Crotalaria retusa, Vigna unguiculata*). Such associations enable biomass to be doubled. The biomass is left in place and forms a dead plant cover for cotton cultivation the following year. In the second system, biomass is produced in the same year as the main crop. This works provided that the rainy season lasts for at least six months, although this is frequently not the case, but for the moment, the results are promising (8). On the other hand, recent data show that this growing technique may favour infestation by new pests (notably Coleoptera, which spend their larval stages in the soil, but also crickets). This means that the effects of this system on beneficial fauna need to be monitored.

The attraction-repulsion (or 'push-pull') method allows, to a certain extent, pest populations and beneficial organisms to be manipulated through modifications in cropping systems (9). This method is based on the use of a range of stimuli to modify the behaviour of insects. The strategy consists of reducing pest populations through repellence or by dissuading them from establishing themselves in the crop to be protected, and of attracting them onto other plant populations where their concentration could facilitate their elimination. The opposite approach is used for beneficial organisms to attract them from the environment in which they are dispersed into the crops to be protected. This technique was initially developed by B. Pyke for the control of *Helicoverpa armigera* in cotton in Australia (10). The stimuli used are often visual, but may also be synthetic or natural chemicals. Most frequently they are extracts of the plant host, which play either an attractive or a repulsive role depending on the concentrations at which they are emitted. Anti-nutrient substances, also plant derived, have this repulsive property, but it is frequently limited to a very short range. A well-known example is azadirachtin, an oil extracted from the seeds and other parts of the neem tree (*Azadirachta indica*). In certain cases, these anti-nutrient substances are anti-aggregation pheromones produced by the insects themselves to optimise their exploitation of the plant host by reducing conspecific competition. Anti-oviposition pheromones, which protect the host plant against egg laying by pests, have been used in cotton against *H. armigera.* Crop associations and especially the use of trap crops, also represent a possible application of this population management strategy, but their use still involves practical problems. These techniques are very suitable for small family farms, where they are still traditionally applied. In the last few years, their use has expanded considerably in the cultivated ecosystems of East Africa to protect maize crops from stem-boring caterpillars. On the other hand, these procedures are not yet widely used in large-scale intensive cropping systems, other than in cotton where Pyke's original work paved the way. *Helicoverpa armigera* is repelled from cotton crops by applications of neem seed kernel extracts and attracted to the field margins by trap crops, including chickpea *Cajanus cajan* or maize. In India, okra (gumbo) *Abelmoschus esculentus* plays this role. Insect feeding behaviour has also been exploited recently to manipulate pest movements. This involves working with the nutritive needs for nectar and pollen of many adult insects, particularly of parasitoids and predators. This is the reason for the recommendation, in certain growing systems, to plant strips of flowering plants both to attract pollinators and to facilitate the development of beneficial insect populations (11).

New growing systems of the type described here have also been progressively developed over the last decade by CIRAD, called 'new cotton growing' (NCG) on the initiative of J-P. Deguine (12). These systems aim to provide a practical response to societal and environmental demands, and to ensure the sustainability of a crop that is threatened by its own success. In French-speaking Africa, the extensification of cropping systems has led to stagnation in yields, an increase in plant health problems, and to soil degradation. In many cases, the growing impact of climate change is also increasing the risks involved in cotton production. Additionally, in West Africa, recent developments in the organisational and institutional side of the cotton chain led to a reduction in (and in some cases, almost the disappearance of) the technical staff who were formerly provided by semi-governmental cotton companies. The sum of these constraints weighs heavily on the practices, production objectives and strategies of farmers, who do not always have the means or the knowledge to clearly express what they expect. This applies to both technical aspects and management methods for their farms in a context where the weight of tradition is considerable. In many cases, small-scale farmers no longer follow conventional technical recommendations, no doubt considering them to be too rigid and unsuited to the changing situation. Farmers often try to adapt the recommendations without having sufficient information to enable them to make better choices. Faced by genuine financial problems, inputs purchased on credit (fertiliser and plant health chemicals) are frequently diverted from their original destination and used for subsistence crops, which are of course indispensible to the food security of families. Cotton growing then moves to the second level, with a growing tendency towards the adoption of intensive farming systems.

The 'new cotton growing' system offers technical options which are appropriate in this context, as they account for the whole range of constraints including those of the cotton companies and cotton production chains, which have to face the current international consensus. This underlines the need for adaptive research to provide solutions which match both local potential and the strategies of the producers and other actors involved. Interactions between the genotype of the cultivated plant, cultural operations, and the local environment need to be studied in a cyclical manner characterised by the following stages: diagnosis of the situation and transformation of its constraints into researchable problems, the breakdown of these problems into research activities, and the identification of potential technical solutions; development and validation of technical programmes with the participation of farmers; recommendation and dissemination of the results within a participatory framework based on this new diagnosis and understanding. Following this process makes it possible to explore research pathways covering not only the world of the small-scale farmer and new technologies, but also to look at new combinations of old solutions, for example the choice of appropriate varieties for the optimal planting date and density, or the use of growth regulators and the shortening of the developmental cycle of the plant. Other areas to explore include growing the crop under plant cover or the use of early varieties with reduced vegetative growth. Reduced vegetative growth of the target plant can also be obtained by appropriate genetic manipulation. This enables cultivation at much higher densities and produces higher yields without increased fertilisation. Such plant architectures produce plant-pest relations which are better for the crop, favouring, for example, the exposure of the pests to insecticides while significantly reducing the length of the vegetative and fruiting stages. In all these cases, the aim of the intervention is to maintain yield and improve the efficacy of the inputs. Encouraging results have been reported from Benin, Cameroon and Mali (13).

Insecticide applications for the control of populations of sucking pests (aphids and whiteflies) have become a major plant heath constraint in many cotton producing countries in the last 25 years. Sucking pests produce sticky fibres due to their sugary exudates. This in turn causes a serious reduction in the marketable value of the harvested fibre. These very polyghagous pests are just as likely to move from one crop to another as from one cotton plant to another, and are also characterised by their strong potential for multiplication. Beyond the technological damage to the yield, they weaken the plant by sucking the sap and transmitting many diseases, including serious viral diseases. In the 1980s, when the outbreaks started, classical control techniques following the principles of directed control, which were already being implemented against the pests of fruiting bodies of cotton, were unsuccessful in reducing outbreaks. Since the 1990s, the principles of rational crop protection have been applied: diversification of active ingredients, respect for intervention thresholds, the use of seeds treated with systemic aphicides or active ingredients which are effective against whiteflies; but once again the results have not been satisfactory. This alarming situation has justified rethinking the plant health strategy and research into the causes of these sudden infestations. Many factors have been shown to characterise the new demographic situations, these being the consequence of the disruption of the former balance between the populations of sucking insects and their environment (Figure 14). These factors include: the rainfall deficit in many tropical regions since the 1970s, which is believed to favour the development of sucking pest populations especially when associated with higher temperatures; the increase in the food resources available for their development due to the

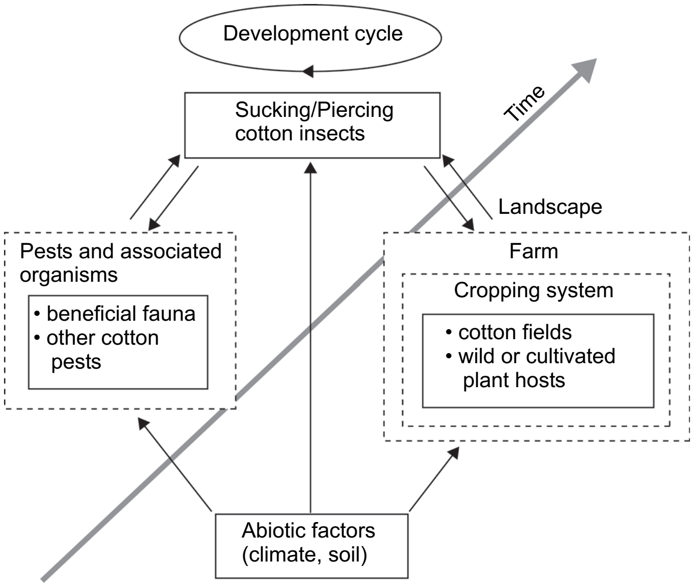

Figure 14 Spatio-temporal relations between sucking/piercing pests of cotton and their environment (14).

extension of cotton growing and market gardening; the advances in technical strategies with an increase in fertilisation rendering the plants both more attractive to insects and more nutritious; the increasing use of insecticides at low volumes per hectare resulting in insufficient coverage of the lower leaf surface, which is the preferred habitat of these particular pests; the reduced efficacy of pyrethroids in tropical climates, although these active ingredients rightly experienced considerable commercial success in the 1980s when they were new and had not yet led to the development of resistance; the selection of smooth or hairy-leaved varieties, which modifies the egg-laying and feeding behaviour of both useful and damaging insects; badly planned insecticide applications in neighbouring vegetable fields, which favour the development of resistance and further upset the balance with indigenous beneficial fauna.

Thanks to this type of detailed diagnosis, there is now leeway for initiatives capable of ensuring a return to equilibrium. One such change involves altering the mind set of all the stakeholders in the cotton chain, notably reorienting scientific research, encouraging technicians to prioritise long-term measures, and raising the awareness of producers to the fact that plant health risks generally lie at the level of pest populations and not simply the presence/absence of the pest. The goal is to keep pest populations at economically tolerable levels in the local socio-economic conditions. The recommended strategy is to manage these populations and no longer to seek to combat them indiscriminately, not only by cutting out the automatic recourse to chemical control but especially by anticipating the appearance of pests through a range of techniques in a holistic and sustainable process (14). Traditional curative measures need to be replaced by preventive measures.

In the particular case of sucking pests, preventive measures applied at the level of both the field and the cropping system need to be part of an approach to the farm as a whole. At the field scale, the following risk avoidance techniques are recommended: early sowing to limit the period during which the sensitive stages of cotton are in contact with the colonising populations of pests (for example, direct seeding under plant cover or a minimum tillage system); increasing seed density, reducing the period between sowing and fruit formation by choosing short-season varieties with reduced vegetative growth; coating seeds with systemic insecticides; using growth regulators; early or repeated harvesting to reduce the period of exposure of the cotton in open bolls to the honeydew produced by these pests. At the scale of the cropping system or of the farm, the choice of crop rotations and the introduction of trap crops for pests and refuge crops for beneficials are effective ways to limit infestations while supporting beneficial fauna.

In these conditions, the ability to quantitatively and qualitatively track populations is of major importance and implies the active participation of the farmers concerned. When intervention thresholds previously calculated for a given area and socio-economic situation are crossed, curative measures become necessary, preferably measures other than chemical control. In places where case studies have been conducted, even where chemical pesticides have been shown to perform well up to now, the farmers usually do not have a choice of which products to use. There is consequently still a major risk involving the use of chemical treatments with inappropriate active ingredients, with immediate results that are not only disappointing but also have long-term harmful effects on the beneficial fauna.

This 'new cotton growing' strategy appears to conform (as do several other systems) with the principles of integrated protection formalised by the International Organisation for Biological Control (IOBC), while making valuable progress towards truly integrated crop management. 'New cotton growing' particularly emphasises the importance of beneficial fauna in the regulation of pest populations, mainly through conservation biological control. However, in this particular case, it also reveals the limits of classical biological control through introductions or inundative releases. This has the advantage of drawing the attention of agronomists to the need to rethink cropping systems and technical methodologies in the context of sustainable development (15).

7.2 CONTROLLING OUTBREAKS BY PLANNING OF AGRARIAN STRUCTURES AND MANAGING PLANT BIODIVERSITY

As reported by H. van Emden (16), Professor at the University of Reading, UK, many references have accumulated over the last 50 years stating that indigenous natural enemies are far more effective in the presence of increased botanical diversity. However, van Emden emphasised that this finding has only recently been exploited from a practical point of view. This may be partly because of the known efficacy of synthetic pesticides and insufficient awareness of their secondary effects and partly because of the focus on classical biological control by the introduction of beneficials, but also — and perhaps mainly — because of the mind set of the actors involved (farmers and technicians), who are not prepared to accept the idea of cultivating 'weeds' on their farms. Even in scientific circles, it is only in the last decade that new research programmes have been set up to understand the phenomena thought to be responsible for this effect within ecosystems. Today, the importance given to the role of indigenous polyphagous predators as a functional group which helps regulate pest populations, is a break with the recent past when the impacts of biological control were credited almost exclusively to specialist predators and parasitoids, which were often introduced species (17). Predatory carabid beetles may soon be able to join the ladybird in the popular image of biological control, and we may also be able to rehabilitate the much maligned spider, which often appears to play a predominant role in biological control in crop fields.

Before the Second World War, hunters and wildlife managers notably in Great Britain, were the first to feel uneasy about the loss of diversity observed in bird populations. Members of the independent research organisation founded in 1968, the Game Conservancy Trust, today support research on the management of game populations, but also of invertebrates such as insects and wild plants in cultivated areas. One of their major activities was to lobby for the planning of agrarian structures with wild plant strips and conservation field borders. They even created a technical vocabulary to describe the different structures and usages which is widely accepted today (Table 10). In outline, the strategy involves creating turning circles at the ends of fields for manoeuvring and turning agricultural machines, and intercalating within large crop fields, herbaceous and flowering plant strips used by indigenous arthropod predators as hibernation sites and as source areas from which they can colonise the crops in spring. It is recommended that the planned areas should together cover at least 5% of the cropped surface, any resulting harvest losses being compensated for by a reduction in the inputs required.

Attention is drawn in particular to the distribution of populations of generalist insect predators within a field, bearing in mind the importance of field margins and borders in certain areas, for example in Northern Europe, where the agrarian structures gave birth to complex landscape mosaics with

TABLE 10 Definition, description and role of different forms of field margins which favour wild flora and fauna while optimising agricultural production (18, modified)

Name	*Description*	*Role*
	Creation of field margins	
Conservation headland	Cultivated strip 6 to 12 m wide and free of all chemical treatments	Protection of small game and rare wild plants
Uncropped wildlife strip	Strip of crop plants not destined for harvest	Conservation of rare wild plants
	Creation of new field borders	
Grass strip	Strip with seeded perennial grasses	Barrier to the penetration of weeds into the field; habitat for natural enemies and small game
Grass and wild flower strip	Strip with seeded perennial grasses and wild flowers	*Ditto*
Flower strip	Mixture of flowering plants	Resource for pollinators and certain arthropod predators
Sterile strip	Mechanical or chemical removal of all herbaceous vegetation	Protective buffer against weeds
Set-aside margin	Natural regeneration of perennial herbaceous vegetation in a fallow area	Role depends on composition and structure of flora
Sown mixtures of wild flowers (strips or blocks)	Seed mixtures destined for birds and bees	Resource for wildlife including game
	New habitats within cropped fields	
Beetle banks	Herbaceous strips within large fields	Overwintering sites for arthropod predators (notably Coleoptera) and sources for the colonisation of fields in the spring
Wild-flower strips	Strips sown with flowering plants	Resource for pollinators and certain arthropod predators

hedgerows and copses. Within the same guild, for example, carabid beetle predators, different species show different behaviours. Some remain in hedges and field margins, while others much more readily colonise the interior of fields. Any generalisations in this area should thus be made with great caution. This type of investigation requires the active collaboration of taxonomists (specialists in species identification), a discipline that has not attracted the interest of decision makers for several decades now! Just at the time when interest in the predatory role of spiders is increasing (and spiders are particularly numerous in cotton fields), the lack of taxonomic competence may prove to be a serious handicap in the development of biological control for conservation.

In continental Europe, it was the experience acquired in the development of integrated crop protection strategies in perennial agricultural settings like orchards which enabled the IOBC to formalise the planning of agrarian structures along sustainable development lines. The IOBC recommends, for example, the planting of mixed hedgerows, whose principal components are chosen as a function of the main orchard pests in a given region, to favour the development of beneficial populations.

In cotton production, a decisive technical step was taken at the end of the 1960s, again in the San Joaquin valley in California, with the idea of interpolating strips of lucerne (alfalfa) between cotton fields. The objective was to overcome infestations of a redoubtable polyphagous bug (*Lygus* sp.), by attracting it to a leguminous plant on which it is inoffensive. Strips of lucerne, 5 to 10 m wide were planted between cotton fields 90-120 m in width, with instructions to farmers to regularly cut part of the lucerne to ensure it remained permanently attractive to the bugs. In practice, in the event of colonisation of a cotton field by *Lygus* bugs from a neighbouring field, these attractive strips of lucerne played the role of trap crops. This system enabled a reduction in the chemical treatments on cotton, to the benefit of the natural enemies of cotton pests.

Currently this technique is strongly recommended in different forms in regions where cotton is grown as a monocrop, especially to favour the action of indigenous beneficial fauna. These permanent reservoirs of parasites and predators facilitate the regulation of pest populations right from the beginning of colonisation of the cotton fields, which significantly increases their effectiveness. A range of different intercrops has been compared including false saffron, sunflower, sorghum, tomato, wheat, rape, field bean, chickpea and Egyptian beans. Comparative studies undertaken in south-eastern Australia by R. Mensah and R. Sequeira give preference to lucerne (19). It has the advantages of being a perennial that re-shoots rapidly after a cut, provides both nectar and alternative prey species and provides conditions that are favourable for the mating and reproduction of beneficial insects. Measurements of the dispersal of predators from the lucerne strips have led to the recommendation to plant cotton fields with a maximum width of 300 m, divided by strips of lucerne 8 to 12 m wide. In Texas, attention was recently drawn to the advantages of planting strips of sorghum (*Sorghum bicolor*) in cotton fields, because of its synchronised vegetative growth with cotton and the similarity of its associated fauna, but especially because of the attractiveness of sorghum for the major generalist predators which are required in the case of aphid outbreaks. Sorghum is also attractive to polyphagous pests like *Helicoverpa zea* and *Helicoverpa armigera* and offers a very favourable environment for the action of predators and parasitoids of these species. The range of associations recommended indicates that it will not be possible to find a single, generalisable, solution, but rather that the choice of which crop or crops will need to be adapted to fit the type of the plant health scenarios at a local level.

These innovations are part of the current movement that is leading us to review our ideas on cropping systems beyond the specific case of cotton growing, by intercalating crops or mixed cropping, and by the creation of field margins or the use of agroforestry systems.

The practice of intercropping is ancient and still characteristic of small-scale farmers in tropical regions, where cotton is sometimes found associated with subsistence crops (maize, sorghum, cow peas). The main reason for the success of this technique is the need of these farmers to avoid production risks and ensure a minimal level of subsistence in indigenous economies, which are practically self-contained. However, in China this traditional practice has become one of the national specialities. The field takes the form of a minutely and laboriously maintained garden, often with many different crops. The difficulty of mechanising manual work in the presence of such different crop plants appears to limit all possibility of increasing production. However, in the case of major cereal crops (wheat, barley and rice, for example), we can see the qualitative and quantitative advantages of interspecific or varietal mixtures for enhanced resistance to bacterial, viral, and fungal diseases. These practices therefore seem promising, with the caveat that there is a need to remove certain agronomic and economic constraints by, for example, increasing the homogeneity of the agronomic characteristics of the varieties used, while retaining the diversity of their disease resistance genes, given the issues that may arise in the market in which mixed varieties are not readily tolerated. In tropical areas like Cameroon, protection against erosion takes priority over crop protection, but recommendations are similar to those made for the management of pest populations. For example, the planting of strips of natural vegetation of variable width between fields measuring 25 x 100 m. Farmers see the benefit of sowing perennial forage grasses. This leads to the creation of functional corridors, although these are mostly linear. This type of organization is also characteristic of some Chinese landscapes, where over the last 30 years agroforestry techniques have been adopted to prevent wind erosion, using hedges as wind breaks.

In industrial cotton production, there is the example of the participatory BASIC programme in California (Box 16), which aims to facilitate a move away from intensive farming towards organic agriculture. However, the scale of the management of communities through habitat planning remains modest. Planting cotton fields next to areas of lucerne is the main recommendation or, if this is not practicable, the creation of herbaceous borders on their windward side, on an area equivalent to only about 1% of the field. The species recommended include wheat, lucerne, mustard, sunflower, yarrow, and fennel (20).

As limited as it is, this advanced technique is nonetheless an example of the principle of ecological compensation in agro-environmental policies. Rather than forbid all impacts in a restricted area, larger areas are identified within which the risky activities are permitted but are ecologically compensated for by other actions. This was demonstrated initially in Switzerland in the mid 1990s with the establishment of 'Ecological Compensation Areas'. Equivalent arrangements exist in the United States in the form of 'Mitigation Banking'. In Switzerland, government measures impose genuine environmental management of 7% of the total potentially farmable area. An inventory of the different types of areas involved is given in Table 11.

TABLE 11 Different types of ecological compensation areas in Switzerland (21)

Herbaceous environments	*Industrial agriculture*	*Woody environments*	*Other environments*
Large scale grasslands	Large contiguous fields of crops (b)	Fruit trees,woody climbers (vineyards)	Damp hollows, swamps and marshes
Low input intensity grassland	Flowering fallow (c)	Isolated indigenous trees adapted to the site, ranks of trees	Wasteland (e), rocky areas
Waste areas (a)	Rotations of fallows (c)	Hedges, copses, wooded banks (d),	Drystone walls
Broad-acre pasture			Natural non-stabilised roadways
Wooded pasture			Vineyards with high biological diversity

(a) grasslands on wet or flooded soils from which the vegetation is used as animal litter and occasionally as forage,

(b) in cereals or hand-weeded crops, crop strips 3 to 15 m wide, located around the crop in a rotation, grown in the normal way but without fertiliser or crop protection treatments,

(c) flowering fallows and rotational fallows: the flowering fallows are strips grown for several years (2 to 6) on areas within industrial crops, market gardens or orchards; they are sown with a mixture of indigenous species and are not suitable for feeding livestock. Rotational fallows are grown for one or two years and sown with annual and biennial species: they serve as a food source (nectar and pollen) for wildlife and particularly for beneficial organisms, for protection against erosion, and as connecting corridors between the natural communities of the landscape,

(d) extensive grass strips, at least 3 m wide, are obligatory along each side of hedges, copses and wooded banks

(e) waste areas are colonised by non-woody vegetation on embankments, talus slopes or rubble. Although the boulder piles and rocky areas may or may not be covered with vegetation, these areas are favourable for reptiles and other small vertebrates.

Under the auspices of the IOBC, E. Boller, of the Federal Research Station at Wädenswill (Switzerland), and his colleagues recently published a detailed technical description of different ecological infrastructures which ensure functional biodiversity in different European agroecosystems: vineyards, orchards and industrial crops, meadows, clover and fields of other legumes. The optimal distance between parallel hedges is given. In the case of major field crops, it is 150 m, ensuring that the centre of a field is no more than 75 m from the field margin. In this way the ideal texture for the landscape mosaic is created (22).

Figure 15 is a schematic diagram of the different techniques to be included in a coherent agroecological system. The aim of the

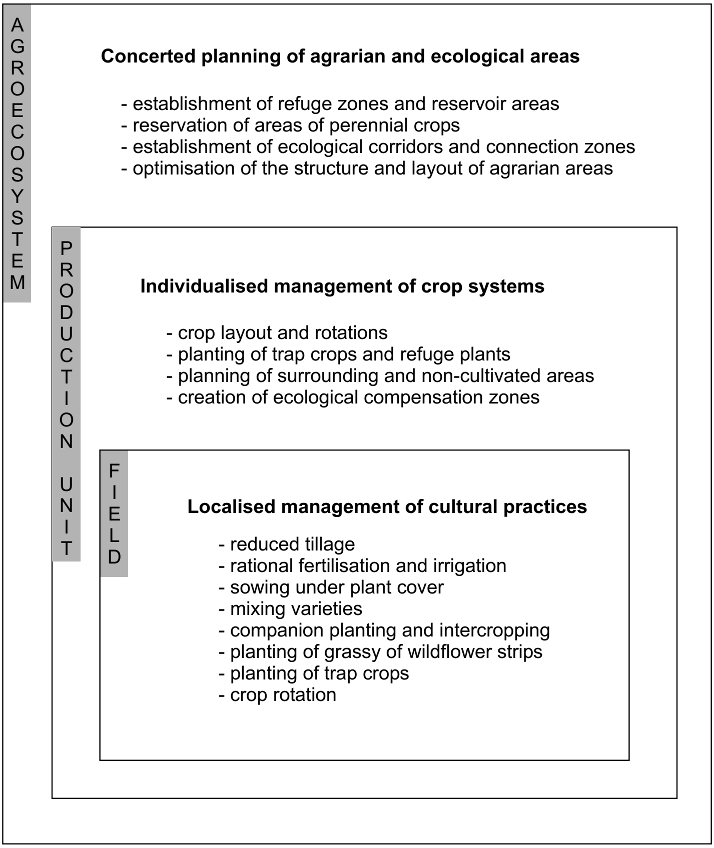

Figure 15 Principal levels of habitat management, from the field to the agroecosystem, in the context of agroecological crop protection.

diagram is to draw attention to the different scales the farmer needs to consider when adopting a new crop protection strategy: appropriate cultural techniques at the scale of the plot, innovative cropping systems at the scale of the farm, and the creation of agrarian and ecological spaces at the scale of the agroecosystem which have to be negotiated with partners and local actors. In these circumstances, we believe that reconciling the concepts of agronomy and ecology is a precondition for the success of the desired changes.

Bibliographic References in Chapter 7

(1) Burel F., Baudry J., 2000. *Ecologie du paysage. Concepts, méthodes et applications.* Tec & Doc, Paris, 2ème èdition, 359 p.

(2) Chevassus-au-Louis B., 2006. Refonder la recherche agronomique: leçons du passé, enjeux du siècle. LeÇon inaugurale du groupe ESA, Angers, 27 septembre 2006, 29 pp. <http://www.espacesciences.org/servlet/com.univ.collaboratif.utils.LectureFichiergwID_FICHIER=3542> (consulted October 25, 2007).

(3) Riba G., 2005. L'agriculture doit se réapproprier la biodiversité. Conference internationale: Biodiversité, science et gouvernance. 24-28 janvier 2005, Paris, <http://www.inra.fr/content/download/3890/40712/file/> (consulted September 15, 2007).

(4) Zadoks J. C., 1993. Crop Protection : Why and How. In: *Crop Protection and Sustainable Agriculture* (Chadwick D. J., Marsh J. eds.), J. Wiley & Sons, New York, pp. 48-55.

(5) Deutscher A. A., Wilson L. J., Mensah R. K., 2005. Integrated pest management guidelines for cotton production systems in Australia. Cotton CRC, Australia, 78 p., <http://www.cotton.crc.org.au> (consulted January 12, 2006).

(6) Norris R. F., Cashell-Chen E. P., Kogan M., 2003. (See reference n° 1 of Chapter 1.)

(7) Seguy L., Bouzinac S., Belot J. L., Martin J., 2004. Sustainable cotton production systems for the humid savannas of central Brazil. In: *Proceedings of the World Cotton Conference-3: Cotton Production for the New Millennium.* 9-13 March 2003, Cape Town, South Africa, ARC, Institute for Industrial Crops, pp. 481-496, Swanepoel A. ed., Pretoria, RSA.

(8) AFD, 2006. Le semis direct sur couverture végétale (SCV). Une solution alternative aux systémes de culture conventionnels dans les pays du Sud. AFD, Paris, 68 p., <http://www.ffem.fr> (consulted March 13, 2007).

(9) Cook S. M., Khan Z. R., Pickett J. A., 2007. The use of push-pull in integrated pest management. *Annu. Rev. Entomol.,* 52, 375-400.

(10) Pyke B., Rice M., Sabine B., Zalucki M., 1987. The push-pull strategy-behavioural control of *Heliothis. Australian Cotton Grower,* May-July, 7-9.

(11) Wäckers F.L., Romeis J., van Rijn P., 2007. Nectar and pollen feeding by insect herbivores and implications for multitrophic interactions. *Annu. Rev. Entomol,* 52, 301-323.

(12) Deguine J.-P., Fok M., Vaissayre M., Crétenet M., Rollin D., Marmotte P., Gourlot J.-P., Lacape M., Chaïr H., Lançon J., 2000. The evolution of research and development work performed by CIRAD in partnership with small cotton growers in French-speaking West Africa. *Proceedings of a Technical Seminar at the 59th Plenary Meeting of the ICAC: Cotton – Global Challenges and the Future.* November 2000, Cairns, Australia, pp. 25-36.

(13) Abba A. A., Hofs J.-L., Mergeai G., 2006. Relever les défis environnementaux pour les filières cotonnières d'Afrique de l'Ouest et du Centre. *Biotechnol. Agron. Soc. Environ.* 10(4), 351-359.

(14) Deguine J.-P., Ferron P., 2005. Gestion écologique des populations d'insectes piqueurs suceurs en culture cotonniere. In: *Enjeux phytosanitaires pour l'agriculture et l'environnement* (Regnault-Roger C. coord.), Tec & Doc, Lavoisier, Paris, pp. 367-383.

(15) Papy F., Baudry J., 2005. Le système de culture : différents niveaux d'organisation territoriale à distinguer et à articuler. In: *Agronomes et Territoires.* Les Entretiens du Pradel 2ème èdition, Prevost Ph. coord., L'Harmattan, Paris, pp. 171-182.

(16) van Emden H. F., 2003. Conservation biological control: from theory to practice. *Proceedings of the 1st International Symposium on Biological Control of Arthropods,* January 14-18, 2002, Honolulu, Hawaii, USA, USDA Forest Service FHTET-03-05, pp. 199-208.

(17) Symondson W. O. C., Sunderland K. D., Greenstone M. H., 2002. Can generalist predators be effective biocontrol agents? *Annu. Rev. Entomol.,* 47, 561-594.

(18) Marshall E. J. P., 2005. Field margins in northern Europe: Integrating agricultural, environmental and biodiversity functions. In: *Field Boundary Habitat: Implications for Weed, Insect and Disease Management* (Thomas A.G. ed.), Société Canadienne de Malherbologie, Topics in Canadian Weed Science, Volume 1, Sainte-Anne de Bellevue, Québec, pp. 39-67.

(19) Mensah R. K., Sequeira R. V., 2004. Habitat manipulation for insect pest management in cotton cropping systems. In: *Ecological Engineering for Pest Management. Advances in Habitat Manipulation for Arthropods* (Gurr G. M., Wratten S. D., Altieri M. A. eds.), CSIRO and CABI Publishing, Collingwood VIC, Australia, and Wallingford, Oxon, UK, pp. 187-197.

(20) Gibbs M., Dufour R., Guerena M., 2005. (See reference n° 11 in Chapter 5.)

(21) SRVA, 2005. La compensation écologique dans l'exploitation agricole. <http://ww.srva.ch/files/env_ce.pdf> (consulted August 20, 2008).

(22) Boller E. F., Höni F., Poehling M., 2004. *Ecological Infrastructures. Ideabook on Functional Biodiversity at the Farm Level. Temperate Zones of Europe.* LBL, Lindau, CH, 212 p.

Conclusion

It is now 30 years since the idea of giving crop protection a more ecological orientation was put forward by a number of academic societies and international organisations. Since then, these ideas have spread only slowly, even though during the same period the harmful impacts on the environment of the former chemical treatments were fully recognised. For example, it was only very recently that the World Bank and the International Monetary Fund (IMF) adopted the principles of sustainability in addressing the development of third world countries, after having for decades defended a productivist agenda marked with the growing use of inputs to develop and produce export crops. In countries which grow crops industrially, like the United States, the extension of integrated production methods has been equally disappointing, as reported by C. Shennan *et al.* (1).

Significant progress has been made in certain cases where insecticide abuse led producers into a genuine economic impasse: orchard crops, glasshouse crops, and in some areas, grape production, but also to a lesser extent major crops such as rice or cotton. As the main market for pesticides, and particularly for insecticides since the middle of the 20th century, cotton production has been used throughout the discussion in this book to provide examples of the development of crop protection strategies. Cotton's worldwide distribution – in extensive industrial-scale production as well as in small-holder systems — has enabled us to learn a variety of lessons from different agronomic situations.

There are many reasons why the evolution of crop protection practices has been so slow. Most are closely linked with the productivist concept of agriculture. The intensive use of inputs such as fossil fuels for the mechanisation of farm work, of water to meet the physiological needs of cultivated plants through irrigation, of fertiliser to increase their vegetative and fruiting growth, and of synthetic pesticides to limit harvest losses caused by pests, were brought to bear to enable the full expression of the genetic potential of varieties selected for their productivity rather than for their quality.

The profit imperative prevailed, as in many other areas of human activity, at the expense of rational long-term management of natural resources. Some alternative agronomic solutions have been recommended, but usually they have not been actually adopted by producers because of their lower efficacy, their cost, the difficult of implementing them, and the time needed before their benefits become apparent. Newer concepts, such as IPM, have even been partially diverted from their original meanings and goals, because of their underlying methodological and technical inadequacy and the practical problems involved in their full implementation. These obstacles resulted largely from insufficient investment in research and in the development of innovative solutions, as the correct priorities were not established in good time. In this unfavourable context, the crop protection industry preferred to invest most heavily in areas of activity considered the safest bets for profitability, such as the synthesis of more selective materials, now called biorational pesticides, in response to advances in the users' understanding. The example of the stalling of development of biopesticides is revealing, although in the 1980s they seemed to have such a promising future.

Founded on the laws of population dynamics, integrated control rapidly transformed itself into population management under the rubric of IPM, but was held up by the gaps in our fundamental knowledge in this field. The operational choices of research institutes in addressing these knowledge gaps have differed considerably across the world. Anglo-Saxon countries were by far the most engaged and still are today, and have been the source of many publications in a range of specialised scientific journals. A number of these outputs focussed on the identification and characterisation of functional ecological groups, giving a much more operational character to fundamental research than had previously been the case.

In France, since the 1980s, the *Centre National de la Recherche Scientifique* (CNRS) has brought together the biosystematics and genetics of populations (evolution, specialisation, adaptation) and the structure and functioning of populations within species, species complexes and communities. Going against the interdisciplinary trend of the time and led by G. Barnaud and J-C. Lefeuvre (2), the CNRS developed a reductionist agenda and made ecosystems a major axis of research. Within the *Institut National de la Recherche Agronomique* (INRA), whose mandate includes promoting applied ecology, the means were often lacking, most likely because of strategic differences between the disciplines concerned. It was only after the elaboration of Agenda 21 following the United Nations Conference in Rio de Janeiro (1992) that researchers realised that the conservation of biodiversity with the aim of preserving the long-term functioning of ecosystems was a major priority. It was not until 1998 that the first inter-organisational centre for the biology and management of populations (CBGP) was built, in AGROPOLIS — the centre for agricultural sciences in Montpellier in southern France. Its twin missions were the study of the structure of populations within species, species complexes and communities, and the study of their interactions as a function of environmental and human selective pressure.

Given the recent recognition of agroecology as a separate scientific discipline (Box 5), "covering integrative studies relevant to agronomy, ecology, sociology and economics undertaken at different scales" (3), we may already have reached the critical stage required for a useful paradigm shift—the moment when a scientific theory which has been refuted, but not immediately rejected because of lack of alternatives, is finally and rapidly replaced. In this case the elimination of crop pests by toxic active ingredients has been discredited and it may now be the right time to replace it with the agroecological management of pest populations.

Are agroecology and its application in crop protection ready to assume this responsibility? Signs that things are moving in this direction have been apparent since the 1980s, with, for example, the adoption of the concept of spatio-temporal crop protection, or 'area-wide pest management'. This concept is characterised by changes in the scale of the perception of phenomena and in the design of strategies. While traditional chemical control (and integrated control in its early days) was seen as responding to plant heath problems at the level of the individual field immediately after a pest outbreak, integrated protection strategies such as IPM attempt to address the populations of all pests in the same crop. Later the entire area colonised by these populations was taken into account, followed by the whole farm, then neighbouring farms, before finally all the agroecosystems indentified in a given region were included. The need to account for the global phenomenon of pesticide resistance has played a determining role in this development, as have, in some places, vast experiments with autocidal control involving the simultaneous aerial release of sterile males over considerable areas.

Likewise, the precautions taken in the creation of refuge zones to prevent the development of resistance to genetically modified plants, has familiarised producers with pest management planning beyond the usual limits of individual fields. To this spatial scale was soon added a temporal dimension, with acceptance of the importance of whole cycles of pest development leading to management operations in areas located far from the crops that had to be protected, such as in non-cultivated areas and outside the periods in which damage usually occurs. The destruction of underground diapausing stages of certain cotton pests in trap crop strips within fields or in non-cultivated areas is a good illustration of this type of management.

Producers have been encouraged to adopt a collective attitude to ensure the efficacy of the new management strategies, sometimes called 'community pest management'. This change of attitude has been influential in enabling a break with earlier habits and in facilitating the adoption of technical innovations. This involved a shift in the vision of the role of the producer, making him (or her) the principal actor in the agreed activities but no longer its single executor, thus replacing individual initiative with collective responsibility, a precondition for improved efficacy. This development has its origins in the extension programmes organised for and by the producers themselves, in development agencies and in non-governmental organisations, for example, the Farmer Field Schools implemented in Asia initially by rice growers supported by donors, then later in a range of agricultural systems, including cotton. The reduction in the number of insecticide treatments enabled by the use of genetically modified varieties, such as Bt cotton, has drawn the attention of producers to the useful role that can be played by beneficial organisms when they are subject to reduced selection pressure by the use of insecticides.

Other authors see this as a continuing development rather than a real break with tradition. They see the so-called IPM Continuum as expanding from an initial minimal stage comprising professional scouting of populations and the rational exploitation of the concept of tolerance thresholds. Certainly forecasting systems have enabled us to better understand the dynamics of the populations of pests and their natural enemies, to better exploit the properties of pesticides, and to understand when it is wiser not to use them. Further, the IPM strategy depends on the implementation of preventative measures such as the use of resistant plant varieties, disruption of the mating of pests by means of artificial pheromones, and the use of biological control and of microbiology. With the aim of reducing secondary effects, the new rule is not to apply synthetic pesticides except as a last resort. The final stage of the process, 'Bio-intensive IPM', is the genuine combination of all these processes which together provide the driving force of the IPM concept!

However, it would be irresponsible to rigidly adhere to that position today, because so far results have not been entirely satisfactory, and the demand for material well-being is growing, even though it is now recognised that the resources of the biosphere are limited. It consequently seems fitting to re-examine these ideas and to give priority to the compatibility of processes following the principles of sustainable development, ensuring coherence by the rational management of populations and in particular by the planning of their habitats. This vision has the advantage of responding to the preoccupations of the agronomist, the crop protection specialist, the nature conservationist, and the hunter as a manager of the countryside (Figure 16). In the field of crop protection this provides the rationale for emphasising preventative actions as opposed to traditional curative interventions, based on an appropriate management strategy (Box 23).

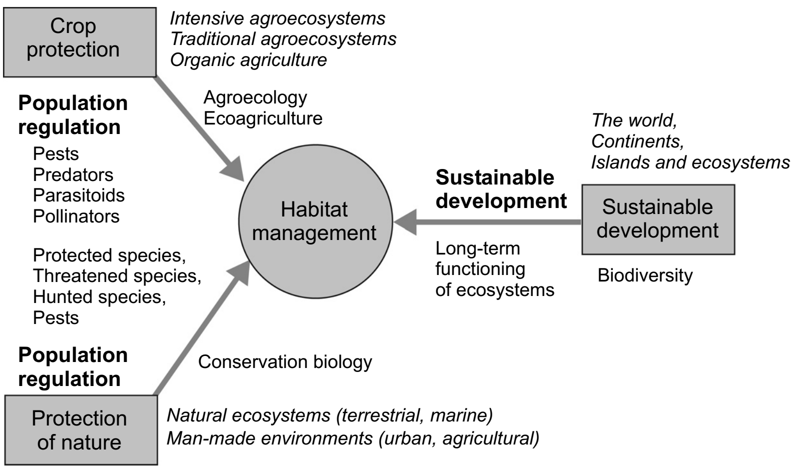

Figure 16 Coherence and convergence of the different concepts of development of ecology and of crop protection with respect to the concept of habitat management (5).

This agenda has finally returned the focus to agronomy while acknowledging the specificity of agroecology, which is capable of providing a substantial and original contribution to solving new questions that are both complex and acute, such as those posed in the report on the global status of ecosystems

BOX 23 Crop protection strategy adapted for the sustainable management of agroecosystems

1. Respect international, national and regional regulatory measures.

2. Prioritise the use of preventative measures through the management of plant populations (whether cultivated on not):

- Grow healthy plants and ensure good soil health utilising prophylaxis, varietal selection, crop rotations, whole-farm crop planning, cultural practices (such as sowing under plant cover and minimum tillage), management of weeds, rational irrigation and fertilisation, use of organic fertilisers;
- Reduce pest populations and increase populations of beneficial organisms (at the level of the individual field, its surroundings, of the farm and of the entire agroecosystem): crops or trap crops, planting of refuge areas, plant associations and intercropping, the *push-pull* technique, establishment of field margins, planning of ecological compensation structures (corridors, hedgerows, grassy and flowering strips etc.), techniques designed to incorporate vegetative diversity;
- Favour concerted actions in time and in space within the agroecosystem.

3. Evaluate the real socio-economic and environmental risks by using pest scouting techniques appropriate for one field, a group of fields, a farm, or the whole ecosystem, with the assistance of the regional agricultural extension services.

4. Take only need-based decisions on curative measures:

- With the aid of decision tools and in collaboration with fellow producers, account for local and ever-changing multiple criteria, intervention thresholds (economic, social, environmental) and of the risk of development of resistance;
- In the framework of whole-of-farm management and at a range of time scales (short to long term), account for the agroecological characteristics of the agroecosystem as a whole (the spatial dimension).

5. Only in the case of absolute necessity, apply curative measures

- Give priority to alternative control measures: cultural techniques (e.g. defoliation, plant topping), biological control, physical and biotechnical control measures;
- Only as a last resort: use the chemical pesticides with the lowest ecological impact, chosen to avoid the emergence of resistance.

(Millennium Ecosystem Assessment) (6). However, bringing together agronomy and ecology remains the subject of internal debate around defining cropping systems among other things, as demonstrated in a number of recent reviews (7, 8, 9) which take up the suggestion of S. Hénin (1967) (10) of defining agronomy as 'ecology applied to the production of communities of cultivated plants and the planning of agricultural land'.

This idea is not new and is relevant to agronomic research in a wider context. It was captured by the title of the report by J. Poly, then the new director general of INRA, who in 1978, called for a 'more economic and more autonomous agriculture' (11). The testimony of several 'gate keepers' in charge of interdisciplinary research programmes concerning the countryside have chalked out the road to be followed (12). B. Chevassus-au-Louis recently took the first step in calling for the rebuilding of agronomic research based on the new agroecological principles (13). In response, new directions are being pursued by the research institutes concerned, including CIRAD, in modified strategic visions and changes in what are considered to be practices that are appropriate for agriculture in the developing world. These directions include 'the spatial organisation of production systems, ecosystems and landscapes; the interactions between ecological dynamics, the behaviour of stakeholders and the taking of public and collective decisions; production chains and the valorisation of environmental goods and services (soil fertility, biodiversity, carbon sequestration, water quality, etc.) by agriculture, livestock rearing and forestry'. These are incitements to design production systems which take advantage of our understanding of, and make use of ecological processes within ecosystems. The elaboration of a new system of agroecological crop protection, as defined below, is one element of the response to this proposal (Box 24).

BOX 24 Agroecological crop protection

A crop protection system based on the science of agroecology. By prioritising preventative measures, the system seeks to establish bioecological equlibria between animal and plant communities within an agroecosystem with the goal of foreseeing or reducing the risks of infestation or outbreaks of pests. To this end, the system emphasises the conservation and improvement of the 'health' of soils (fertility, biological activity, structure, etc.) and the maintenance or incorporation of plant biodiversity in the agroecosystem.

Beyond the classical techniques of integrated crop protection, emphasis is placed on cultural practices and plant management systems which help maintain or create habitats to attract indigenous beneficial fauna and/or repel pest fauna. Agroecological crop protection operates at larger scales in time and space, from a single crop cycle to several years, and from a single field to an agroecosystem or a landscape. It brings together the management of plant communities (crops and non-cultivated plants in areas surrounding the field and in the wider agroecosystem) with that of the animal communities of pests, beneficials and pollinators. Agroecological crop protection thus requires concerted action by stakeholders, notably farmers and land managers.

As with integrated crop protection, curative practices are only a last resort to be used in the case of absolute necessity, and then only using methods compatible with the functional biological groups which ensure the provision of ecological services. According to these criteria, the future use of pesticides may only be short term, at least in their present form, given the current status of many pesticides whose use is already restricted for environmental and toxicological reasons.

According to this vision, prophylaxis, habitat management, and biological control are the principal components of crop protection.

As indicated in the introduction (1), we have tried to show that the development of crop protection since the middle of the 20th Century not only provides a good illustration of the successive steps in scientific and technical innovation in this particular field, but also of our awareness of the complexity of the interactions of living things in a world whose limits we are finally beginning to understand. Our previous actions, based on our earlier understanding, exacerbated the global and long-term food crisis we now face at the beginning of the new millennium.

Bibliographic References in the Conclusion

(1) Shennan C., Pisani Gareau T., Sirrine J. R., 2005. (See reference n° 1 of the introduction.)

(2) Barnaud G, Lefeuvre J.-C., 1992. L'écologie avec ou sans l'homme ? In: *Sciences de la nature, Sciences de la société. Les passeurs de frontiéres* (Jollivet M. dir.), CNRS, Paris, pp. 69-112.

(3) Dalgaard T., Hutchings N. J., Porter J. R., 2003. (See reference n° 15 of Chapter 1.)

(4) Jacobsen B. J., 1997. (See reference n° 9 of Chapter 4.)

(5) Deguine J.-P., Ferron P., Russell D.A., 2008. (See reference n° 2 of Chapter 2.)

(6) Millennium Ecosystem Assessment, 2005. (See reference n° 3 of the introduction.)

(7) Capillon A., 2005. Agriculture durable: faut-il repenser les systémes de culture ? *Déméter 2006,* 57-168.

(8) Prevost P., 2005. *Agronomie et Territoire.* Deuxiéme édition des Entretiens du Pradel. L'Harmattan, Paris, 502 p.

(9) Doré T., Le Bail M., Martin P., Ney B., Roger-Estrade J. coords., 2006. *L'agronomie aujourd'hui.* Quae, Versailles, collection Synthéses, 367 p.

(10) Hénin S., 1967. (See reference n° 13 of Chapter 1.)

(11) Poly J., 1978. Pour une agriculture plus économe et plus autonome. INRA, Paris, 65 p.

(12) Jollivet M., 1992. *Sciences de la nature, Sciences de la société. Les passeurs de frontières.* CNRS, Paris, 589 p.

(13) Chevassus-au-Louis B., 2006. (See reference n° 2 of Chapter 7.)

Further Reading

A SELECTION OF ANALYSES, LATEST DEVELOPMENTS AND REVIEW PAPERS

On Crop Protection

Acta, 2008. *Index Phytosanitaire Acta 2008.* Acta, Paris, 844 p.

Altieri M. A., Nicholls C. I., 2004. *Biodiversity and Pest Management in Agroecosystems.* Food Products Press, Binghamton, NY, 236 p.

Barriuso E., 2004. *Estimation des risques environnementaux des pesticides.* Éditions INRA, Paris, 123 p.

Boller E. F., van Lenteren J. C., Delucchi V. eds., 2006. *International Organization for Biological Control of Noxious Animals and Plants — History of the first 50 years (1956-2006).* IOBC, Zürich, 287 p.

Bonny S., 2005. Quelle place pour les cultures transgéniques en protection des plantes? Aspects agro-économiques. In: *Enjeux phytosanitaires pour l'agriculture et l'environnement* (Regnault-Roger C. ed.), Tec & Doc, Lavoisier, Paris, 43, 895-917.

Bonny S., 2008. How have the opinions about GMOs changed over time? The situation in the European Union and the USA. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources,* 3, 1-17.

Chandler D., Davidson G., Grant W. P., Greaves J., Tatchell G. M., 2008. Microbial biopesticides for integrated crop management: an assessment of environmental and regulatory sustainability. *Trends in Food Science & Technology* 19, 275-283.

Ciancio A., Mukerji K. G. eds., 2007. *General Concepts in Integrated Pest and Disease Management.* Series: Integrated Pest Management of Plant Pests and Diseases, Vol. 1, Springer, 360 p.

Copping L. G., 2004. *The manual of biocontrol agents.* British Crop Protection Council, Farnham, UK, 752 p.

Devillers J., Farret R., Girardin P., Rivière J.-L., Soulas G., 2005. *Indicateurs pour évaluer les risques liés ã I'utilisation des pesticides.* Tec & Doc, Paris, 278 p.

Dhaliwal G. S., Koul O., Arora R., 2004. Integrated Pest Management: Retrospect and Prospect. In: *Integrated Pest Management. Potential, Constraints and Challenges* (Koul O., Dhaliwal G. S., Cuperus G. W. eds.), Cabi Publishing, Wallingford, Oxon, UK, 1, 1-20.

Gatehouse J. A., 2008. Biotechnological Prospects for Engineering Insect-Resistant Plants. *Plant Physiol.,* 146, 881-887.

Gray M. E., Ratcliffe S. T., Rice M. E., 2009. The IPM paradigm: concepts, strategies and tactics. In: *Integrated Pest Management. Concepts, Tactics, Strategies and Case Studies* (Radcliffe E. B., Hutchison W. D., Cancelado R. E. eds), Cambridge University Press, Cambridge, UK, 1, 1-13.

Hajek A., 2004. *Natural enemies: An introduction to biological control.* Press Syndicate of the University of Cambridge, UK, 378 p.

Hendrichs J., Kenmore O., Robinson A. S., Vreysen M. J. B., 2007. Area-Wide Integrated Pest Management (AW-IPM): Principles, Practice and Prospects. In: *Area-Wide Control of Insect Pests. From Research to Field Implementation* (Vreysen M. J. B., Robinson A. S., Hendrichs J. eds.), Springer, Dordrecht, 3-33.

Horn D. J., 2009. IPM as applied ecology: the biological precepts. In: *Integrated Pest Management. Concepts, Tactics, Strategies and Case Studies* (Radcliffe E. B., Hutchison W. D., Cancelado R. E. eds.), Cambridge University Press, Cambridge, UK, 5, 51-61.

Horowitz A. R., Ishaaya I., 2004. Biorational Insecticides—Mechanisms, Selectivity and Importance in Pest Management. In: *Insect Pest Management. Field and Protected Crops* (Horowitz A. R., Ishaaya I. eds), Springer-Verlag, Berlin, Heidelberg, 1-28.

Ignacimuthu S., Jayaraj S., eds. 2005. *Sustainable Insect Pest Management.* Narosa Publishing House, New Delhi, 310 p.

Marrone P. G., 2007. Barriers to adoption of biological control agents and biological pesticides. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources,* 2(051), 1-12.

Philogéne B. J. R., Fabres G., Regnault-Roger C, 2005. Protection des cultures, environnement et développement durable : enjeux pour le

XXIème siècle. In: *Enjeux phytosanitaires pour l'agriculture et l'environnement* (Regnault-Roger C. ed.), Tec & Doc, Lavoisier, Paris, Introduction, 1-14.

Pimentel D., 2007. *Encyclopedia of Pest Management, Volume II.* CRC Press, Boca Raton, Fla, 784 p.

Pretty J. ed., 2005. *The Pesticide Detox—Towards a more sustainable agriculture.* Earthscan, London, Sterling, VA, 314 p.

Regnault-Roger C., Philogène B. J. R., Vincent C. (coord), 2008. *Biopesticides d'origine végétale.* Tec & Doc, Lavoisier, Paris, 2nd ed., 546 p.

Sanchis V., Bourguet D., 2008. *Bacillus thuringiensis:* applications in agriculture and insect resistance management. A review. *Agron. Sustain. Dev.* 28, 11-20.

van Driesche R., Hoddle M., Center T., 2008. *Control of Pests and Weeds by Natural Enemies: An Introduction to Biological Control.* Wiley-Blackwell, 484 p.

van Emden H., Service M. W., 2004. *Pest and Vector Control.* Cambridge University Press, Cambridge, UK, 362 p.

Walters D. ed., 2009 (in press). *Disease Control in Crops: Biological and Environmentally-Friendly Approaches.* Wiley-Blackwell, 280 p.

On Cotton and Cotton Plants

Allen C. T., 2008. Boll Weevil Eradication: an Areawide Pest Management Effort. In: *Areawide Pest Management. Theory and Implementation* (Koul O., Cuperus G. Elliott N. eds.), CAB International, Wallingford, Oxon, UK, 20, 467-559.

Naranjo S. E., Luttrell R. G., 2009. Cotton arthropod IPM. In: *Integrated Pest Management. Concepts, Tactics, Strategies and Case Studies* (Radcliffe E. B., Hutchison W. D., Cancelado R. E. eds.), Cambridge University Press, Cambridge, UK, 25, 324-340.

Orsenna E., 2006. *Voyage aux pays du coton. Petit précis de mondialisation.* Fayard, Paris, 289 p.

Prasifka J. R., Heinz K. M., Minzenmayer R. R., 2004. Relationships of landscape, prey and agronomic variables to the abundance of generalist predators in cotton *(Gossypium hirsutum)* fields. *Landscape Ecology* 19(7), 709-717.

Rao G. V. R., Chari M. S., Pawar C. S., Sharma O. P., Rao V. R., 2005. *Helicoverpa* Management: Successes and Failures—Lessons for the Future. In: *Heliothis/Helicoverpa Management. Emerging Trends and*

Strategies for Future Research (Sharma H. C. ed.), Oxford & IBH Publishing Co. Pvt. Ltd., New Delhi, 431-452.

Russell D., 2004. Integrated Pest Management for Insect Pests of Cotton in Less Developed Countries. In: *Insect Pest Management. Field and Protected Crops* (Horowitz A. R., Ishaaya I. eds), Springer-Verlag, Berlin, Heidelberg, 141-179.

Russell D., 2004. Emerging trends in insect pest management in cotton. *Proceedings International Symposium Strategies for Sustainable Cotton Production. A Global Vision.* 23-25 Nov. 2004, Univ. of Agric. Sciences, Dharwad, India. Vol. 3-Crop Protection, 1-14.

Spurgeon D. W., 2007. Ecologically Based Integrated Pest Management in Cotton. In: *Ecologically Based Integrated Pest Management* (Koul O., Cuperus G. W. eds.), Cabi Publishing, Wallingford, Oxon, UK, 16, 367-405.

Wilson L. J., Mensah R. K., Fitt G. P., 2004. Implementing Integrated Pest Management in Australian Cotton. In: *Insect Pest Management. Field and Protected Crops* (Horowitz A. R., Ishaaya I. eds), Springer Verlag, Berlin, Heidelberg, 97-118.

Wu K. M., Guo Y. Y., 2005. The Evolution of Cotton Pest Management Practices in China. *Annu. Rev. Entomol.* 50, 31-52.

On Agronomy and Agriculture

Aselage J., Johnson D. T., 2009. From IPM to organic and sustainable agriculture. In: *Integrated Pest Management. Concepts, Tactics, Strategies and Case Studies* (Radcliffe E. B., Hutchison W. D., Cancelado R. E. eds.), Cambridge University Press, Cambridge, UK, 39, 489-505.

Bajwa W. I., Kogan M., 2004. Cultural Practices: Springboard to IPM. In: *Integrated Pest Management. Potential, Constraints and Challenges* (Koul O., Dhaliwal G. S., Cuperus G. W. eds.), Cabi Publishing, Wallingford, Oxon, UK, 2, 21-38.

Benoit M., Caneill J., Messian A., Pay F., Prevost P. coords, 2008. *Les agronomes pour demain. Accompagner la diversité des agricultures pour un développement durable.* Editions Quae, Versailles, 95 p.

Chevassus-au-Louis B., Griffon M., 2008. La nouvelle modernité : une agriculture productive á haute valeur écologique. *Déméter 2008, Économie et stratégies agricoles,* 7-48.

Francis C. A., Poincelot R. P., Bird G. W., 2006. *Developing and Extending Sustainable Agriculture. A New Social Contract.* The Haworth Press, Binghampton, NY, 343 p.

Gliessman S. R., 2006. *Field and Laboratory Investigations in Agroecology.* CRC Press, Boca Raton, Fla, 2nd ed., 302 p.

Malézieux E., Crozat Y., Dupraz C., Laurans M., Makowski D., Ozier-Lafontaine H., Rapidel B., de Tourdonnet S., Valantin-Morison M., 2008. Mixing Plant Species in Cropping Systems: Concepts, Tools and Models. A review. *Agron. Sustain. Dev.,* 29, 43-62.

Ratnadass A., Michellon R., Randriamanantsoa R., Seguy L., 2006. Effects of Soil and Plant Management on Crop Pests and Diseases. In: *Biological Approaches to Sustainable Soil Systems* (Uphoff N., Ball A. S., Fernandes E., Herren H., Husson O., Laing M., Palm C., Pretty J., Sanchez P., Sanginga N., Thies J. eds.), Taylor & Francis, CRC Press, Boca Raton, London, New York, 41, 589-602.

Reau R., Doré T., coords., 2008. *Systémes de culture innovants et durables. Quelles méthodes pour les mettre au point et les évaluer?* Collection Transversales, Educagri editions, Dijon, 175 p.

Scherr S. J., McNeely J. A., 2007. *Farming with Nature. The Science and Practice of Ecoagriculture.* Island Press, Washington, 472 p.

Vilain L., 2008. *La Méthode IDEA. Indicateurs de durabilité des exploitations agricoles.* Guide d'utilisation, Educagri éditions, Dijon, 184 p.

On Ecology

Ausden M., 2007. *Habitat Management for Conservation. A Handbook of Techniques.* Oxford University Press, Oxford, UK, 411 p.

Barbault R., 2008. *Ecologie générale. Structure et fonctionnement de la biosphere.* Collection Sciences Sup, Dunod, Paris, France, 6éme édition, 390 p.

Cardinale B. J., Srivastava D. S., Duffy J. E., Wright J. P., Downing A. M., Sankaran M., Jouseau C., 2006. Effects of biodiversity on the functioning of trophic groups and ecosystems. *Nature Letters,* 443, 989-992.

Chevassus-au-Louis B., 2007. La biodiversité : un nouveau regard sur la diversité du vivant. I. Immensité et complexité. *Cah. Agric.,* 16, 219-227.

Chevassus-au-Louis B., 2008. La biodiversité : un nouveau regard sur la diversité du vivant. II. Utilité et fragilité. *Cah. Agric.,* 17, 51-57.

Clergue B., Amiaud B., Pervanchon F., Lasserre-Joulin F., Plantureux S., 2005. Biodiversity: Function and Assessment in Agricultural Areas. A review. *Agron. Sustain. Dev.,* 25, 1-15.

Coll M., 2009. Conservation Biological Control and the Management of Biological Control Services. Are they the same? *Phytoparasitica* (Guest Editorial) 37(3), 205-208.

Fiedler A. K., Landis D.A., Wratten S. D., 2008. Maximazing ecosystem services from conservation biological control: The role of habitat management. *Biol. Control,* 45, 254-271.

Fischesser B., Dupuis-Tate M.-F., 2007. *Le Guide illustré de l'écologie.* Éditions de La Martiniére - Éditions Quæ, 350 p.

Frontier S., Pichod-Viale D., Leprêtre A., Davoult D., Luczack C., 2008. *Ecosystémes. Structure, Fonctionnement, Evolution.* Collection Sciences Sup, Dunod, Paris, 4éme édition, 558 p.

Hooper D. U., Chapin F. S., Ewel J. J., Hector A., Inchausti P., Lavorel S., Lawton J. H., Lodge D. M., Loreau M., Naeem S., Schmid B., Setälä H., Symstad A. J., Vandermeer J., Wardle D. A., 2005. Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. *Ecological Monographs* 75(1), 3-35.

Hunter M. D., 2008. The role of landscape in insect ecology and its implications for agriculture. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources,* 3(029), 1-11.

Tscharntke T., Klein A., Kruess A., Steffan-Dewenter I, Thies C., 2005. Landscape perspectives on agricultural intensification and biodiversity—ecosystem service management. *Ecology Letters,* 8(8), 857-874.

Winder L., Woiwood I. P., 2007. Populations, metapopulations: elementary units of IPM systems. In: *Perspectives in Ecological Theory and Integrated Pest Management* (Kogan M., Jepson P. eds.), Cambridge University Press, Cambridge, UK, 3, 65-86.

On Agroecology

Gliessman S. R., 2007. *Agroecology: The Ecology of Sustainable Food Systems.* CRC Press, Boca Raton, Fla, 2nd ed., 384 p.

Hendrickx F., Maelfait J.-P., van Wingerden W., Schweiger O., Speelmans M., Aviron S., Augenstein I., Billeter R., Bailey D., Bukacek R., Burel F., Diekötter T., Dirksen J., Herzog F., Liira J., Roubalova M., Vandomme V., Bugter R., 2007. How landscape structure, land-use intensity and habitat diversity affect components of total arthropod diversity in agricultural landscapes. *J. Appl. Ecology,* 44, 340-351.

Hill S. B., 2004. Redesigning Pest Management: A Social ecology approach. In: *New Dimensions in Agroecology* (Clements D., Shrestha A. eds.), Food Product Press, The Haworth Press, Inc., Binghampton, NY, 491-510 and *J. Crop Improv.,* 12, n° HS 1-2, 491-510.

Jarvis D. I., Padoch C., Cooper H. D., 2006. *Managing Biodiversity in Agricultural Ecosystems.* Columbia University Press, NY, 492 p.

Marshall E. J. P., 2004. Agricultural landscapes: field margin habitats and their interaction with crop production. In: *New Dimensions in Agroecology* (Clements D., Shrestha A. eds.), Food Product Press, The Haworth Press, Inc., Binghampton, NY, 365-404 and *J. Crop Improv.*, 12, n° HS 1-2, 365-404.

Menalled F. D., Landis D. A., Dyer L. E., 2004. Research and extension supporting ecologically based IPM systems. In: *New Dimensions in Agroecology* (Clements D., Shrestha A. eds.), Food Product Press, The Haworth Press, Inc., Binghampton, NY, 153-174 and *J. Crop Improv.*, 11, n° HS 1-2, 153-174.

New T. R., 2005. *Invertebrate Conservation and Agricultural Ecosystems.* Cambridge University Press, Cambridge, UK, 354 p.

Ribier V., Griffon M., 2006. Quelles politiques agricoles pour accompagner la transition vers l'agroécologie ? In: *Déméter 2006 Economie et Stratégies Agricoles.* Club Déméter, Paris, 145-163.

Snapp S., Pound B. eds., 2008. *Agricultural Systems: Agroecology and Rural Innovation for Development.* Academic Press, London, San Diego, CA, 400 p.

Warner K. D., 2007. *Agroecology in Action: Extending Alternative Agriculture Through Social Networks.* The MIT Press, Cambridge, MA, 273 p.

Wojtowski A., 2004. *Landscape Agroecology.* Food Product Press, New York, London, Oxford, 330 p.

On Agroecological Crop Protection

Altieri M. A., Nicholls C. I., Ponti L., 2009. Crop diversification strategies for pest regulation in IPM systems. In: *Integrated Pest Management. Concepts, Tactics, Strategies and Case Studies* (Radcliffe E. B., Hutchison W. D., Cancelado R. E. eds.), Cambridge University Press, Cambridge, UK, 10, 116-130.

Bianchi F. J. J. A., Booij C. J. H., Tscharntke T., 2006. Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. *Proc. R. Soc. B* 273, 1715-1727.

Brewer M. J., Noma T., Elliott N. C., 2008. A Landscape Perspective in Managing Vegetation for Beneficial Plant-Pest-Natural Enemy Interactions: a Foundation for Areawide Pest Management. In: *Areawide Pest Management. Theory and Implementation* (Koul O., Cuperus G. Elliott N. eds.), CAB International, Wallingford, Oxon, UK, 20, 467-559.

Elliott N. C., Onstad D. W., Brewer M. J., 2008. History and ecological basis for areawide pest management. In: *Areawide Pest Management. Theory and Implementation* (Koul O., Cuperus G., Elliott N. eds.), CAB International, Wallingford, Oxon, UK, 2, 15-33.

Faust R. M., 2008. General introduction to areawide pest management. In: *Areawide Pest Management. Theory and Implementation* (Koul O., Cuperus G., Elliott N. Eds.), CAB International, Wallingford, Oxon, UK, 1, 1-14.

Ferron P., Deguine J.-P., 2005. Crop protection, biological control, habitat management and integrated farming. A Review. *Agron. Sustain. Dev.*, 25, 17-24.

Ferron P., Deguine J.-P., 2005. Vers une conception agroécologique de la protection des cultures. In: *Enjeux phytosanitaires pour l'agriculture et l'environnement* (Regnault-Roger C. ed.), Tec & Doc, Lavoisier, Paris, 15, 347-366.

Fiedler A. K., Landis D. A., Wratten S. D., 2008. Maximizing ecosystem services from conservation biological control: The role of habitat management. *Biol. Control,* 45, 254-271.

Gardiner M. M., Fiedler A. K., Costamagna A. C., Landis D. A., 2009. Integrating conservation biological control into IPM systems. In: *Integrated Pest Management. Concepts, Tactics, Strategies and Case Studies* (Radcliffe E. B., Hutchison W. D., Cancelado R. E. eds.), Cambridge University Press, Cambridge, UK, 12, 151-162.

Gurr G. M., Scarratt S. L., Wratten S. D., Berndt L., Irwin N., 2004. Ecological engineering, habitat manipulation and pest management. In: *Ecological Engineering for Pest Management. Advances in Habitat Manipulation for Arthropods* (Gurr G. M., Wratten S. D., Altieri M. A. eds.), CSIRO and Cabi Publishings, Collingwood VIC, Australia and Wallingford, Oxon, UK, 1, 1-12.

Gurr G. M., Wratten S. D., Altieri A. M., 2004. Ecological engineering for enhanced pest management: towards a more rigorous science. In: *Ecological Engineering for Pest Management. Advances in Habitat Manipulation for Arthropods* (Gurr G. M., Wratten S. D., Altieri M. A. eds.), CSIRO and Cabi Publishings, Collingwood VIC, Australia and Wallingford, Oxon, UK, 14, 219-225.

Ignacimuthu S, Jayraj S. eds., 2006. *Biodiversity and Insect Pest Management.* Narosa Publishing House, New Delhi, 399 p.

Langer V., Kinane J., Lyngkjear M., 2007. Intercropping for pest management: the ecological concept. In: *Ecologically Based Integrated Pest Management* (Koul O., Cuperus G. W. eds.), Cabi Publishing, Wallingford, Oxon, UK, 5, 74-110.

Levins R., 2007. From simple IPM to the management of agroecosystems. In: *Perspectives in Ecological Theory and Integrated Pest Management* (Kogan M., Jepson P. eds.), Cambridge University Press, Cambridge, UK, 2, 45-64.

Marshall E. J. P., 2009. The impact of landscape structure and sown grass margin strips on weed assemblages in arable crops and their boundaries. *Weed Research* 49, 107-115.

Nicholls C. I., Altieri M. A., 2004. The agroecological bases of ecological engineering for pest management. In: *Ecological Engineering for Pest Management. Advances in Habitat Manipulation for Arthropods* (Gurr G. M., Wratten S. D., Altieri M. A. eds.), CSIRO and Cabi Publishing, Collingwood VIC, Australia and Wallingford, Oxon, UK, 3, 33-54.

Nicholls C. I., Altieri M. A., 2007. Agroecology: Contributions towards a renewed ecological foundation for pest management. In: *Perspectives in Ecological Theory and Integrated Pest Management* (Kogan M., Jepson P. eds.), Cambridge University Press, Cambridge, UK, 431-468.

Norris R. F., 2007. Weed ecology, habitat management and IPM. In: *Perspectives in Ecological Theory and Integrated Pest Management* (Kogan M., Jepson P. eds.), Cambridge University Press, Cambridge, UK, 11, 361-392.

Norton G. W., Rajotte E. G., Luther G. C., 2005. The Participatory Integrated Pest management (PIPM) Process. In: *Globalizing Integrated Pest Management–A Participatory Research Process* (Norton G. W., Heinrichs E. A., Luther G. C., Irwin M. E. eds), Blackwell Publishing, Ames, Iowa, 2, 13-26.

Potting R.P.J., Perry J.N., Powell W., 2004. Insect behavioural ecology and other factors affecting the control efficacy of agro-ecosystem diversification strategies. *Ecological Modelling* 182, 199-216.

Prokopy R. J., Roitberg B. D., 2007. Arthropod pest behavior and IPM. In: *Perspectives in Ecological Theory and Integrated Pest Management* (Kogan M., Jepson P. eds.), Cambridge University Press, Cambridge, UK, 4, 87-121.

Schowalter D., 2007. Ecosystems: concepts, analyses and practical implications in IPM. In: *Perspectives in Ecological Theory and Integrated Pest Management* (Kogan M., Jepson P. eds.), Cambridge University Press, Cambridge, UK, 13, 411-430.

Shelton A. M., Badenez-Perez F. R., 2006. Concepts and Applications of Trap Cropping in Pest Management. *Annu. Rev. Entomol.*, 51, 285-308.

Thomas A. G. ed., 2005. *Field Boundary Habitats: Implications for Weed, Insect and Disease Management.* Topics in Canadian Weed Science, Volume 1. Sainte-Anne-de-Bellevue, Québec : Canadian Weed Science Society – Société Canadienne de Malherbologie, 223 p.

Thomas M. B., Arthurs S. P., Watson E. L., 2006. Trophic and Guild interactions and the influence of multiple species on diseases. In: *Progress in Biological Control, vol. 3, Trophic and Guild Interactions in Biological Control* (Brodeur J., Boivin G. eds), Springer, Dordrecht, 101-122.

Tscharntke T., Bommarco R., Clough Y., Crist T. O., Kleijn D., Rand T. A., Tylianakis J. M., van Nouhuys S., Vidal S., 2007. Conservation biological control and enemy diversity on a landscape scale. *Biol. Control,* 43, 294-309.

Tscharntke T., Tylianakis J. M., Wade M. R., Wratten D., Bengtsson J., Kleijn D., 2007. Insect Conservation in Agricultural Landscapes. In: *Insect Conservation Biology* (Stewart A. J. A., New O. R., Lewis O. T. eds.), The 23rd Symposium of the Royal Entomological Society, Cabi Publishing, Wallingford, Oxon, UK, 16, 383-404.

Wratten S. D., Hochuli D. F., Gurr G. M., Tylianakis J., Scarrat S. L., 2007. Conservation, biodiversity, and integrated pest management. In: *Perspectives in Ecological Theory and Integrated Pest Management* (Kogan M., Jepson P. eds.), Cambridge University Press, Cambridge, UK, 7, 223-245.

Glossary

active substance: substance or micro-organism (including viruses) that have a general or specific action on pest organisms or on plants, parts of plants or plant products; in the case of a chemical substance the term 'active ingredient' is generally used (1).

adventitious: in the botanical sense, a species of plant foreign to the indigenous flora of an area which has naturalised itself; in the agronomic sense, a plant which accompanies a cultivated species and whose presence is consequently unwelcome (2).

agenda 21: adopted by 173 countries during the Earth Summit at Rio de Janeiro (1992), Agenda 21 outlines an action programme for the 21st Century in a wide range of domains for the sustainable development of the planet (3).

agrarian structure: totality of long-lived and profound connections between people and the land which are expressed in rural landscapes; method of organisation of cultivated areas which results in a type of habitat, a certain form of cultivated fields, a particular cropping system, which in combination, express themselves in the agricultural landscape (9).

agrobiology: the doctrine of organic agriculture (2).

agrochemistry: all the activities of the chemical industry providing products for agriculture, notably fertiliser and pesticides (4); used here in its original sense of that part of chemistry which studies the chemical substances used in agriculture (pesticides, fertilisers, antibiotics, etc.).

agroecological crop protection: system of crop protection resting on the scientific basis of agroecology. In emphasising preventative measures, it seeks to establish bioecological equlibria between the animal and plant communities within an agroecosystem, with the goal of forecasting or reducing the risks of infestations or outbreaks of pests. To this end, this system involves the conservation and improvement of the "health" of the soil (fertility, biological activity, structure, etc.) and the maintenance or incorporation of biodiversity in the agroecosystem (Box 24). To date the main focus have been in subsistence agriculture.

agroecology: the science bringing together disciplines concerning the relationships between living organisms present in crops; study of the interactions between plants, animals, people and their environment in the context of agricultural ecosystems (5).

agroecosystem, agrosystem, cultivated ecosystem: artificial ecosystem most often made up of only the cultivated plant or by a single livestock species and characterised by low spatial homogeneity and weak biodiversity, especially in the areas of industrial monocultures. The genetic uniformity of the cultivated plants renders them susceptible to pest attack. Agrosystems are dependent on people who must usually apply the fertiliser, control the pests and practice irrigation in the case of crops which, like maize, consume a lot of water (6).

agroforestry: crop type in which one or a few herbaceous or woody plants are grown under the cover of trees. The trees provide the shade necessary to reduce water loss by evaporation and the resulting drying out of soil, additionally providing wood and various fruits and sometimes forage for livestock (6).

agronomy: In the wider sense, our total scientific, technological, economic and social knowledge of relevance to agriculture (7); in the narrow sense used in this work, knowledge of the functioning of a complex system or agrosystem and/or the reasoning underlying action in the field of plant production (8).

allele: the particular form which is taken by a gene at a given locus and which determines one of the possible states of the same character within the overall phenotype (2).

allelochemical: a substance produced by an organism which has an impact on an individual of another species (thus contrasting with a pheromone which acts between individuals of the same species) (3).

aphicide: a substance or preparation having the property of killing aphids and whiteflies (9).

arthropod: invertebrate animal, with a chitinous exoskeleton, a segmental body and articulated appendages. Arthropods, including crustaceans, centipedes and millipedes, insects, spiders, comprise a division of life's diversity which includes around 80%, of all animal species (4).

autocidal control: methods which aim to exterminate a species from a particular area by using it as the agent of its own destruction (10). Use of the insect against itself by liberating into natural populations mass-reared sterilised males or individuals carrying infectious pathogens or carrying lethal genes (2).

auxiliary organism: animal predator or parasite of other living things, which contributes to the regulation of populations of cultivated plant pests (2); by extension, all living organisms (bees, earthworms, etc.) whose activity is favourable to agricultural production. Now little used in the English speaking world.

baculovirus: family of viruses specific to invertebrates and whose genome is comprised of circular long double stranded DNA. In addition to their use in biological control, they are used in biotechnology for the production of recombinant proteins (3).

biodiversity or biological diversity: concept applied to different types of variability in living things. Biodiversity is studied at three levels of increasing complexity: genetic diversity at the species level, species diversity amongst the diverse taxons in the whole biosphere, and the diversity of ecosystems (6).

biogeography: branch of physical geography and of ecology which studies the distribution of life on the surface of the planet by descriptive and explanatory analysis of the distribution of living things and particularly of their communities (3).

biological control: the use of living organisms to reduce the density of pest populations or to influence a particular pest by rendering it less abundant or less dangerous than it would otherwise have been. Four different strategies are recognised: classical biological control, inoculative biological control, inundative biological control and conservation biological control (11).

biological or ecological connection area: a space or several biological corridors functioning together, each biological corridor comprising a specific natural or semi-natural structure relevant to the dispersion of a species or a community of species between different plots of the same habitat type or between different habitats (12).

biopesticide: crop protection product of biological origin (2).

biosphere: the outer layers of the earth which houses all living things (6).

biotope: surface or volume of which the physical and chemical characteristics are relatively uniform, allowing the development and maintenance of a species or a community (6).

carpophage: insect which, at the larval or adult stage, develops at the expense of fruits (2).

chemical control: method for the reduction or destruction of populations of organisms which are pests of humans or their crops or animals by the application of natural or synthetic chemical substances (10).

chemical ecology: discipline of ecology which studies the role of chemical mediators in the interactions within and between species of animals and plants (3).

community: biological or ecological assembly of populations of different species having in common a functional unity in space and time (3). In a restricted ecological sense this is a group of species populating an environment which is well defined in space and having a functional unity. A community comprises the plants, animals and micro-organisms. It is characterised by a specific composition which is roughly constant and by numerous interactions (competition, predation, parasitism, symbiosis, etc.) between the species, which ensure the maintenance of stability (6).

companion planting: practice consisting of cultivating two or more plants simultaneously in the same field; often this practice reduces pest attacks and provides better yields than those of a monoculture (6).

conservation biological control: modification of the environment or of cultural practices to protect or favour natural enemies or other organisms in such a way as to reduce the impacts of pests (11).

conservation biology or conservation ecology: recent expression designating the area of ecology which uses scientific approaches to ensure the conservation of species, and most especially those which are threatened with extinction (6).

conservation ecology: see conservation biology.

corridor: a functional connection between ecosystems or between different patches of habitat for a species or an interdependent group of species (3).

crop rotation: order of succession, in the same field, of plants belonging to different species or varieties and interspersed with fallows, this succession is repeated regularly over time (2).

cropping system: part of a defined production system for a land area treated uniformly, for particular crops and their rotations and technical practices; one or several cropping systems may be found on the same farm (2).

cryptogrammic: referring to cryptogams or non-flowering plants (algae, mosses, fungi, ferns, lichens) (2).

cultivar: group of cultivated plants within a species which can be clearly defined by morphological, physiological, cytological, chemical or other characters and which, after sexual or asexual multiplication, retains its distinctive characters (2).

cultural control: crop protection methods which use appropriate agricultural techniques: crop rotation, resistant varieties, etc. (10).

delta-endotoxin: crystal insecticidal toxin from the bacteria *Bacillus thuringiensis,* used for the production of microbiological preparations for phytosanitary purposes and expressed through the genetic manipulations of certain cultivated plants, thus creating GMOs.

diapause: slowing down or prolonged interruption of the development processes of an insect as a result of a prolonged modification of one or more metabolic processes (depending on the stage of development of the insect, we speak of embryonic, larval, nymphal or imaginal diapause) (2).

diploid: character of cells, tissues or organisms which possess two haploid versions of each chromosome (2).

doubly green revolution: production techniques inspired by natural processes incorporated into the framework of agricultural policies related to the economy of agricultural markets of developing countries, and a programme inciting technological changes to improve the environmental quality of agriculture in general (13).

ecoagriculture: landscape approach to the management of natural resources in such a way as to make agricultural production sustainable, to conserve biological diversity and the services rendered by ecosystems, while at the same time ensuring food needs locally (14). Initially developed for intensive agricultural systems and using precision agricultural technologies.

ecodevelopment: mode of socio-economic development which does not profoundly alter natural or semi-natural ecosystems and which utilises non-renewable resources parsimoniously (2).

ecological compensation areas or structures: agrarian management structures for habitats maintained to compensate for the loss of biodiversity in cropped fields: grassy strips, hedges, fallows, extensive grazing areas, etc.; the expression 'ecological infrastructures' is recommended by the IOBC (15).

ecological control: method of reducing or destroying pest animal or plant populations by modifying one or more environmental factors (10).

ecological intensification: innovative conception of agroecosystems capable of ensuring simultaneously crop production and ecological services (16).

ecological service: advantage resulting from the balanced functioning of an ecosystem (synonyms: environmental service, ecosystem service) (Box 18).

ecology: science comprising disciplines whose object is the study of the relationships between living things or their communities, with each other and with their environments (2).

economic damage threshold: level above which the damage caused by a pest of crop plants or stored products corresponds to an expected reduction in the harvest or an alteration of the quantity or quality of the resulting stored products (2); EDT is also the level at which the expected damage to the crop exceeds the cost of control and the control becomes economically profitable.

ecosystem: relational and functional spatial grouping, formed by a biological community and its biotope (2).

edaphic: that which pertains to the soil in relation to living things (2).

egg parasitoid: micro-hymenopteran insect, frequently chalcidian, parasitic on the eggs of other species during its own egg and larval stages, although the adult leads a free life and feeds on sugary materials (e.g. aphid honeydew) or proteinaceous substances (e.g. pollen). Trichogrammatids are most commonly used as agents of biological control by inundative release against several crop pests: maize stem borer, vineyard leafrollers and noctuid moths in market gardens, for example (3).

elicitor: metabolite produced by a pathogenic agent, fungus or bacteria, which induces in its plant host metabolic mechanisms which tend to inhibit the development of the pathogenic agent (2).

endocarpic: something which happens inside a fruit (here inside the cotton boll and referring to feeding by certain caterpillars) (2).

entomophage: animal, generally an arthropod, which feeds on insects which it captures (predator) or on which it entirely depends (parasitoid) (2).

entomotoxin: toxin active against insects, for example those produced by *Bacillus thuringiensis.*

etiology: group of factors implicated in the origin of a disease (2).

fallow: state of a field, or the field itself, left temporally without crops; a cultivated fallow is a fallow which has been ploughed or shallowly cultivated (2).

fire blight: one of the most dangerous diseases of pear and apple trees, quinces, medlars and certain ornamental plants such as *Cotoneaster,* caused by the bacteria *Erwinia amylovora.* Transmitted by insects, birds, wind or rain, but also by agriculturalists in the course of grafting operations. Control methods are essentially prophylactic (3).

food chain or trophic chain: suite of living things in which each species eats those which precede it before being eaten in their turn by those who follow. A simple food chain comprises autotrophic producers (chlorophyll containing plants), primary consumers (herbivorous animals), secondary consumers (carnivorous animals) and decomposers (generally bacteria and fungi). Food chains are linked by polyphagous organisms to form food webs (6).

gene: nucleotide sequence consisting of a unit of genetic information and determining the expression of a character, directly for a structural gene, or indirectly for a regulatory gene (2).

generalist predator: predator which hunts prey belonging to a wide range of taxonomic groups.

genetic control: method consisting in altering the genetic patrimony of a large number of individuals of a pest species and releasing them into the environment so they can perturb, by mating, the reproductive cycle of their wild conspecifics (10).

genetic engineering: the concepts, methods and in *vitro* techniques enabling modification of the genome of a cell or an organism by introducing new combinations of genes or of sequences of genes (2).

genetically modified organism (GMO): organism transformed using the methods and techniques of genetic engineering (2).

genomic: relating to the genome, all the genes present in a virus, an organelle, a single-celled organism or in the cells of multicellular organisms which programme and controls their structure, their functioning and their development (2).

genotype: the particular combination of genes which creates an individual; group of individuals with the same genetic constitution (2).

green revolution: movement in agriculture or livestock production using improved varieties or races, techniques which make intensive use of chemical inputs and benefitting, at least in its initial phase, from government measures in agricultural policy, reducing the risks and increasing the profit margins (13).

guild: designates the fraction of a community which comprises a group of species exploiting the same resource in the same manner. A guild is a functionally simple and homogeneous group the species of which are frequently (but not always) closely related taxonomically (6).

hybridisation: a cross between two varieties, two races of the same species or between two different species (4).

input: factor input to increase production (most often used to refer to fertilisers and pesticides) (2).

integrated biological control: method of crop protection which gives priority to the biological control of pests through the release of beneficial organisms, or to measures favouring their development. If biological methods do not allow adequate control of the pests or if the cost of such control becomes too high, chemical products which are relatively benign to indigenous or introduced beneficials are applied. These products are then said to be 'compatible' (17). By extension, the expression 'integrated biological protection' introduced initially by the French national organisation *Protection Biologique en Horticulture Ornementale* is now frequently used in French-speaking countries to designate a type of integrated production which gives priority to biological control (18).

integrated control: system of management of pest populations which, in the context of the particular environment and the population dynamics of pest species, implements all the appropriate techniques, in as compatible a manner as possible, to maintain them at levels below those which cause significant economic damage. In its narrowest sense, it applies to the management of single pest species in a given crop or specific locality. In a broader sense, it applies to the harmonious management of all the populations of pest organisms in their agricultural or forestry environment. This is not the simple juxtaposition or superimposition of two control techniques (such as chemical control or biological control) but the integration of all appropriate management techniques which fit natural regulatory factors and the local environmental limitations (Box 10).

integrated management: see integrated control and integrated protection.

integrated pest management (IPM): very many definitions have been provided for this concept, a sign of the confusion surrounding the idea. There is no real French equivalent, for example, and the term is generally translated as 'integrated protection' (see Table 5) (19).

integrated protection: method closely allied to integrated control, which accounts for and combines different biological methods, biotechnologies, the pest resistance characteristics of cultivated plant varieties, phytotechnical and environmental characteristics in an ecologically based system of crop protection (2).

intensive: description of a production system which uses large quantities of inputs, in particular of fertiliser, with a view to obtaining high yields (2).

intensive or industrial agriculture: agriculture which seeks to obtain high yields by the use of high performing varieties, intensive crop production practices and massive quantities of chemical fertiliser and pesticides, etc. (20).

intercrop: crop planted between the rows of a crop of another species which reaches its full development after the harvest of the other crop (2).

intervention threshold or level: in a particular crop, level of population of a pest above which an economic threshold is crossed and renders control necessary (2).

introgression: incorporation of genes from one species into the genotype of another species by hybridisation following repeated backcrossing.

invasive species: all species (exotic or imported) voluntarily or fortuitously entering a cropping system, but especially species whose proliferation in natural or semi-natural areas causes, or is capable of causing, pest problems (2).

landscape: portion of countryside observable from a given point (on the ground or in the air), comprising a grouping of natural structural elements (geomorphological, hydraulic, plant formations) and/or elements of human origin (cultivated land, buildings, communication routes, etc.) (2).

landscape ecology: an ecological approach used to study the relationships between complexes of biological communities partially or fully making up the landscape, and the development of these groupings (2).

lectin: plant glycoprotein with agglutinating properties which render it capable of specific recognition of particular glucocidic residues and of fixing them (2).

mating disruption: perturbation of the behaviour of an individual male's searching behaviour for a virgin female as a result of the presence in the air of synthetic molecules of the natural female sex pheromone artificially liberated from traps or other diffusers (2).

metapopulation: see population.

monoculture: cropping of a single plant species (2).

mulch: bed of straw or other plant material, and today strips of plastic sheet spread over the soil surface to reduce desiccation by evaporation (2).

organic agriculture: a specific system of agricultural production which excludes the use of synthetic inputs (fertilisers and pesticides) including genetically modified organisms. It operates holistically by focussing on the overall agroecosystem, but also on biodiversity, the biological activity of soil and biological cycles. Organic production requires certification, which conforms to legal norms (3).

parasite: animal or plant whose development depends on another organism called the host, during all or part of its life cycle, causing damage to the host without necessarily killing it (2).

parasitoid: an animal whose development depends on the host and which invariably kills it (for example: trichogrammatid egg parasitoids) (2).

pesticide or phytosanitary product: active ingredient, or a preparation of such, aimed at protecting crops or their harvested products against their enemies (2).

phenological: a chronological study of the relations between the climate and the stages of development of plants or animals (2).

phenotype: all visible characters resulting from the expression of the genotype in a given environment (2).

pheromone: substance secreted by the exocrine glands of an animal, which, by operating directly on the receptor organ of another individual of the same species, modifies the behaviour of the recipient. Depending on the behavioural modification produced, they are classified as aggregation pheromones, alarm pheromones, defence pheromones, repellent pheromones, marking pheromones, trail marking pheromones, spacing pheromones, etc. By extension, synthetic product with the same properties (sometimes called parapheromones): those used in crop protection are most commonly sex attractants effective at very low concentrations; imitating the sex pheromone emitted by virgin females. They attract the males over very long distances (see also mating disruption) (2).

phytosanitary: describing all products or substances destined for the protection of plants, crops and harvested products from their pests and diseases (10).

polyculture: simultaneously growing different plant species in the same farm or in the same region (2).

population: the individuals of the same species which occupy a common territory and are capable of reproduction amongst themselves. Frequently populations of a species are not isolated from one another. Migrating individuals move between populations and exchange genes, thereby creating metapopulations (6).

population dynamics: the study of the variations in abundance of populations of animals and plants and of their causes (6).

precision agriculture: the concept of field management based on the existence of variability within fields, which has required the use of new technologies, such as satellite positioning systems and the computerised handling of data (3).

predator: animal which kills its prey before feeding on it (2).

prophylaxis: the precautions and methods taken with a view to avoiding the appearance and spread of diseases (2); in crop protection, measures taken with a view to avoiding, limiting or retarding the appearance of pests early in the crop season. A technical illustration of the concept is given by the harvesting and buryingof leaves in apple orchards to avoid the dispersion, in spring, of the spores of the fungus *Venturia inaequalis,* the main agent of apple scab.

pyrethroid: chemical substance similar to natural pyrethroids produced by pyrethrum or chrysanthemum flowers, utilised as an insecticide and as a repellent (3).

refuge plants: vegetation that is particularly attractive for a phytophagous pest insect or a beneficial organism, by providing shelter, the plant may support all or part of its development in favourable conditions (see also: refuge zone).

refuge zone or area, plural refugia: term specifically used in crop protection to designate the areas in which non-genetically transformed varieties are grown in the neighbourhood of GMOs in such a way as to favour the production of sufficient pest insects to effectively interfere with mating between any resistant insects surviving in the genetically modified crop (in the case of plants genetically transformed for the expression of the Bt insect toxin). In nature conservation, the term refuge zone designates a space or an ecosystem which is not subject to strong perturbations (see Figure 6, Chapter 5).

resilience: property of an ecosystem remaining in a state of equilibrium in spite of the various perturbations to which it is subjected (7).

sequestration (of carbon): trapping or capture of carbon dioxide from the atmosphere; naturally (fixing of carbon in plants and in the oceans) or artificially (in a liquid or solid matrix) (4).

sharka: the sharka potyvirus is responsible for a plant disease (plum pox virus) which affects species of stone fruit of the genus *Prunus,* such as peaches, nectarines, apricots, almonds and certain ornamental varieties. It is transmitted by an aphid as well as by grafting. The disease seriously affects production. The only treatment known to be effective is to cut down and burn the trees which are affected or likely to play a role as a reservoir for the disease (3).

sustainable development: development which responds to the needs of the present without compromising the chances of survival of future generations (6).

systemic or ecosystemic approach: approach used in certain studies, which considers ecosystems as a whole and not based on their individual elements (2).

taxonomist: specialist in taxonomy, the science whose objective is to describe living organisms and to group them into entities called taxons (families, genera, species) in order to be able to name and classify them (3).

tolerance threshold: in integrated control, the level of a pest population above which the forecast damage is not tolerable if the conditions for pest multiplication become favourable and such outbreaks can no longer be limited by natural enemies (2). This tolerance threshold varies with local socio-economic conditions.

traditional agriculture: agriculture practised with the techniques transmitted from generation to generation and utilising species of animals and plants obtained by empirical selection (20).

transgenesis: natural or technical phenomena related to the construction of transformed organisms (2).

transgenic: said of an organism resulting from cells modified by the introduction of a foreign gene and which possesses the introduced gene in all or the majority of its cells. The transgenic organism has thus acquired a new character which it can then transmit to its descendants (2).

trap crop: vegetation which is particularly attractive to a phytophagous pest insect and used to attract them with the aim of destroying them or limiting the infestation of the plants to be protected (2).

turning area: strip of land situated at the extremities of a field on which the farmer turns his machinery (2).

variety: in plant production, variety listed in an official catalogue of species and varieties allowing its commercialisation and protecting the owner who has registered it (2).

waterlogged area: part of a field which remains very wet, even outside the rainy season, which often prevents the soil from being worked productively (2).

weed scientist: specialist in weed (as opposed to crop) science (3).

Bibliographic References in the Glossary

(1) Index Phytosanitaire ACTA 2008. ACTA, Paris, 44éme édition, 844 p.

(2) Dictionary of agriculture (French-English-German). CILF, Paris, 1009 p.

(3) On-line encyclopedia WIKIPEDIA, <http://www.fr.wikipedia.org> (consulted August 12, 2008).

(4) Le Petit Larousse Illustré Grand Format, 2007. Larousse, Paris, 1874 p.

(5) Dalgaard T., Hutchings N. J., Porter J. R., 2003. (see reference n° 18 of Chapter 1).

(6) Dajoz R., 1996. Precis d'écologie. Dunod, Paris, 6ème édition, 551 p., Glossaire : <http://www.dunod.com/documents/49627/49627_Glossaire.pdf> (consulted May 21, 2008).

(7) Boulaine J., Moreau R., 2003. Olivier de Serres et l'évolution de l'agriculture. L'Harmattan, Paris, Collection Acteurs de la Science, 124 p.

(8) Doré T., Le Bail M., Martin P., Ney B., Roger-Estrade J., 2006. L'agronomie aujourd'hui. Collection Syntheses, QUAE, Versailles, 367 p.

(9) Lebeau R., 2000. Les grands types de structure agraire dans le monde. A. Colin, Paris, 182 p.

(10) Parent S., 1990. Dictionary of Environmental Sciences (French-English). Hatier-Rageot, Paris, 748 p.

(11) Eilenberg J., Hajek A., Lomer C., 2001. Suggestions for unifying the terminology in biological control. *BioControl* 46, 387-400.

(12) Clergeau P., Desire G., 1999. Biodiversité, paysage et aménagement: du corridor à la zone de connexion biologique. *Mappemonde,* 55, 19-23.

(13) Griffon M., 2006. (see reference n° 4 of the introduction).

(14) Scherr S. J., Meredith A., 2005. (see reference n° 18 of Chapter 1).

(15) Boller E. F., Häni F., Poehling M., 2004. (see reference n° 22 of Chapter 7).

(16) CIRAD, 2007. Le 3 août au Cirad: une journée thématique sur « l'intensification écologique ». Communiqué de presse du 03.08.07 <http://www.cirad.fr/fr/presse/communique.php?id=299> (consulted October 4, 2007).

(17) Gurr G. M., Wratten S. D., 1999. FORUM "Integrated Biological Control": a proposal for enhancing success in biological control. *Intern. J. Pest Manag,* 45, 81-84.

(18) Anonymous, 1998. La protection biologique intégrée en horticulture ornementale sous abris. Astredhor, *Dossier technique,* Paris, 59 p.

(19) Bajwa W. I., Kogan M., 2002. Compendium of IPM Definitions (CID). What is IPM and how it is defined in the worldwide literature? IPPC Publications n° 998, Integrated Plant Protection Center (IPCC), Oregon State University, Corvallis, OR <http://www.ipmnet.org/IPMdefinitions/definel.html> (consulted October 9, 2004).

(20) Sournia J. C., 1991. *Dictionnaire de Génétique.* CILF, Paris, 352 p.

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Acronyms

ACTA: *Association de Coordination Technique Agricole*

AGROPOLIS International: Association of research and higher education institutions of Montpellier and the French Region of Languedoc-Roussillon in the fields of agriculture, food and the environment, BGP: Centre for the Biology and Management of Populations

CAP: Common Agricultural Policy (of the European Union)

CIRAD: *Centre de Coopération Internationale en Recherche Agronomique pour le Développement* (Centre for International Co-operation in Agronomic Research for Development - France)

CNRS: *Centre National de la Recherche Scientifique* (French National Centre for Scientific Research)

DDT: dichlorodiphenyltrichloroethane

DNA: deoxyribonucleic acid

EISA: European Initiative for Sustainable Development in Agriculture

FAO: Food and Agriculture Organization of the United Nations

FARRE: *Forum de l'Agriculture Raisonnée Respectueuse de l'Environnement* (Forum for Rational Agriculture which is Respectful of the Environment)

GMO: Genetically Modified Organism

GPS: Global Positioning System

HCH: hexachlorocyclohexane

IAASTD: International Assessment of Agricultural Science and Technology for Development

IMF: International Monetary Fund

INRA: *Institut National de la Recherche Agronomique* (French National Institute for Agricultural Research)

IOBC: International Organisation for Biological Control

IPM: Integrated Pest Management

IUCN: International Union for the Conservation of Nature

LEAF: Linking Environment and Farming

LEC: *Lutte Étagée Ciblée* (Staged targeted control)

MAB: Man and Biosphere

NCC: *Nouvelle Culture du Cotonnier* (new cotton growing)

UNCCD: United Nations Conference on Commerce and Development

UNESCO: United Nations Educational, Scientific and Cultural Organisation

UNO: United Nations Organisation

US-EPA: US Environmental Protection Agency

US-NSF: US National Science Foundation

USSR: Union of Soviet Socialist Republics

WTO: World Trade Organisation

WHO: World Health Organisation

About the Book

At a time when agricultural systems in northern countries are being heavily criticised with respect to environmental and human health, and when the crisis in food production and costs in southern countries is crying for attention worldwide, how can we protect crops against pests and diseases within agroecosystems which need to be socially, economically and environmentally sustainable?

This work traces the development of the concepts and practices of crop protection, taking cotton production, which has often been the source of pioneering technical innovations, as a case study. It presents a detailed analysis of the state-of-the-art in crop protection, discusses the limits of agrochemical protection and explores the need to consider agroecosystems in their entirety, leading to the concept of agroecology. We believe this integrative approach is appropriate and sustainable, as it enables us to protect crops in an efficient and socio-economically viable way, while also respecting the environment and human health.

The world-wide experience of the authors, their scientific expertise in agronomy, ecology and crop protection and the rigour of their scientific reasoning, give depth to this original work which fills a gap in the literature on the subject. It will be a valuable tool for those who wish to reflect on how we produce and protect our crops: students, practitioners, crop protection specialists, researchers and, perhaps more especially, citizens of the 21st century.

About the Authors

Dr Jean-Philippe Deguine is an entomologist, agroecologist, and CIRAD researcher with 25 years of experience in crop protection in a range of agroecosystems, particularly cotton, across the world and notably in southern countries. He is currently responsible for multidisciplinary research programmes within CIRAD. He was crop protection advisor in the scientific management team of CIRAD and was president of the European IPM Network.

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Dr Derek Russell is a teaching and research entomologist with the Natural Resources Institute at the University of Greenwich, UK, and a Professor at Melbourne University in Australia. He has 30 years of experience in crop protection world-wide and is an acknowledged expert in the area of reduction in the use of insecticides and in the management of resistance in the developing world, especially in cotton. He was responsible for an assessment of the sustainability of GM cotton in China for the European Union and is now leading a global public-private partnership developing insect-resistant (Bt) brassicas for Asia and Africa on a pubic-good basis.

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