Sustaining Soil Productivity in Response to Global Climate Change

Science, Policy, and Ethics

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Sustaining Soil Productivity in Response to Global Climate Change

Science, Policy, and Ethics

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Foreword

Ecosystem services are the benefits people obtain from ecosystems, the services that support life and our basic well-being. The Millennium Ecosystem Assessment found that we are losing the world's ecosystem services at an alarming rate. Soil health and productivity are foundational to the provision of nearly *all* of these life-sustaining services, including food and fuel production, carbon sequestration, water filtration, flood control, and biodiversity. Much of the damage to ecosystem services has resulted from unsustainable land-use practices—like loss of productive land to development, chemical pollution, erosion, and deforestation. And human activities are growing—dramatically. As Yale Dean Gus Speth noted a few years ago: "*It took all of history to build the $7 trillion world economy of 1950, and today we add that amount of economic activity every 5 to 10 years*." Climate change and its concomitant pressures exacerbate these trends because extreme weather events and warmer temperatures change basic ecological processes. The combination presents a daunting challenge in terms of how we feed, fuel, and house the planet's growing population, projected to exceed nine billion people by the middle of this century.

Policies addressing climate change must be holistic to capture the complex interdependent nature of global food supplies, energy needs, and the provision of ecosystem services. Maintaining or enhancing soil productivity is an essential component of food security policy, for example, and food security is fundamental to national security. As our soil resources face increasing stress in response to rapid environmental change, we have to ensure that society's short-term needs and demands are met without sacrificing long-term soil health and productivity. And we must urgently invest in strategies to reverse soil degradation and the loss of ecosystem services.

This conference brought together a most impressive cross-section of scientists, thought leaders, and policy makers to consider *not* just the effects of climate change on soil productivity, but also to reflect on the broader implications of climate change on people. It is my strong hope that more conferences like this will be held, where the economic, social, and governance challenges of living in an ever-more globalized economy are examined—where we can begin to honestly contemplate policies that will address how to live sustainably on this planet.

It was an honor for me to be a part of this.

Sally Collins
Director, Office of Environmental Markets
US Department of Agriculture

Introduction

Global climate change has potential to sharply accelerate soil degradation due to environmental stresses induced by changes in temperature and precipitation and increasing occurences of extreme climatic events. Growing demand for food and commitments to increase biofuel production to meet global energy demands are putting intense pressure on soil resources to sustain or increase productivity. Maintaining or enhancing soil productivity is a high priority area for developing food security policy at national and global scales. Policies to reduce or avoid potential climate change consequences for global food supplies must be crafted in a holistic fashion to ensure that short-term supplies can be met without sacrificing long-term degradation of the soil resource due to erosion, pollution, and physical and chemical deterioration. Strategies to reverse current practices leading to soil degradation are also urgently needed. The critical role of the soil system in influencing ecosystem processes at the local, national, and global scale is being increasingly appreciated by policy makers and earth scientists in general. Greater awareness also exists of the role of human management in affecting the capability of the soil to supply human needs and buffer climatic changes. Unfortunately this comes at a time when soil scientists and the discipline itself are struggling to maintain an identity and improve public awareness of the value of soil science.

In the summer of 2009, an interdisciplinary group of leading scientists from 11 countries assembled on the shores of Lake Mendota in Madison, Wisconsin, for a 3-day conference on sustaining soil productivity in response to global climate change. Although there have been numerous conferences on climate change, the unique perspective of this conference was the focus on maintaining or enhancing soil productivity, and in particular, the ethical implications of policies intended to ameliorate climate change effects. The integrated nature of this conference created a special opportunity for scientists from widely varying backgrounds to interact on a topic of intense mutual interest. The conference emphasized the broad sweep of issues that relate to soils and climate change: policy, philosophy, ethics, social issues, global modeling, science politics, economics, cultural adoption constraints, defining ecosystem services, bureaucratic conflicts, and of course, intellectual inertia. The dynamism and constructive nature of the discussions from such a diverse group showed that interested parties can dialog constructively on this broad playing field.

The issue of culpability on the part of developed countries that dominate greenhouse gas production and then resist measures to ameliorate global climate effects, many of which have a disproportionate impact on developing countries, is an example of the scale and breadth of issues addressed. Such behavior, although understandable from the perspective of national self-interest, presents dramatic implications for global welfare and is seen by some parties as an egregious violation of accepted human rights standards. This perspective on climate change is likely to elicit strong emotional responses from interest groups that advocate for the poor and citizens of developing countries. It was also clear that scientists as individuals have values implicitly built into their work. This is a concept that many scientists resist at first but deserves further consideration. Many feel that to be truly objective, personal ideology can have no influence. However, each culture has their own set of norms that are also inherent in the beliefs of its members, of which scientists are not excluded.

Coupling the science of global climate change and soil sustainability within an ethics framework and with policy makers as the intended audience creates a deeper discussion. A midconference field trip to the Aldo Leopold Legacy Center near Baraboo provided an informal setting to continue these conversations and observe the site of Aldo Leopold's personal efforts to restore ecosystem function to a "worn out" farm. Leopold, known as the father of game management and author of the land ethic, was also a passionate soil conservationist. He stressed that much progress could be made in conservation issues by just deeper thinking. By broadening the climate change debate, this conference illuminated some of the human aspects that are so relevant yet generally overlooked by the economic analyses and political expediencies that currently control the debate.

The primary conference sponsor was the Co-operative Research Programme on Biological Resource Management for Sustainable Agricultural Systems (CRP) of the Organisation for Economic Co-operation and Development (OECD), an international organization helping its 34-member countries tackle the economic, social, and governance challenges of a globalized economy. The financial support of the CRP made it possible for most of the invited speakers to participate in the conference. Major support was also provided by the Department of Soil Science at the University of Wisconsin, Madison; the World Meteorological Organization (WMO); the Office of Technology Transfer of the USDA-Agricultural Research Service (USDA-ARS); and the Leopold Center for Sustainable Agriculture. Additional support was provided by Campbell Scientific, Inc.; Decagon Devices, Inc.; LI-COR Biosciences; Cilas; the University of Wisconsin, Madison Arboretum; and the USDA-Natural Resources Conservation Service. The conference organizers sincerely appreciate the generous support of all the sponsors.

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Thomas J. Sauer

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Sustaining Soil Productivity in Response to Global Climate Change

Science, Policy, and Ethics

1 Science, Ethics, and the Historical Roots of Our Ecological Crisis

Was White Right?

Thomas J. Sauer and Michael P. Nelson

1.1 Introduction

Continuing debate and proposed coordinated actions, such as the Endangered Species Act and Clean Water Act in the 1970s, to address global climate change have stimulated a broad, intense public discourse on environmental management. Such debates raise questions about the sacrifices or investment society is willing to make to protect or preserve natural resources. The climate change discussion is the most recent example of a dialogue that has been repeated throughout recorded history; that is, what degree of human exploitation of natural resources is acceptable? A brief essay in *Science* by respected medieval historian Lynn White, Jr., (1967) suggested that values developed and perpetuated by Christian theology permeate western science and technology and are responsible for human's seemingly continuous abuse of the environment. White's assertions have prompted more than 40 years of strident arguments by both passionate critics and defenders, making this paper one of, if not, the most important contributions to the developing field of environmental ethics.

Defenders of White argue that the chronic inability of societies to effectively address pressing environmental challenges is generally not due to a lack of knowledge or resources. Instead, failure to solve problems, such as soil erosion, air and water pollution, deforestation, and now climate change, are due to a deep-seated yet generally tacit belief that humans are ordained to control and dominate, not care for and protect, nature. A broader interpretation of White's argument can easily be extended beyond singling out Christianity as the sole culprit. Several counterarguments include the observation that poor environmental management is not exclusive to western cultures dominated by Christian beliefs, and many other tenets of Christianity (e.g. "love they neighbor") are not universally applied. Recent archaeological evidence suggests that environmentally destructive tendencies of humans predated Christianity by centuries (Eisler 1987). The increasing severity of environmental crises in the second half of the twentieth century that White laments has also been blamed on the powerful economic forces driving materialism and luxury consumption (Kasser 2002; Kaplan 2008). If the failure to recognize or act on environmental crises is indicative of a deficient moral or ethical perspective, then it likely has deep roots in multiple cultural and historical sources, including religious traditions.

Climate change can be seen as a global manifestation of a legacy of poor environmental stewardship over millennia leading to increasing emissions of greenhouse gases (GHGs), especially carbon dioxide (CO_2), through aggressive, unsustainable exploitation of natural resources including soil. Mitigating climate change effects will be an immense

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undertaking on numerous levels, but improving the capacity of soil resources will be a critical component of any meaningful strategy.

1.2 Historical Perspective on Soil Degradation

In his recent bestseller, *Collapse—How Societies Choose to Fail or Succeed*, the geographer Jared Diamond (2005) chronicles how past cultures succumbed to various environmental threats. Notable among these threats was soil degradation by erosion, loss of soil fertility, and land salinization. These key factors contributed to the rapid disintegration of not only the marginal (e.g. the Norse in Greenland) but also some of the most advanced civilizations of their time (e.g. the Maya in Mesoamerica). Diamond proposed four types of failures by societies trying to address their environmental threats: (1) failure to anticipate the problem, (2) failure to recognize the problem after it develops, (3) failure to try and solve the problem, and (4) trying unsuccessfully to solve the problem. He goes on to identify two keys for societal decision making to enable successful mitigation of environmental threats: (1) long-term planning and (2) willingness to reconsider core values. Success stories (i.e. societies choosing to succeed), such as eliminating swine production on the Pacific island Tikopia and reforestation in Japan, are employed as examples of societies making sacrifices to enable long-term sustainability that included difficult, often painful changes to their value systems. Interestingly, even Diamond's definition of success is quite anthropocentric and is based primarily on the sustainability of human cultures, which in many cases resulted in devastating effects on the local ecosystems.

Diamond's popular press account is but a recent addition to a litany of reports cataloging human destruction of natural resources in general and soils in particular (Marsh 1864; Lowdermilk 1948; Hyams 1952; Glacken 1967; Hughes 1975; Hillel 1991; Redman 2001; Hudson & Alcántara-Ayala 2006; Montgomery 2007). Localized, visual assessments of degraded lands presented in early accounts have given way to modern methods of quantitative measurements and global remote sensing (Oldeman et al. 1990; Lal et al. 2004; Bai et al. 2008; Sivakumar 2011). Land degradation, defined as long-term decline in ecosystem productivity and functioning (Bai et al. 2008), includes physical (i.e. wind and water erosion, compaction, waterlogging, and loss of structure), chemical (i.e. nutrient depletion or imbalance, acidification, and salinization), and biological (i.e. loss of organic matter, reduced diversity, and increase in soil pathogens) factors. In the most recent analysis, Bai et al. (2008) concluded that 24% of the global land area, home to 1.5 billion people, was currently degrading. Although many of these areas were in developing countries, some degree of soil degradation is almost universal, as demonstrated by the extent of erosion in developed countries. For example, recent estimates of soil erosion by water in the United States (Fig. 1.1) indicate that 18.2% of cultivated US cropland (22.5 million ha) had annual erosion rates above tolerable levels (US Department of Agriculture 2009). This is consistent with Oldeman et al.'s analysis (1990), which identified extensive areas of the United States and other developed countries as having soils that were highly degraded when compared to their natural condition. The extent and severity of soil degradation, especially in developed countries, appears inconsistent with the current productivity of these regions. This disparity may reflect a growing realization that there is a gradual, insidious loss of inherent soil productivity in areas under intensive cultivation that is obscured by significant improvements in crop genetics and pest control and ready access to nutrients via inorganic fertilizers (Larson et al. 1983; Pimental et al. 1995; Lal 2009).

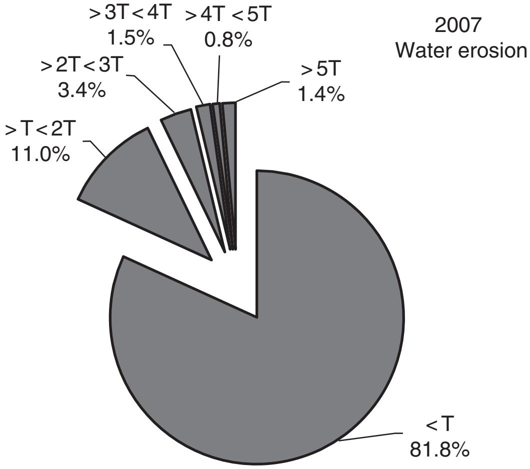

Figure 1.1 Estimated percentages of nonfederal US crop land having sheet and rill erosion rates below tolerable rates (<T) or at various multiples of T up to greater than five times the tolerable erosion rate (>5T).
Data from US Department of Agriculture (2009).

1.3 The New Challenge of Global Climate Change

The causes and consequences of global climate change remain the subjects of intense study. Recent climate trends are likely due to a complex combination of natural cycles and anthropogenic effects acting over multiple overlapping time scales. Increases in atmospheric GHG concentrations include contributions from both fossil fuel combustion and human-induced land-use change, especially cultivation of paddy rice and forest clearing over the last several millennia (Ruddiman 2005). Any successful climate change mitigation strategy will need to include elements that both reduce future GHG emissions *and* current atmospheric GHG concentrations (i.e. reduce GHG sources *and* increase carbon sinks). Although the Kyoto Protocol emphasizes carbon sequestration in forest biomass as a primary land-based carbon sink, even an aggressive global reforestation/afforestation program alone will only be capable of a short-term delay or modest slowing of atmospheric CO_2 concentration increases (Vitousek 1991; Nilsson & Schopfhauser 1995). Any technically or economically viable emission reduction or carbon sequestration strategy will, by necessity, need to include multiple components for GHG emission reduction and carbon sequestration.

With a rapidly increasing world population and expectations for greater affluence in many developing countries, it is prudent to consider whether available soil resources will be capable of producing the food and fiber needed to sustain the global population. This is especially challenging when increased severity and frequency of weather extremes along with shifts in mean temperature and precipitation are predicted (IPCC 2007). The United Nations predicts the world population will increase from 6.8 billion in 2008 to greater than 9 billion in 2050 (United Nations 2008). Because many of the world's best agricultural soils have already been degraded, the prospect for significantly increasing food production to meet rising demand is seriously in doubt (Cassman et al. 2003; Koning & van Ittersum 2009; Godfray et al. 2010). Increasing the intensity of production practices, including increased tillage, nutrient application, and pesticide usage to meet growing demand for agricultural products, will further stress the long-term sustainability of cultivated soils and pose an ever-greater risk to water and air quality and overall ecosystem health.

Restoration of soil functionality and the enhancement of soil productivity are achievable and also provide an opportunity to contribute to climate change mitigation. Carbon sequestration through management practices that increase soil organic matter content tend to make soils much more effective in nutrient cycling and resilient to climatic extremes such as flood and drought, and ultimately, the soils are more productive in the long term (Bot & Benites 2005). All of these benefits can be achieved by employing practices that encourage carbon sequestration in agricultural soils such as reduced tillage, crop rotation, and agroforestry (Sanchez et al. 1997; West & Post 2002; Schoeneberger 2008).

If the multiple benefits of increasing soil organic matter content are well known, why have efforts to increase soil carbon sequestration not met with greater success? Modern agriculture has relied largely on increasing external inputs to maintain or increase productivity. Economic analyses that often exclude deleterious effects on soils favor increased investment in external inputs compared to other practices with greater carbon sequestration potential that may be cheaper to employ but involve greater risk and more management skill. Recent volatility in energy prices and the associated global food crisis was partially driven by diversion of food crops to bioenergy production and may serve as an example of potential future scenarios of food versus energy production. This crisis further reinforces the need for a much more focused, thoughtful assessment of soil management practices.

In June 2009, the Soil Science Society of America sponsored a Bouyoucos Conference on Soil Stewardship in an Era of Climate Change to address some of these scientific and ethical issues of land management from a global climate change perspective. A transdisciplinary group of experts including philosophers, policy analysts, agronomists, and soil scientists explored the recent trends in soil quality, the economic and ethical implications of different land-use options, and strategies to better communicate the challenges and consequences for soil quality in the future. This group drafted a statement that summarized their assessment of the current trend in soil quality and called for greater awareness of the vital role soil resources have and the urgent need to improve soil stewardship (Box 1.1).

Box 1.1 Statement on Soil Stewardship Drafted from the 2009 Bouyoucos Conference on Soil Stewardship in an Era of Global Climate Change

An Urgent Appeal for Soil Stewardship

From the 2009 Bouyoucos Conference on Soil Stewardship
in an Era of Global Climate Change

Upon viewing the deforested and eroded landscape near Attica, Greece in the 4th century BC, the philosopher Plato vividly described the loss: “What now remains compared with what then existed is like the skeleton of a sick man, all the fat and soft earth having wasted away, and only the bare framework of the land being left.” Plato’s observation of soil degradation is no less relevant 2400 years later. If the importance of healthy soils for nutritious food and clean water has been known for millennia, why has an enduring commitment to thoughtful soil stewardship proven so elusive to so many and for so long?

Soil is a fundamental source of life. It plays a critical role in providing water, nutrients, and support for plant growth, recycling organic materials and protecting surface and ground waters from contaminants. Soil is the base of the terrestrial food chain, directly or indirectly providing over 97% of the calories that now nourish more than six billion people. This modern bounty was enabled by a providential combination of weathering processes that created fertile soils from inert rock and favorable climates suitable for growing a variety of food plants. At the start of the 21st century we express our deep-felt concern that three of the integral resources of agricultural production, soil, water and climate, are increasingly impaired by human actions with potentially serious consequences for global food security.

We are, each of us, people of the soil. Most indigenous peoples and organized religions have oral or written accounts of human origin or experiences that include a deep reverence associated with the life that springs from the soil. Our cultural traditions acknowledge the significance of soil even if our environmental practices do not. The facts about the current condition of global soil resources are sobering. Recent estimates are that one fourth of the earth's inhabitants already depend on degrading lands. Future generations may be forced to obtain ever more sustenance from decreasingly available productive land. Potential changes in rainfall and temperature patterns and their variability as the global climate changes add yet another challenge. There is a long and tragic correlation between cultures that fail to protect the health of their soil and the demise of those same cultures. Life, as we perceive it, exists only on a planet having soil, as we know it. Soil is the interface between lifeless cosmic rock and all terrestrial life. Healthy soil is itself a living community, containing up to four billion microorganisms in each teaspoon. But soil is also a fragile, finite resource requiring care. Destroying soil is the equivalent of destroying the self-renewing capacity of the Earth.

Too often we forget our shared human history and the reality of our dependence on the soil. Too often we fail to enact our historical and rightful commitment to the land, our home place. We are therefore shirking our inherent responsibility to care for the planet. The poor of the world are those most immediately and dramatically affected by both soil degradation and climate change, therefore, soil stewardship is both an environmental and a moral challenge to society.

What is the way forward? What is our task in the face of this reality, this disconnect between the importance and the condition of our soil? We recognize and affirm a cultural and physical link to soil. We assert a shared obligation to soil stewardship that is based on more than purely utilitarian concerns. We acknowledge that soil degradation is an ethical issue, that science and economics alone will not and can not determine a proper course of action. We cannot therefore ignore the mistreatment of our lands and at the same time escape moral denunciation. Encouraging a more broad and thoughtful soil stewardship ethic is not naïve, idealistic, or altruistic but rather perceptive, pragmatic, and essential to our societal response to the challenges posed by global climate change and an increasing human population.

Given that our environmental problems stretch beyond the domain of any particular discipline, genuine solutions to these problems will only be found by engaging all facets of the human mind. **We call for soil scientists to humbly and dutifully work across disciplines – including the humanities and the arts, in efforts to engage in a practice of public scholarship with the goal of building new relationships and networks that advance the soil stewardship ethic. We call for the products of such collaborations to be openly communicated to the public and to policy makers, raising awareness and urging proactive action. Finally, we call for the recognition and celebration of successful soil stewardship stories to serve as examples, to inspire, and to lead us forward**.

Meeting the growing global demand for agricultural products will require greater awareness and commitment to the essential role of healthy soils and clean water to sustainable of food and fiber production. One component of this awareness should be a far greater commitment to ethical discourse on the obligations of the current generation to protect the livelihood and well-being of future generations (Moore & Nelson 2010).

1.4 White

There is a long history of episodic realizations that ethics and values lay at the core of our environmental behaviors. Perhaps one of the most dramatic and reverberating (though ultimately unheeded) came from White (1973, p. 57):

> The artifacts of a society, including its political, social and economic patterns, are shaped primarily by what the mass of individuals in that society believe, at the sub-verbal level, about who they are, about their relation to other people and to the natural environment, and about their destiny.

White locates the origin of our environmental crisis squarely in the realm of philosophy and ethics. Humans do not enter in to an abusive relationship with the nonhuman according to White simply because they can or simply because technologies advance to the point where humans can have massive and detrimental impacts on nature. According to White's analysis, pinning the blame for the environmental crisis on technological advance is as naïve, distracting, and ultimately dangerous as it is common. In addition to acquiring the ability to negatively impact nature, humans have to acquire the philosophical and ethical structures that either allow for, or even sanction, such human-nature interactions. That is, environmental abuse (like any form of abuse) requires *both* an ability and a willingness to abuse.

Specifically, White argues that in the West, Judeo-Christian interpretation of the human-nature relationship is primarily to blame for environmental problems. Humans treat things, according to this interpretation, as they are seen. And Westerners have decided (until perhaps quite recently) to perceive the human-nature relationship in despotic terms: portraying humans as separate from, and in charge of, nature, ordered by God to "dominate and subdue" their charge. Of course, other interpretations of the human-nature relationship are possible. Most recently, and in response to White's challenge (or arguably a misinterpretation of White's challenge), Westerners have offered a "stewardship" interpretation of the human-nature relationship, one in which humans are charged with the care, not despoliation, of God's creation (e.g. Gottlieb 2006). But as White points out, this is a recent, late twentieth-century phenomenon. For literally hundreds and hundreds of years, the world's dominant cultural and religious tradition has instead been actively and righteously engaged in a far more tyrannical relationship with nature:

> In the middle of the fifteenth century the artists of northern France and Burgundy invented a novel iconography for the seven Virtues. For intricate reasons, by that time Temperance (or Moderation) had displaced Charity as the supreme Virtue. In the new iconography Temperance—and she alone—is associated with the new technology. On her head she wears a mechanical clock (invented in the 1330s), the most significant and elaborate recent bit of automation; in her right hand she holds eyeglasses (invented in the 1280s), the greatest boon to the mature intellectual; on her heels she wears rowel spurs (of about 1290), and she stands on a tower windmill (of about 1390), the most spectacular new power machine of the age. *The message could scarcely be more emphatic: technological advance is superlatively virtuous*." (White 1973, pp. 58–58, emphasis added)

The point is, people “commit their lives to what they consider good” (White 1973, p. 59). And people of the Judeo-Christian West believed that employing the ability to impact nature through technology was not only acceptable, but also “superlatively virtuous.”

It is easy to react dismissively to White placing the blame for the environmental crisis on the doorstep of Christianity. By far the most common reaction to White’s article was, and remains (after anger perhaps), an attempt to suggest that he was wrong because the human-nature relationship in the Biblical tradition should be interpreted as one of stewardship not despotism (see especially Barr 1972; Dobel 1977; Moncrief 1970). Although this response is understandable—maybe even predictable, even White himself offers this interpretation at the end of his original essay—it misses the most important and fundamental point of White’s commentary: people’s interactions with nature, how they treat one another, and the environment “depends on what they think about themselves in relation to things around them” (White 1967, p. 1205). That is to say, humans abuse the environment not merely because they can or because they possess the technological ability to do so, humans abuse land because they are *willing* to do so and because the philosophical and ethical predisposition toward the land is such that abuse is allowable, even praised.

There is then an important warning here as well as an explanation. To the degree that humans focus efforts at environmental remediation only on technologies and laws that curb their ability to impact nature, and to the degree that humans therefore fail to address the underlying philosophical and ethical issues of willingness, humans will continue to fall desperately short of the approach that is critical to sustainability or whatever word is applied to a proper relationship to nature (Vucetich & Nelson 2010). Aldo Leopold echoes this sentiment when he refers to the development of a land ethic not as a quaint but decadent rumination of an otherwise pacified group, but as an absolute “ecological necessity” (Leopold 1949; see also Flader 2011). In White’s words, “more science and more technology are not going to get us out of the present ecologic crisis until we find a new religion, or rethink our old one” (White 1973, p. 57).

At the end of the day, White suggests the task at hand “is to find a viable equivalent to animism” (1973, p. 62). That is, to conceptualize humans’ relationship with nature such that humans are not perceived to be separate from nature, and such that nature, like human beings is viewed as imbued with what environmental philosophers later come to call “intrinsic value.” Intellectual and value systems that overcome the metaphysical and value dualism between humans and nature will create the possibility for remediation, merely applying more science and more technology—arguably the main, if not sole, thrust of most environmental initiatives—will not.

1.5 Other Views on the Ethics of Land Use: Leopold et al.

Forward thinkers have long been concerned about the deteriorating state of our natural environment. The environmental movement beginning in the mid- to late 1960s and continuing today has created a crescendo of concern. Though previously unpublished in his own lifetime, Leopold, while still in the employ of the US Forest Service, penned an essay in 1923 in which he abstracted outward from his own experience in the Southwest to comment more generally on the state of natural resources in the United States:

> All of our organic resources are in a rundown condition. Under existing methods of management our forests may be expected to improve, but our total possible farm areas are dwindling and our waters and ranges are still deteriorating. In the case of our ranges, deterioration could be easily

> checked by conservative handling, and the original productiveness regained and restored. But the deterioration of our fundamental resources—land and water—is in the nature of permanent destruction, and the process is cumulative and gaining momentum every year. (1979, p. 133)

Leopold's sobering analysis ultimately leads the young land manager to search out and label the root cause of environmental problems: humans' fundamental moral relationship with nature.

Though arguably this call for the inclusion of ethics has not yet been heeded, conservation leaders have, throughout the recent past (and often in the twilight of their careers), returned repeatedly to this realization. After recounting the current land-use problems, Leopold (1979) pointed out that conservation was a "moral issue," likewise warning against conservation's reduction to mere economics,

> Thus far we have considered the problem of conservation of land purely as an economic issue. A false front of exclusively economic determinism is so habitual to Americans in discussing public questions that one must speak in the language of compound interest to get a hearing. In my opinion, however, one can not round out a real understanding … without likewise considering its *moral* aspects (p. 138).

Late in his life, this ethical epiphany becomes a major focus in Leopold's work, a focus that he articulates powerfully in perhaps the most important and celebrated conservation essay ever written, "The Land Ethic" (1949). Building off both the metaphysical realization that humans are "part and parcel" of a biotic community, and the recognition that any given community only hangs together under the auspices of an ethic corresponding to that level of community organization, Leopold implores human to "quit thinking about decent land-use as solely an economic problem." He asks instead to "examine each question in terms of what is ethically and esthetically right, as well as what is economically expedient." In the final analysis, Leopold suggests that humans replace narrowly anthropocentric and utilitarian ethical obsessions with a summary moral maxim suggesting, "A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it tends otherwise" (Leopold 1949, pp. 224–225).

Just a few years after Leopold's death in 1948, and the release of *A Sand County Almanac* in 1949, leading wildlife biologist Olaus Murie (1954) called for a similar "big hearted code of ethics." Writing in the *Journal of Wildlife Management*, Murie says,

> Whether we like it or not, we find ourselves in the midst of a struggle. Thoughtful people are trying to understand our place in Nature, trying to build a proper social fabric, groping for a code of ethics toward each other and toward Nature. The current controversies in the diverse field of conservation are an expression of this ethical struggle. We, as wildlife technicians, cannot escape it … we have a responsibility to contribute to the highest thinking in this field" (pp. 289–290).

In the same essay Murie expresses deep concern that humans simply are not training resource professionals to fulfill this responsibility, "Our training in the universities should be such that we do not come out pretty good technicians but philosophical illiterates" (Murie 1954, p. 293).

More recently, retired California fisheries biologist Edwin "Phil" Pister made a similar observation and plea for ethical training. "Lacking adequate exposure to the principles of environmental ethics, most practitioners of conservation (especially those emerging from university resource management programs) quickly become missiles without guidance systems" (quoted in Vucetich & Nelson 2007, p. 1267).

The pedigree of those calling for attention to ethics seems impeccable, their argument for the necessity of ethical discourse in conservation seems sound and valid, so why do we attend so minimally to ethics?

1.6 Ethical Considerations of Strategies for Climate Change Mitigation: An Example

The current concern for climate change and the global economic downturn have some striking parallels with the severe drought in the United States during the 1930s Great Depression. An extended drought, ill-advised cropping practices, and subsequent wind erosion in the Great Plains states (the so-called "Dust Bowl") created a major environmental crisis. The deep economic depression beginning in 1929 produced severe economic and social disruption throughout the country. Desperate to improve bleak conditions in the drought-ravaged plains states, the federal government considered several novel, large-scale programs designed to bring immediate physical and economic relief.

One of the key Dust Bowl relief programs was the Prairie States Forestry Project (PSFP), commonly known as the "Shelterbelt Project." The primary goals of the PSFP were providing jobs for unemployed citizens and alleviating drought conditions by creating multirow tree windbreaks that would arrest wind erosion and create a more favorable microclimate for crops and more comfortable conditions for humans. In seven years (1935–1942), the PSFP program would plant over 217 million trees in almost 30,000 km of shelterbelts in six states (Fig. 1.2) stretching from Canada to Texas (Droze 1977).

By modern standards, the PSFP had several fascinating characteristics. First, it was conceived, designed, and implemented in an amazingly short time. Within a year of President Franklin D. Roosevelt's announcement of the program, a detailed, comprehensive report on the scientific aspects of the project was prepared (US Forest Service 1935), and almost 2 million trees were planted. A crucial factor of the PSFP success was the personal interest and direct involvement of Roosevelt and US Secretary of Agriculture Henry A. Wallace, attention that encouraged project managers to devote extra effort to the project's success.

The PSFP remains the largest single afforestation program in US history. Reforestation, afforestation, and soil carbon sequestration are three land management strategies that are among the best options available for reducing atmospheric CO_2 concentrations (see Eglin et al. 2011; Polglase & Paul 2011; Tonon et al. 2011). Although climate change is a much more complex and global phenomena, there may be important lessons from the PSFP experience that are consistent with Diamond's analysis proposed in *Collapse*. The PSFP fits the profile of a highly successful decision-making process (i.e. long-term planning and willingness to reconsider core values). One of the major criticisms of the PSFP was that the trees would grow too slow to mitigate the drought conditions quickly enough. Proponents countered that although the potential benefits may take longer to reach their full effect, the trees would have greater long-term benefits. In this regard the proponents were proven right because a follow-up survey quantified impressive tree growth and survival rates (Read 1958).

One of the groups most opposed to the original PSFP project plan was the professional foresters. In scathing editorials (Chapman 1934a, 1934b, p. 952), the president of the Society of American Foresters H. H. J. Chapman (one of Leopold's former professors at Yale; see Flader 2011) expressed serious misgivings that the project would fail and "shake the public confidence in our professional integrity." The PSFP also had to overcome intense resistance from politicians and tree nursery operators who believed that it was too expensive, that the trees would not survive, or that it was wrong to use federal resources for plantings on private land.

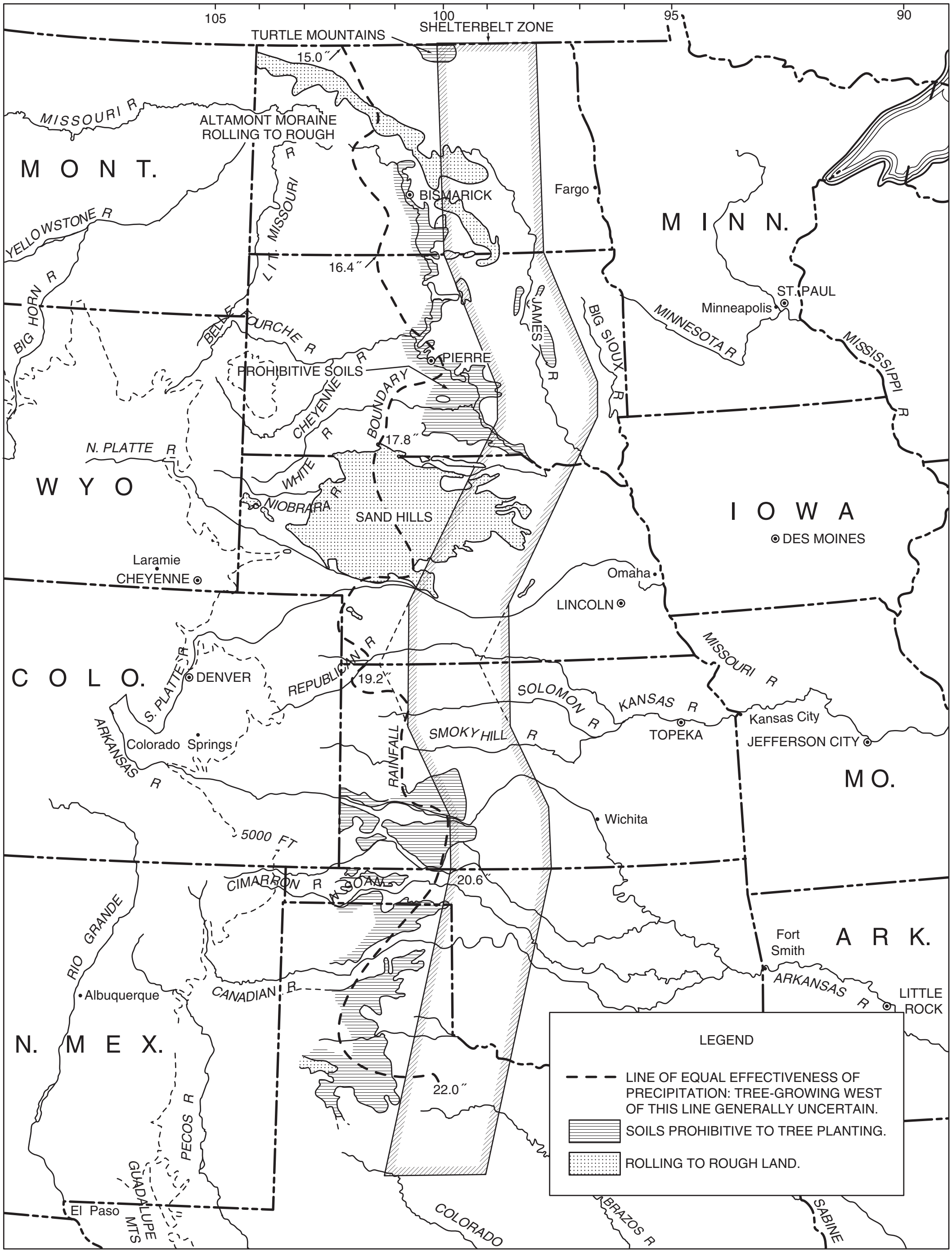

Figure 1.2 Map of the planned tree planting zone for the Prairie States Forestry Project. US Forest Service, 1935.

For the PSFP, it was strongly held beliefs regarding the role of government in relief efforts and whether the government should invest federal resources on private land that had to be overcome. Ultimately it was unwavering belief and confidence in the project by US Forest Service scientists Carlos Bates, Raphael Zon, and Paul Roberts and the personal support of Roosevelt that enabled the project to succeed (Droze 1977).

Successfully addressing global climate change will require similar long-term, holistic strategies but operating on even more extensive spatial scales and longer time horizons. Like the PSFP though, bold and innovative leadership will be needed to enact global measures that reduce net GHG emissions and increase carbon sinks. Any strategies for climate change mitigation or adaption will also have both expected and unintended consequences for the different socioeconomic classes and geographic regions and for future generations. The effects of climate change are likely to have a greater impact on the poor in developing countries than on the affluent in developed countries who are the greatest GHG contributors (Howarth & Monahan 1996; Thomas & Twyman 2005; Paavola & Adger 2006; Stigter 2011; Westra 2011). The challenge now is to engage similar successful decision-making methods as proposed by Diamond and demonstrated by the PSFP of the 1930s to craft effective policies and programs for addressing global climate change today and into the future.

1.7 Conclusions

It seems safe to say that there has long been recognition (as sporadic and ignored as it might be) that issues in natural resource management are fundamentally ethical issues. Likewise, there is a long-standing and widely accepted recognition that humans' well-being is entwined with the well-being of the environment. And finally, there seems to be long-standing recognition that the state of the environmental context is in trouble. It would appear safe to assume, therefore, that there exist all of the elements necessary for profound and rapid reaction to environmental threats. And yet this is not the case. There is instead a failure to appropriately address these issues. Of course there is always some minority voice in opposition to one of these "recognitions": suggesting that humans are not a part of the environment, that the environment is not threatened, or that technology alone will cure what ails. But this does not really explain humans' collective failure to respond. In fact, most humans probably believe they are responding. Humans perhaps all decry the condition of soils, water, and air. According to White (1973), "We deserve [these environmental harms] because, according to our structures of values, so many things have priority over achieving a viable ecology…. [This] gap between our words and our deeds is not hypocrisy, it is something more dangerous: self-deception."

Perhaps one of the most troubling forms of this self-deception is the failure to adequately integrate science and ethics. Scientists often go to great lengths to neglect ethics (Wolpe 2006) and ethicists (even those self-identifying as "applied" or "engaged") seem to go to equally great lengths to avoid doing helpful philosophy (Nelson 2008). This disassociation is both predictable and tragic. But humans might do well to heed White's (1973) words here:

> We shall not cope with our ecologic crisis until scores of millions of us learn to understand more clearly what our real values are, and determine to change our priorities so that we not only wish but also are able to cope effectively with all aspects of [our environmental crisis]" (p. 56).

A solution might be found less in the attempt to train or retrain scientists to be ethicists or ethicists to be scientists (each being such highly expert fields of knowledge), but in creating overt and intentional modes and opportunities for collaboration, that is, coauthoring papers and grants, sharing graduate students, adding ethicists to science projects, inviting each to the others' meetings. We should not, however, underestimate the obstacles here. There are in fact major challenges for each side: for scientists little or no formal training or expertise in philosophy and ethics and for ethicists there is an almost total lack of familiarity with collaboration and with the recognition of the value of outreach.

So, was White right? If his 1967 *Science* article is interpreted as an indictment of Christianity as the lone or even primary causal factor for poor environmental stewardship, the answer is no. Within Christianity there is such a wide spectrum of views regarding human interaction with nature from humans as nurturer to humans as holding complete dominion. This interpretation is too narrow for such a complex facet of societal decision making. However, if a broader interpretation is taken that the environmental crisis is fundamentally a moral or ethical crisis, and that remediation will only come in the form of values alteration brought forth through ethical discourse, then he was indeed right. Science and technology alone will not lead to a solution to environmental problems such as sustaining soil productivity under the influence of global climate change without the recognition and incorporation of ethical principles in the development of effective and fair policy.

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2 Intellectual Inertia

An Uneasy Tension between Collective Validation of the Known and Encouraging Exploration of the Unknown

John M. Norman

2.1 Introduction

Science is a creative human endeavor with most scientists placing a high value on being innovative, that is, doing something no one else has done. However, the execution of science requires accepted methodologies with stable collective standards, so the world that the scientist is accustomed to is likely to be resistant to change that challenges orthodoxy (Campanario & Martin 2004). The schizophrenic nature of science, which arises from the tension between established concepts and new ideas, favors contentious interactions and fitful progress. Of course, resistance to change is not unique to scientists; human beings thrive in stable environments, as do all living things that adapt by changing themselves and their immediate environment. Recent advances in neuroscience demonstrate that human decision making is embedded in emotion and accumulated experience as well as conscious thought (Lehrer 2009). Thus, all humans have a vested interest in stability and resisting change.

The quality of resisting change has been referred to as "inertia" (Webster's New World Dictionary 1988), which is considered analogous with Newton's Laws of Motion. When this resistance to change is manifested in conscious thought, it will be referred to as "intellectual inertia" in this chapter. Although intellectual inertia is accepted as commonplace among the general population, it can be detrimental in science. A quick Google search of *intellectual inertia* produced 18,900 hits with various attempts at short definitions; for example, intellectual inertia "is the desire to believe that we are right in our opinions" (www.salguod.net/weblog/archive/2004/03/inellectual_ine.shtml). The term *intellectual inertia* is in general use, but a substantive definition has not been developed. Therefore, a definition of intellectual inertia will be given, drawing heavily on analogy with Newton's laws of motion, and some classic examples of intellectual inertia will be included, followed by some implications for climate change science.

2.2 Defining Intellectual Inertia

Newton's First Law of Motion, which is referred to as the law of inertia and was first stated by Aristotle and later refined by Galileo, states that "Every body persists in its state of being at rest or of moving uniformly straight forward, except insofar as it is compelled to change its state by

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Table 2.1 Newton's original Laws of Motion and the human behavioral equivalent, which might be referred to as the "intellectual laws of action."

	Newton's Laws	Intellectual Laws
1	Every body persists in its state of being at rest or of moving uniformly straight forward, except insofar as it is compelled to change its state by force impressed.	People have a tendency to resist engaging new ideas or persist with their established line of thinking until they are compelled to change their perspective by forces impressed upon them.
2	Force is equal to the change in momentum per change in time. For a constant mass, force equals mass times acceleration (F = m × a).	The longer an idea exists and the more evidence compiled in its favor, the greater the "intellectual momentum" of that idea, so that change requires greater force or longer time.
3	For every action there is an equal and opposite reaction.	The greater the change associated with a new idea, the greater the resistance to adopting it.

force impressed" (Cohen & Whitman 1999). Using Newton's First Law as a guide, intellectual inertia might be defined as follows:

> People have a tendency to resist engaging new ideas or persist with their established line of thinking until they are compelled to change their perspective by forces impressed upon them.

At this point, considering the human behavioral equivalent of all three of Newton's laws of motion might be instructive (Table 2.1). In fact, Newton's laws, which are framed independently of humans as interactions among inanimate objects, actually may come from observations of how humans interact with the world.

That is, Newton's laws may be an attempt on the part of humans to animate the inanimate world. Essentially the three "intellectual laws of action" have to do with intellectual inertia, intellectual momentum, and action/reaction.

The intellectual laws of action listed in Table 2.1 likely apply to all human endeavors, including science. However, science seems to require an optimum amount of intellectual inertia, not so much that it threatens the scientific method and unnecessarily delays or inhibits discovery, but enough to avoid rejecting established concepts prematurely. Some examples might be instructive.

2.3 Examples of Intellectual Inertia

Several examples of the intellectual laws of action can be extracted from the historical development of earth sciences. In the interest of brevity and illustration, the examples described here are taken mainly from Bryson (2003).

James Hutton, often referred to as the "Father of Geology," challenged the prevailing paradigm of the "catastrophists," who believed that the Earth's surface was shaped by the biblical flood over 4,000 years ago, with his theory of "uniformitarianism"; that is, the same processes working today have been working over eons of time to create what humans see today. In the late 1700s, Hutton suggested that the large boulders and polished rocks with gouges in them high up in mountains might have come from widespread glaciations. Naturalists of the day did not pick up this idea from Hutton and continued with the preferred ideology that large boulders were deposited high up on mountains by floods. Therefore, the idea of glaciers did not surface in science again for 50 years, even though the idea was known by local mountain peasants (Bryson 2003).

Even with the accumulation of abundant supporting evidence from decades of observations, much of it promoted by Louis Agassiz, those supporting the idea of glaciers were ridiculed by the prevailing geologists. The famous geologist Charles Lyell, who authored the influential *Principles of Geology* (Lyell 1830), openly criticized Agassiz at meetings in 1840. According to Bryson (2003), Lyell eventually accepted glaciers but refused to speak out publicly. Perhaps Lyell's reticence arose from a fear of retribution, an example of the third intellectual law of action (i.e. action/reaction). Wide acceptance of the idea of glaciers did not occur until the 1860s when James Croll published a paper on how variations in the Earth's orbit might explain ice ages (Croll 1864). The importance of variations in the Earth's orbit is now more clearly understood and fundamental to our understanding of climate change (Hays et al. 1976).

Intellectual inertia has been alive and well in geology for a long time. The catastrophist view was replaced by the "uniformitarianist" view in the mid-1800s when the idea of glaciers took form; then the uniformitarianist view, itself, became entrenched in orthodoxy and that leads to the next example of intellectual inertia. Uniformitarianists tried mightily to explain for decades the Scablands in the US Pacific Northwest. The Scablands are an incredibly complex and dissected feature encompassing four states (i.e. Montana, Idaho, Washington, and Oregon) with continuity from Montana to the Pacific Ocean. A Google search of *scablands megaflood* will provide thousands of hits and reveal profoundly spectacular pictures of various regions of the Scablands with useful descriptions of what likely occurred there.

In 1920, J. Harlen Bretz proposed a "megaflood" theory suggesting the Scablands were created by an ice dam collapse that released a 900-foot high wall of water at a flow of 60 km^3/hr. This theory challenged the accepted uniformitarianism and met considerable resistance because a megaflood was catastrophism, which was viewed as having been rejected decades before. Even when Joseph Pardee provided more evidence in 1925, the idea of megafloods was not widely accepted in geology. Over the decades, the evidence has accumulated to such an extent that geologists now accept that numerous megafloods were responsible for creating the Scablands.

The development of the theory of plate tectonics is probably one of the best examples of the challenges involved in overcoming intellectual inertia. Even Albert Einstein wrote a glowing forward to Charles Hapgood's book, which did not support continental drift (Hapgood 1958). The theory of continental drift was proposed by Frank Bursley, an independently wealthy geologist. In 1912, a German meteorologist named Alfred Wegener hypothesized Pangaea and published on continental drift. Wegener was respected by some geophysicists for his geophysical contributions, but he was largely rejected by US geologists (Oreskes 1999). An alternative hypothesis was proposed by Austrian Alfred Suess, namely that the earth wrinkled upon cooling. However, existing observations did not support this theory. Considerable evidence supported Wegener's theory. For example, Wegener found similar fossils in South America and Australia, in Scandinavia and New England. In response to the fossil evidence, geologists postulated "land bridges" with no supporting data and no explanations for how they were formed or why they no longer existed (an example of excessive intellectual inertia). Eventually as fossil data accumulated, land bridges were postulated from North America to Europe, Brazil to Africa, Southeast Asia to Australia, and Australia to Antarctica.

In 1944, Arthur Holmes, an English geologist, published a theory about currents of molten rock below the Earth's crust, providing a mechanism for continental drift. He was so criticized, especially in the United States, that he felt guilty enough to write the following: "I have never succeeded in freeing myself from a nagging prejudice against continental drift; in my geological bones, so to speak, I feel the hypothesis is a fantastic one" (Bryon 2003, p. 177). In 1964, *Encyclopaedia Britannica* contained a discussion of rival theories, and Wegener's had "numerous grave theoretical difficulties" (Bryson 2003, p. 176). Oil geologists knew that to find oil, allowance had to be made for movements implied by continental drift, but they did not write academic papers. A simple and compelling argument for continental drift arises because estimates of long-term erosion from continental rivers suggested a quantity of sediment that was sufficient to fill all the ocean basins of the world several times over. Where did all this sediment go? Of course with continental drift, it went back into the Earth to be remelted, but this was not the prevailing orthodoxy.

Princeton geologist Harry Hess, using data he had collected during World War II, wrote a paper hypothesizing mid-oceanic ridges and subduction at the continental masses, but it was ignored by US geologists. In the 1950s, Patrick Blackett (University of London) and S. K. Runcorn (University of Newcastle) found that magnetic orientations in Britain and the United States fit together by using the discovery of Bernard Brunhes in 1906 that rocks preserve their magnetic fields when they harden. Although they wrote a paper on this and it was accepted to some degree in Europe, it was ignored by most geologists in the United States who preferred uniformitarianism (Oreskes 1999).

In 1963, Cambridge geophysicist Drummond Matthews and his graduate student, Fred Vine, verified Hess's "sea floor spreading" hypothesis with magnetic anomaly measurements, showing that Hess was right years before (Vine & Matthews 1963). Unfortunately Canadian geologist Lawrence Morley had the same conclusion at the same time, but his paper was rejected by the *Journal of Geophysical Research* with the following comment from the editor: "Such speculations make interesting talk at cocktail parties, but it is not the sort of thing that ought to be published under serious scientific aegis" (Bryson 2003, p. 180).

Morley's experience demonstrates the principle that peer review can prevent exceptionally innovative material from entering formal scientific discourse as well as removing most of the erroneous material, primarily preserving the status quo and bolstering intellectual inertia. As a young academic I was informed that when reviewing a paper three criteria were important: (1) Is it correct? (2) Is it interesting? and (3) Is it new? Further, if a manuscript meets any two of the three criteria, it is acceptable. I have used this guidance for 35 years because, as a reviewer, discerning what is "correct" is fraught with peril; that is, distinguishing between erroneous thinking and my lack of adequate understanding is most challenging. These three criteria and their origin, which remains unknown to me, are a way to limit intellectual inertia in the peer-review process.

Old ideas die hard. In the 1970s, a popular and influential geology text *The Earth* by Harold Jeffreys insisted that plate tectonics was a physical impossibility, just as in the 1924 edition (Jeffreys 1970). In 1980, apparently one in eight American geologists did not believe in plate tectonics (Bryson 2003). Plate tectonics or continental drift is now widely accepted by the geology community because these ideas result in the whole Earth "making sense." However, the movements are now believed to be much more complex than originally thought.

To make a point here, this is an overly simplistic picture of geology. Clearly geology did not have a single view on the field, and many perspectives were represented in the discipline as observations became available. However, the notion of a prevailing view is not unreasonable, that is, a view perpetuated by prominent and influential individuals in professional societies and research agencies and the writers of text books (a consequence of individuals with too much personal influence on the science). Such bias increases intellectual inertia and often makes it difficult for renegade views to successfully navigate the journal-review process.

Examples of intellectual inertia abound in all branches of science. Individual egos of prominent scientists can inhibit progress; for example, the prominent Jean-Dominique Cassini refused to accept young Ole Roemer's clever estimate of the speed of light in 1676, which was reasonably accurate for the time, and delayed the acceptance of the idea that the speed of light was not infinite for 50 years (Bodanis 2000). Perhaps the most ruthless example of intellectual inertia was Lysenkoism. Trofim Denisovich Lysenko (1898–1976) was a Ukrainian plant breeder who created a set of repressive political and social campaigns in science and agriculture that began in the late 1920s and ended in 1964. During this era, opposition to Lysenko's prevailing ideas could result in imprisonment or even execution. An end result of this extreme example of intellectual inertia was a setting back of genetics in the Soviet Union for a generation or more.

During the controversy associated with whether glaciers existed, Alexander von Humboldt proposed three stages of discovery:

1. People deny that it is true.
2. They deny that it is important.
3. And then they credit the wrong person (Bryson 2003, p. 421).

Perhaps the training of every young scientist should require exposure to the history of science to reduce the likelihood of repeating that history.

2.4 Intellectual Inertia is Unavoidable But Requires Vigilance

Within the realm of science, humans do have reasons for skepticism; after all, falsification is an essential part of the Scientific Method. However, anyone who reads the philosophical literature on applying the Scientific Method will quickly realize that the methods used by scientists are not easily characterized (Losee 2005), even though science texts present idealized descriptions (Botkin & Keller 2007). Progress in science is often fitful and chaotic as well as steady and systematic. Rejecting a theory that has had much support should not be possible with a single experimental result without painstaking efforts at reviewing possible sources of error, thoroughly ruling out alternative explanations, and exploring the possibility that the original theory simply needs some modification or applies under a more limited set of conditions. Considerable study was required to reject such concepts as phlogiston, caloric, pangenesis, bodily humors, ether, and so on. Such issues of progress abound in climate science (Schneider 2009).

Clearly, intellectual inertia is important to the steady and systematic expansion of the realm of science. After all, even the process of measurement itself requires collective standards that all scientists must agree on to proceed in science, and these agreed-upon standards predispose us to intellectual inertia. Thus, in science, an uneasy tension exists between intellectual inertia associated with stable expansion of knowledge and open exploration of the unknown. Being aware of the strengths and weaknesses of intellectual inertia should help scientists keep these opposing forces in some kind of suitable balance. This uneasy tension associated with intellectual inertia means that trust in the integrity of a researcher often is more important than the experimental result itself (Gooday 2004).

Virtually all science depends on a premise put forth by René Descartes (1596–1650) almost 400 years ago; namely, the observer can be independent of the observation. Such behavior is what we refer to as objective. How does the dictionary define "objective"?

> Objective (def.): regarded as being independent of the mind (Webster's New World Dictionary 1988), belonging to the object of thought rather than the thinking person, unbiased (American College Dictionary 1958).

Clearly humans can not behave in a manner that is "independent of the mind" or be unbiased. Because humans can not be objective, intellectual inertia is inevitable. Thus, the objective of a scientist is not to eliminate intellectual inertia but to contain it so as to minimize bias. In science we rely on the potentially opposing influences of numerous individual biases as scientists check each others work; however, we have no assurance that many individual biases cancel to minimize bias, especially in the presence of a collective motivation (e.g. funding, see Resnik 2007) or extremely persuasive and influential individuals.

> Intellectual inertia is undesirable when it increases support for a concept without a commensurate increase in observational evidence, or when it discards a concept without the same due diligence used to uphold accepted ideas.

Some have argued that science eventually gets at the truth and intellectual inertia is overcome in time. Although previous historical examples support this view, this is little consolation for the current state of science. Unfortunately, no one knows when science does not succeed in overcoming intellectual inertia because those ideas may be long forgotten or so deeply opposed by the scientific community that they are continually suppressed. For example, "intentionality" experiments in which collective human intentionality affects the outcome of physical events (www.livingthefield.com), random event generator experiments such as the Princeton "Global Consciousness Experiment" of Dr. Roger Nelson (www.noosphere.princeton.edu), or plant consciousness experiments (http://myspace.com/mileece). These experiments are an anathema to established science because they imply that human observers can not behave in a way that is independent of their observations; that is, humans inevitably affect the outcome of any observation whether they acknowledge it or not.

The best example of interactions between observer and observation is at the quantum level. Experiments have clearly established that the presence or absence of an observer changes the outcome of a two-slit light experiment (Jacques et al. 2007). However, many deny that quantum phenomena occur at the macrolevel of everyday life. Recently O'Donnell et al. (2010) demonstrated that quantum phenomena can occur on the scale of an object that can be seen with the unaided human eye. The neglect or denial of quantum-level paradoxes on the macroscale represents intellectual inertia that tends to retard the exploration of consciousness phenomena. After all, funding for consciousness experiments can be made to look like a waste of a short supply of money, such as cold fusion; see http://en.wikipedia.org/wiki/Cold_fusion for an interesting example of how science deals with a discredited concept.

Until these seemingly outrageous phenomena are legitimate subjects for investigation within the existing peer-review system without threat of researchers being ostracized, maverick experimenters will continue to produce questionable results and humanity will remain ignorant from excessive intellectual inertia in the scientific community.

A classic example of intellectual inertia is embodied in the clash between supporters of the book *The Secret Life of Plants* (Tompkins & Bird 1973) and established scientists. A thoughtful and thorough assessment of these "Secret-Life" phenomena was published by Galston and Slayman (1979), who clearly demonstrated the nonreplicable nature of the original experiments, and therefore rightly discredit the original claims as failing a test using the Scientific Method. Supporters of the Secret-Life claim that intentionality is important, but scientists are working with a premise that intentionality is irrelevant because "the observer is assumed independent of the observation." Therefore, Galston and Slayman (1979, p. 340) rightly conclude here that "The scientific Method is excluded, the question posed quickly became irrelevant to science." But Galston and Slayman (1979, p. 343) could not resist inserting a final bit of ridicule by writing "and we are left in the realm of Ben Kenobi and Darth Vader." Because this last statement was unnecessary to the paper, it suggests the author's professional opinion of anyone who seriously considers a topic like this. What purpose does a statement like this serve but to use stature as a scientist to ridicule others who might be bold enough to consider exploring further? Such derogatory comments only perpetuate an undesirable form of intellectual inertia.

As a scientist I clearly know the difference my attitude makes; that is, I approach an experiment differently if I want to learn something new than if I want simply to discredit someone else. I can discredit someone else by concentrating on some particular detail intensely, and I stop when my goal of discrediting is met. On the other hand, if I am enthusiastic about learning something new, I try experiment after experiment and idea after idea tirelessly until after many struggles something new emerges.

I subscribe to the approach of remaining neutral on topics for which there is inadequate observational evidence, whereas I speak out when someone claims to have such observational evidence that falls far short of the Scientific Method. We should be able to revisit any idea and be open to evaluating new approaches, no matter how discredited previous approaches have been. As geologist Eugene Shoemaker noted when geologists exhibited considerable intellectual inertia resisting observed evidence that an asteroid impact could have caused the extinction of the dinosaurs; Shoemaker suggested that the asteroid-impact idea was "against their scientific religion" (Bryson 2003, p. 198).

2.5 Intellectual Inertia and Climate Change Science

The intellectual inertia issues related to global climate change are classical in the sense of transitioning from strong resistance within the scientific community in the early years (1970s) to unprecedented solidarity within the climate science community some three to four decades later. The late Stephen Schneider (2009) records several episodes of collegial resistance from early in his career, including being warned by his institute director in 1975 that if he did not stop this "interdisciplinary bent" he might not get promoted to tenure (Schneider 2009, p. 75). However a decade into the twenty-first century, the intellectual inertia issues in global climate change are associated with an extraordinarily broad consensus among the most knowledgeable climate scientists that the Earth's climate is warming and humans have had a major hand in causing that warming (see Kintisch 2010). This pervasive influence of intellectual inertia appears often in science as seen in the examples in Section 2.3.

What is different about the current global climate change issue is that a strong opposition community has arisen to deny that humans have contributed significantly to global climate change (e.g. Robinson et al. 2007). Thus, intellectual inertia from consensus in the global change science community is encountering nonclimate scientists, oil and coal interests, and policy makers who have no intellectual inertia associated with the Scientific Method, but rather intellectual inertia associated with maintaining the status quo. With a global change, scientific community that appears so monolithic, some outsiders assume bias or collusion among scientists.

Some scientists are prominent in this opposition community and oppose anthropogenic climate warming using climate data gathered by established climate scientists. However, they often approach the subject of carbon dioxide (CO_2) and global warming in a piecemeal fashion with linear extrapolations of simple correlations (Robinson et al. 2007), when we know the climate system is highly nonlinear and a defendable treatment requires an integrated approach. Such simple, selective, intuitive arguments are deceptive but influential because nonspecialists can understand them when they do not understand the complex climate models. Multivariate nonlinear systems tend to be nonintuitive, and small changes in even a single variable, such as a fraction of a % change in Earth's outgoing radiative flux caused by elevated greenhouse-gas concentrations, can have significant effects, especially if those changes come when a system is near its tipping point (Gladwell 2002). Simple intuitive arguments, which may be irrelevant, can provide rational support for the a priori feelings of the uninformed (Lehrer 2009). Unfortunately to me, an outsider to global climate science, some prominent members of the climate science community seem more concerned with indignant responses to challenges from the "outside" (see Science Letter 2010) than taking on the challenge of responding thoughtfully to critics such as Robinson et al. (2007). Such reluctance is understandable because of the difficulty of distinguishing between challenges that deserve rebuttal and outright smear campaigns with dubious origins that are designed to simply confuse and deceive (Oreskes & Conway 2010). Such a "Denial Machine" (Begley 2007) is mostly misinformation based on ideology. Unfortunately, resistance to open dialog among climate scientists and deniers, a form of intellectual inertia, results in the opposition community resorting to tricks, such as "Climategate," or as some scientists prefer "Climate-denier gate" (http://en.wikipedia.org/wiki/Climatic_Research_Unit_email_controversy). Although Wikipedia is not an archival reference, this controversy is so far reaching and recent (4.5 million hits on Google), that no archival reference seems to be available. In November 2009, several thousand e-mails were hacked from the Climate Research unit of the University of East Anglia in the United Kingdom, leading to allegations from skeptics of anthropogenic climate change that scientists withheld data, interfered with the peer-review system to suppress dissenting papers, deleted raw data, or manipulated data to favor the climate warming process. Numerous independent reviews rejected these allegations but recognized problems with "data rights" that scientists maintain to get appropriate credit for their work. Climategate appears to be a well orchestrated and illegal smear campaign against a half-dozen climate scientists by taking e-mail communications out of context and exploiting several inherent weaknesses in the execution of science in the entrepreneurial research world today, two of these seemingly unavoidable weaknesses being in the reward system and peer review.

In any event, those who deny that greenhouse gases are a major cause of global warming do not deny that the rising CO_2 is anthropogenic in origin, but they do seem to ignore the devastating effect of this rise in CO_2 on acidification of the oceans, where pH is lower than it has been for 20 million years (Kerr 2010). Denying the pervasive global influence of humans is wishful bias.

The exploration of global climate dynamics is so complex that the scientific community has settled on general circulation models (GCMs), also known as global climate models, as the primary means for quantitative study. Large, complex, expensive, computer-based models like GCMs maximize intellectual inertia because much of the global climate community is collaborating on the coding and measurement efforts necessary to build and validate such exceptionally complex computer programs. Recent increases in computer speed and capacity do permit many research groups around the world to work with GCMs and carry out independent studies, but these programs are expensive and generally supportive of the mainstream modeling agenda. The mainstream measurement and modeling programs require such massive investments of human and financial capital that sacrificed alternative approaches become increasingly "unthinkable" with resources always in short supply, and challenging the results of such global models becomes increasingly difficult as an established scientist. Essentially,

> an earth scientist who challenges global climate models meets the same intellectual inertia as an ecologist who challenges evolution.

In general, most scientists tend to accept assertions from the global climate change community because these interpretations come from decades of applying the Scientific Method; further, we scientists believe we are honest and thus assume the integrity of our colleagues unless we have specific information to the contrary. In fact, we must assume this integrity of our colleagues, otherwise the Scientific Method will not work.

The ever-widening chasm between scientists and society is apparent in a growing distrust of science (Maddox 1995; Specter 2009), and we scientists must share a portion of the responsibility for this schism. Decreased base funding of universities by state legislatures and increased dependence on competitive federal and private funding has driven these institutions of higher learning to profiting from discoveries of their scientists, contributing to compromising the credibility of their scientists in the process (Greenberg 2001; Press & Washburn 2000). Public skepticism will continue to grow as the politics of science and humanness of scientists becomes more visible.

As science has moved into the mainstream of our culture, compromising motivations seem to be increasingly apparent, which further increases intellectual inertia and public skepticism (e.g. recognition awards [Nobel Prize], National Academy status, celebrity status, money, influence, political rewards, and national pride). Global climate change science is at the heart of a power struggle and quality science may be a casualty. The stakes in this power struggle are exceedingly high: If the climate science is correct, the consequences for humanity and the planet are formidable, and if that science turns out to be an exaggeration, then damage to the scientific endeavor will be unprecedented.

The Intergovernmental Panel on Climate Change (IPCC) represents a valiant attempt to provide a formal interface between the global climate scientific community and the public. However, bringing together hundreds of scientists to focus on a single document to inform policy makers on the “state of the science” may have inadvertently increased the intellectual inertia of the climate science community by forcing agreement and diminishing the visibility of a less well-organized minority who object to the process of making such reports. Thus, the well-intentioned effort to summarize climate science through the IPCC may have contributed to polarizing proponents and opponents of anthropogenic climate warming.

As a scientist I find it extremely difficult to believe that an ideological agenda exists in the climate science community to promote global climate change warnings. With the highly competitive nature of modern, entrepreneurial science and the elevated stature achieved by anyone who can undo an existing paradigm, such a conspiracy seems unreasonable. I hypothesize that the global change community is suffering from unprecedented intellectual inertia, arising from the need to focus available human and financial resources on a most elegant approach to make progress with a massive global experiment; so many resources must be concentrated on this one approach that the usual checks and balances of the Scientific Method may be compromised. One could argue that particle physics suffers from similar intellectual inertia (e.g. the $10 billion Large Hadron Collider with 10,000 scientists and engineers from more than 100 countries), but no particular commercial entities obviously stand to lose market share depending on the outcome, and public policy does not appear to be influenced. Therefore, unlike the global climate change issue, the Hadron controversy seems confined to fiscal conservatives and catastrophists.

Personally I believe that the mainstream climate science community has the best information available on the relationship between human beings and the global climate. However, no absolute certainty exists in science or any other human endeavor; consider nutritional scientists who recommended that transfats were healthier in diets than saturated fats only to find out after 30 years that transfats are the only fats that correlate significantly with increased heart disease (Pollan 2008). The Scientific Method can take scores of years to vet ideas.

2.6 Optimizing Intellectual Inertia

Intellectual inertia can be considered to arise from two sources: (1) The balance between innovation and human resistance to change from within the scientific community, and (2) external influences, such as money, prestigious awards, national pride and politics, that compromise scientists and undermine the Scientific Method. A healthy amount of intellectual inertia within the scientific community preserves an optimal balance between innovation and resistance to change, which is a happy medium between destructively unstable and rigidly unchanging. To me, the external influences identified herein have no positive influence on the application of the Scientific Method but are unavoidable practicalities. Both internal and external sources of intellectual inertia seem inextricably intertwined. Following are a few suggestions for exploring the reduction of intellectual inertia in the global climate change research arena.

Do established scientists currently control too much of the execution of science? This seems inevitable in a paternalistic society in which a hierarchy of influence is inherent. After all, young scientists are establishing their reputations and assumed to be less able to judge creativity than their experienced elders; however, this is a premise. Suppose the alternative hypothesis is made: young scientists, who are nearer the well-known peak of their creativity than older scientists, are less biased by an archaic, self-serving system and more able to recognize true creativity than those calloused by the school of hard knocks.

I suggest that the current system builds in too much intellectual inertia because elder scientists control too much of the following:

- Peer review of journal articles and research proposals.
- Priority setting of granting agencies.
- Proposal review panels and international advisory panels.
- Advising to policy makers.
- Excessive influence of award winners and members of the National Academy of Science.
- Promotion and tenure decisions.
- Disciplinary parochialism through administrative influence.

As most of us age, we have a tendency to become more risk adverse and emphasize accountability more than creativity; scientists are not likely to be an exception except for a small number of highly successful scientists who operate outside the traditional reward system for scientists. The reward system consists of salary, position, prestige, awards, research funding, speaking circuits, political power, royalties, and so on. Perhaps older scientists resist innovation more strongly than young scientists because they have more to relearn and less ability to learn it if traditional views are overturned (not to mention reduced influence with paradigm shifts). Senior scientists are particularly influential in the politics of science (e.g. Nobel laureates, National Academy members, and so on). The overwhelming influence of older scientists is apparent in the intellectual inertia examples described previously in this chapter, and many more examples exist. Clearly older scientists exert considerable influence over promotion and tenure decisions, but this seems unavoidable. Although I am not sure of the source, an old adage that I recall encountering in graduate school was that the prominence of scientists during their active career was proportional to their retarding influence in their waning career. Unfortunately academic research does not have the benefit of the “free market” brutality that business does (at least when business is competitive) for combating intellectual inertia.

I suspect that this first point will meet considerable resistance from my elder colleagues, but a quick read of Michael Mendillo's exposé of solar and space physics will convince most skeptics that the "seniority system" and manipulation by insiders is alive and well (Mendillo 2009).

Is the scientific community guided by a "seniority rule" like the US Congress with similar consequences? Although the seniority rule in Congress is not actually a "rule" at all, but rather a custom or convention, it is believed to have a major impact on the conduct of that body. Clearly placing the power in the hands of elders who have been thoroughly trained in the conduct of that system likely will favor the perpetuation of that system at the expense of new ideas. Although the seniority rule in Congress is controversial, a rational justification for it as a means to distribute power does exist (Celler 1961). Concentrating power in the hands of the more experienced may be justifiable for stable government. If a kind of seniority rule is operating in the scientific community by custom, then similar to Congress it becomes a way to consolidate power. However, consolidating power has nothing to do with applying the Scientific Method and everything to do with the politics of science. Unlike Congress, in which power and opinion dominate, science has a set of precepts based on observation, in which power and opinion have no place in the pure practice of the Scientific Method. The uneven distribution of power among scientists and science-program managers undermines the Scientific Method and builds excess intellectual inertia. In a study of the Apollo moon scientists, Mitroff (1974) found that the most experienced scientists were so strikingly committed to their ideas that contrary evidence seemed to have little influence on their views.

Pragmatists might justifiably claim that scientific research does not exist in a vacuum and must get its funding through the political process; therefore, some deference to the politics of science is necessary. To this I would agree, but we should make every effort to allow the Scientific Method to work its magic and not prostitute ourselves to a political machine. In the case of global climate science, the seniority politics of science may be exerting too much influence for the long-term benefit of human kind.

Perhaps we should reduce the influence of elder scientists in the conduct of scientific research? Clearly this is a provocative and heretical statement. Greater efforts could be made to involve younger scientists in the priority setting of granting agencies to broaden the suite of areas that receive support. However, the treadmill that young scientists are on while acquiring tenure in universities and establishing themselves in government labs all but prohibits this. Thus, some changes in the expectations of young scientists would have to occur to make room for their increased participation in decision making. Just as disciplinary doctorate degree programs provide little preparation for future university teaching responsibilities, such programs also provide little or no preparation for the "politics of science" that researchers will encounter. Some creative exploration here for graduate students could reduce the likelihood of young researchers adopting the patterns of their elders for professional survival.

Could we make a sustained effort to include more young scientists (those in the first 10 years after doctorate) on proposal review panels and policy advisory panels? Because often young scientists are reluctant to express their ideas for fear of offending someone who later will be involved in reviewing their manuscripts, proposals, or promotion, a way to insulate these young scientists from such consequences seems necessary. I find it difficult to believe that as creative as we scientists are, we can not find a better way to achieve such an objective.

Is guidance available for challenging orthodoxy? An excellent resource for challenging orthodoxy is available in Campanario and Martin (2004), who have studied resistance to scientific innovation and ways to dissent. They created a list of ways of overcoming obstacles in three areas of crucial importance: obtaining funding, getting published, and dealing with attacks.

Could we study intellectual inertia in science using the Scientific Method and improve the educational process? Sociologists (Hull 1988) and science historians (Kuhn 1970) certainly have been studying the endeavor of science for a long time, and their ideas are profoundly controversial and fascinating for many scientists. The sociology of science has been explored to some extent for some traditional disciplines, such as physics (Campanario & Martin 2004), but more applications of the Scientific Method to studies of intellectual inertia in global climate science seem warranted. Certainly the "climate change controversy" has been studied in the journal literature (Oreskes 2004) and in the popular press (Begley 2007), and intellectual inertia is implicated. Surely intellectual inertia would be a worthy topic to investigate more thoroughly so ideas for how to optimize its effect on climate change studies might be forthcoming.

A greater respect for how scientific inquiry is actually practiced would begin with the education of graduate students. Our system of examinations and degrees is a sorting process that screens out most of those who would question orthodoxy (Schmidt 2000). With modest changes, universities could implement requirements for every doctorate student to explore the history and sociology of science, presenting a balanced view of orthodoxy and dissent (Campanario & Martin 2004). The publication by Corredoira and Perelman (2008) titled *Against the Tide* would be an interesting place to begin. Perhaps such an effort could shorten the time constant for change in science represented by the famous comment of Max Planck: "A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it" (Planck 1949, pp. 33–34).

Perhaps the most important suggestion that I have for reducing excessive intellectual inertia is an appeal to scientists always to be mindful of the limitations of intellectual and observational endeavors and recognize the importance of some nonscientific principles. As a scientist I am painfully aware of how much I depend on the integrity of my colleagues. No scientist can personally verify all the evidence on which his or her concepts depend; that is, we trust others and a process, hoping biases and conspiracies are quickly exposed. We assume someone will check everything, but often, at least in some cases of excessive intellectual inertia, no one has actually carefully checked evidence. Thus, we scientists depend heavily on integrity, and believe that if virtually all of our colleagues do not have integrity the entire observationally based endeavor will collapse into chaos. Even innocent mistakes by colleagues with integrity can propagate for decades.

For example, in 1986 an instrument comparison prior to a large field experiment demonstrated significant differences in accuracy among commercial net radiometers (Field et al. 1992). For years, many micrometeorologists believed that uncertainty in net radiation measurements were primarily responsible for what was referred to as a "closure" problem, namely, the inability to get all the independently measured components of a surface energy budget to balance out to zero within estimated experimental errors (Culf et al. 2004). Eventually the contribution of errors in net radiometer measurements was shown to be much less in magnitude than closure errors (Twine et al. 2000). Even though many individuals knew net radiation measurements were not the culprit, and this was alluded to in publications, considerable effort was required to prove this unequivocally to the larger community. Most of this controversy, which persisted for about 15 years, arose from an innocent design flaw combined with a minor calibration anomaly in a single model of a popular commercial net radiometer that was relatively quickly corrected by the manufacturer. In this case, the intellectual inertia was fed by a community consensus that eddy covariance measurements of two of the four components of the surface energy budget were fundamentally superior to the measurements of net radiation and soil heat flux. If this kind of struggle can occur with a single innocent mistake, imagine what would occur if even 1% of researchers acted with maliciousness, or out of self-interest with no regard for integrity. The importance of integrity is one reason that researchers are generally not given even a second chance to redeem their reputations after a single serious error in the archival literature. In general, the scientific community is so aware of the importance of integrity that there is zero tolerance for perceived lack of it in a colleague.

A footnote on the use of eddy covariance techniques to measure environmental fluxes related to climate change seems in order here. Although eddy covariance measurements are now recognized to frequently and systematically underestimate surface fluxes in the energy balance, the intellectual inertia associated with this measurement technique persists in its application to net ecosystem exchange of CO_2, even though unacceptably large uncertainties remain.

The previous discussion emphasizes the importance of integrity among scientists. Integrity is difficult to define, and concepts that lack rigorous definitions are difficult for scientists to deal with directly. This is demonstrated by how quickly disciplinary tribunals and courts get involved in integrity issues with scientists. A visit to any dictionary will reveal why this word *integrity* is not easy to define. One quickly realizes that integrity has to do with honesty, honesty has to do with truthfulness, truthfulness has to do with honesty and morality, morality has to do with right and wrong conduct, and clearly we have run into the area that courts deal with in which the opinion of 12 people is used to decide who is honest. However, we know that the Scientific Method has nothing to do with opinions. Science has to do with agreeing with reality, but that is in the definition of truthfulness, too, and we know that each of us has our own truth and our own reality. Clearly we quickly get into circularity in the definitions and a quagmire ensues if we explore integrity deeply. Essentially, we rely on nonscientific human traits to conduct science; traits we all know when we encounter them and when they are absent, but we are challenged to define them.

My point in this digression is to emphasize that scientists should cultivate traits we refer to as virtues, namely, humility, kindness, patience, gentleness, tolerance, and self-control, which do not appear to be a part of the science itself. I hypothesize that practicing these and other virtues will optimize intellectual inertia in the application of the Scientific Method. A corollary to this hypothesis is that practices opposed to virtues, such as arrogance, intolerance, rudeness, and impatience will maximize intellectual inertia in the conduct of the Scientific Method.

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3 The Ethics of Soil

Stewardship, Motivation, and Moral Framing

Paul B. Thompson

3.1 Introduction

The occasion of an Organisation for Economic Co-operation and Development OECD conference on the ethics of soil is itself a remarkable event. For much of the last century, inquiry and decision making on soil largely became conceptualized as a technical discourse with no clear role for ethics. The causes of this trend could be traced in the way that various technical disciplines such as soil science, ecology, or economics have been institutionalized in universities, corporations, and government agencies. In each case, specialists working on aspects of soils or land management understood their work in classically positivist or value-neutral terms (Zimdahl 2007). There are often good practical reasons for *not* talking about ethics: Ethics involves surprising terminological complexity, and the possibility of unintentionally offending someone or stigmatizing their effort by raising questions about ethics discourages ethical discourse.

It should be obvious, however, that soil utilization, management, and conservation involve questions of the form “What should we do?” Such questions refer technical considerations to practical aims and directives. The practice of “ethics” is the attempt to express, specify, and justify human aims and aspirations. Thus, there are at least implicit ethical dimensions to be articulated in soil utilization, management, and conservation. Further discussion of the trend that led to a repression of ethics in technical disciplines would not contribute to a more positive reconstruction of these ethical dimensions. Yet because the ethics of soil have been neglected for so long, we are at a stage where the most useful task for a philosopher to undertake is simply one of providing an early and provisional inventory of the ideals or values that have and might reasonably be expected to be invoked in ethical inquiries centered on soil.

As argued in *The Spirit of the Soil* (Thompson 1995), the ethics of soil is often understood with reference to the idea of stewardship. Following this idea, the focus of the chapter will be to sketch a variety of ways in which ethical questions involving the stewardship of soils might be framed or characterized in ethical terms. We use ethical language—language stressing verbs such as *ought* or *should*—in a number of distinct ways that bear on soil management. In practice, this ethical vocabulary is probably nearly as variegated as are the relationships that human beings have to soils. Therefore, the task for this chapter is to develop a systematic frame for surveying this variety, recognizing that no succinct treatment can be fully inclusive of all variants. As such the task will be approached by considering the way that ethical considerations motivate action in three distinct contexts. First, there are clear cases in which management of the soils in question is understood to be the responsibility of a single individual. This is

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especially the case for many farmlands held as private property. There are also some complex cases in which soils are better conceptualized as a common pool resource, that is, as a resource or good used by many and managed, if at all, through voluntary or informal and traditional conventions. Finally, there are public policies that govern a wide variety of soil management practices, including those of private property owners, but whose ethical justification takes a somewhat different form than that of personal action. In each of these domains, three dominant modes of ethical discourse assert themselves: duties, virtues, and payoffs. An extensive review of the role that this three-way rubric might play in considering questions for international agriculture was published by Thompson (2008).

This chapter is organized with sections dedicated to each of these three ways in which ethics can be understood to motivate, rationalize, or justify behavior. These sections are followed by a fourth that discusses how soils have been understood to have ethically significant value in so far as they serve as important, and sometimes indispensable, means to the procurement of other goods deemed to be of fundamental ethical importance. Here soil is properly characterized as having *instrumental value*, that is, as becoming ethically significant because it is a tool or means to securing other goods. In such contexts, soil has ethical significance in a derivative sense. It is other goods or ends that are the primary target or bearer of ethical value, and soil derives its ethical significance from its contribution to the pursuit of these ends. A fifth section discusses some ways in which soil might be thought to have ethical significance in ways that cannot be easily reduced to an instrumental model. Here soils play more constitutive ethical roles. I will follow a common, but possibly misleading, practice among philosophers in referring to these as *intrinsic values*. Soils might be conceptualized as involving instrumental or intrinsic value in all three modes of agency discussed in the previous sections. The final section concludes with a few brief remarks on how soil researchers and concerned citizens might use these various moral vocabularies in taking further steps toward soil stewardship.

3.2 Private Property and Personal Ethics

Where soil stewardship is understood to be the responsibility and prerogative of a person who has the authority to make management decisions, it is common to understand ethics as encompassing motivations and considerations that oppose or constrain purely self-interested or self-regarding motives. Within such contexts, stewardship is the long-term or permanent responsibility to maintain soil quality, usually in reference to agricultural production, but potentially in reference to broader environmental or conservation goals. Stewardship is implicitly understood as an *ethical* responsibility when short-run profit-seeking behavior dictates practices contrary to long-term maintenance of soil quality. As Thorsten Veblen discussed in his classic book on absentee ownership (1923), business incentives do not always support the utilization of a resource that maximizes its long-run value. Ethics may, in such cases, dictate reasons why decision makers should act contrary to their personal, short-run interests.

There are at least three ways in which ethical considerations might be understood to motivate a constraint on profit seeking. First, soil stewardship may be understood as a moral duty. Duties may be understood as rules commanding specific conduct. Duties put forth on ethical grounds are presumed to override or countermand rationales, including profit seeking, that evaluate a course of action in terms of the outcomes that the action brings about. “The rule must be followed, whatever the consequences,” would be an extreme interpretation that nonetheless captures the essential spirit of conceptualizing stewardship norms under the concept of duty. However, there are many different ways in which the underlying moral force of a stewardship duty might be conceptualized. Classic religious treatments articulated stewardship as a duty to

God. In the Christian tradition, humanity was authorized to exercise dominion over God's creation, but human beings were understood to have a responsibility to administer this responsibility in a manner consistent with God's intention and God's judgment that the creation was good. More conventional secular treatments would articulate stewardship duties as duties to other people. One should not use one's soil in a way that could harm others, and one may have duties to conserve fertility that are owed to future generations. Finally, some have argued that humans should be understood to have duties to nature itself. This view was advanced in the eighteenth century by the German romantic philosopher Georg Friedrich Philipp von Hardenberg, who published under the penname Novalis (Gjesdal 2009). It is an approach that has gained popularity in recent years.

Second, stewardship may be readily conceptualized as a moral virtue. In this context, the motivation for stewardship would be for the person to fulfill standards of moral character taken to be indicative of a good or admirable person. Virtues are often taken to be characteristic of specific practices, professions, or ways of life. In this vein, stewardship virtues may be particularly characteristic of what is taken to be excellence in farming. Although duties may stipulate a specific form of conduct in a situation, virtues are more typically operationalized by asking oneself what some particularly well-admired person would do in a given situation. This practice may make virtues into a particularly effective motivator of action because one may feel a sense of shame or disgrace at failing to live up to the example of an admired role model, such as a parent, a mentor, or another person with whom one has had close association.

Finally, stewardship may be conceptualized as a form of saving either for one's own future benefit or for the benefit of future generations. This conceptualization of the ethical rationale for stewardship sees the benefit derived from good soil management in roughly the same terms as the benefit that would have been derived from the short-term profit seeking that stewardship is thought to constrain. The moral force of stewardship is to defer returns over the short term to ensure returns in the future. In emphasizing beneficial returns that accrue as a result of stewardship, this approach to the ethics of soil management applies a broadly utilitarian method of moral evaluation in which actions that are ethically justified maximize benefits for the largest number of affected people. These utilitarian connections make this outcome-optimizing way of addressing ethical concerns match up will with farm management approaches that have been developed by agricultural economists.

Any given individual may be motivated to some degree by any or all of these considerations, although one can imagine circumstances in which a utilitarian emphasis on maximizing benefits might pull in a different direction than the desire to live up to the model of virtuous conduct one associates with a revered figure. Academic philosophers have struggled to develop theoretical approaches in ethics that resolve or at least ameliorate such tensions. However, it is unlikely that tensions among competing moral frameworks will cause great consternation in circumstances in which a given individual truly is authorized to make soil management decisions according to their own lights. Most farmers have almost certainly felt the moral compulsion associated with one or more of these ways that an ethical norm of stewardship might be articulated at one time or another and have been more likely to experience doubt or tension when these principles oppose short-term profit seeking than when they oppose one another.

3.3 Common Pool Resources

Discussion of ethics in natural resource contexts often proceeds (as in the previous section) as if ethical norms impinge on decision makers as isolated and autonomous individuals who have full authority to use, conserve, or preserve the resource in question. The tradition of private property encourages this presumption. Nevertheless, a common pool management regime has been far more typical in human history. Here, the resource in question is used or drawn upon by a number of people, none of whom have the kind of control over the resource associated with fee simple property rights. When overuse of the resource has the potential to cause a decline in its productive potential, these users must collectively develop some mechanism for coordinating and governing their use. The classic example of the common pool resource was fisheries, although the model can be widely applied to many natural resource settings (Taylor 2005).

Common pool resource problems were introduced into ethics through the writings of Garrett Hardin, who described the basic problem as "the tragedy of the commons" and illustrated how it could be applied to frame ethical discussions of water use and global population growth (Hardin 1968, 1972). The model was also used to analyze the Dust Bowl phenomenon in the Great Plains of the United States during the 1930s. The Dust Bowl is one of the most thoroughly studied instances of a failure in soil stewardship. The extensive wind erosion of Great Plains soils are now widely understood to have occurred subsequent to overcultivation of soils that became vulnerable to winds during a predictable period of relatively low rainfall (Worster 1979). More effective soil stewardship would have prevented the crisis by limiting tillage (Faulkner 1943). The analysis that interprets this failure as an instance of the tragedy of the commons notes that although Great Plains lands were managed under a regime of private property rights, the adverse effects of wind erosion were experienced by all users, irrespective of whether they employed conservation tillage or not. As such, resource use was motivated by a "use it or lose it" mentality because farmers, even farmers who might have been personally inclined toward stewardship, could not expect others to curtail short-term interests for purely ethical reasons (Scherer 1983).

Hardin believed that there were essentially only two solutions to the tragedy of the commons. One was government regulation, which he referred to as "mutual coercion, mutually agreed upon." The other was more effective privatization, a strategy that would have been difficult to deploy in the case of the US Dust Bowl. In an extensive review of common pool resource studies since Hardin's pathbreaking work, Peter J. Taylor argues that in many instances, a community ethic has proved to be an efficacious alternative to regulation and privatization. Citing cases involving both fisheries and soil management regimes throughout the world, but especially in Africa, Taylor finds that ethical norms reinforce conservation behavior, provided they are coupled with institutions that provide for community monitoring of individuals' resource use and some mechanism of moral sanction for those who do not follow stewardship norms (Taylor 2005).

In many respects, the configuration of these moral norms is not different from the case of individuals who act on their own. Stewardship may be conceived as a duty, although in the case of a common pool resource regime, identifying the people to whom the duty is owed is usually much more straightforward; duties are owed to other users of the resource. Stewardship may also be conceived as a virtue. In the common pool resource case, this virtue can take the form of loyalty to the community of resource users or of solidarity among users. In both these cases, stewardship becomes aligned with straightforward ways to understand moral norms. The sense in which stewardship can be articulated as either a duty or a virtue is thus much clearer in the case of a common pool resource management situation than when soils are conceived as elements of private property. This would suggest that empirical work documenting the way that soil management reflects the structure of a common pool resource will be materially helpful in articulating and rationalizing stewardship.

It is the case of payoffs for stewardship in which the common pool setting makes a significant difference. Under the assumption that there are indeed common understandings of appropriate use and some mechanism for monitoring, the effect of a common pool management scheme is to dramatically alter the costs of inappropriate use. At a minimum, individuals who violate community norms will be subjected to forms of shunning and social exclusion. In some cases sanctions will involve fines, penance, or expulsion. The costs that are imposed on those who do not conform to community expectations bring purely self-interested decision making in line with a usage pattern more consistent with collective community welfare. Social sanctions thus alter the cost-benefit calculations performed by individuals.

The informal moral sanctions imposed in common pool resource regimes may be effective at regulating individual behavior, but they pose certain ethical problems of their own. One might question whether individual decision making made in an environment in which one expects severe disapproval from neighbors and peers if one deviates from their expectations is truly worthy of being characterized as motivated by ethical considerations. This is, on the one hand, a conceptual and philosophical worry that may provoke little interest on the part of someone primarily focused on appropriate soil management. On the other hand, there is a sense in which all ethical norms are socially reproduced through similar mechanisms of expectation and approval or disapproval. There are also cases in which social sanctions may reinforce discriminatory resource use or may seem to apportion access to a resource unfairly. Thus, it is entirely possible to subject informal social sanctions to the same type of critique associated with public policy (which will be discussed). Although it is worth taking note of these potential issues, pursuing them further would take the present discussion far beyond its goal of providing an initial inventory.

3.4 Public Policy

The language for characterizing and encouraging ethical motivations shifts again when a state agency is brought into the picture. Land-use laws and policies clearly constrain and shape individual users' conduct. Here, incentives and rationales for stewardship must blend with philosophies of state power, social justice, and regulation. One such philosophy holds that state power is justified only when it is sharply focused on protecting the liberties of individual citizens. This libertarian philosophy has been traditionally associated with the defense of private property rights and would be sharply critical of public policies that constrained a property owner's discretionary use of land or soil resources (Hospers 1971). A more utilitarian philosophy holds that state power should be utilized to promote the most extensive growth of net welfare or well-being for all citizens. "Net welfare" here implies that growth in welfare acknowledges both economic and more qualitative costs, including costs to future generations and sometimes even nonhuman users of a resource (Singer 1993). Each of these philosophies—and the universe of philosophies for use of state power can be extended considerably—suggests different limits on and purposes for the use of the state's regulatory power to incentivize soil stewardship.

The libertarian approach to state power is a good example of a political theory that conceptualizes the problems of public policy in terms of rights and duties. Individuals have moral duties not to harm others, and the state is justified in using its monopoly on the use of coercive violence just in case it is enforce those duties. Otherwise, the state should not intervene in the life of its citizens. The utilitarian approach, in contrast, is one that evaluates policy in term of the payoff, in terms of its additive effect on the welfare of all parties affected. As such, we again see the pattern of one moral vocabulary articulated in the language of duty and a second articulated in the language of optimizing impacts on health, wealth, and well-being. Are there parallel arguments at the policy level that would justify the application of state power in terms of its cultivation of the virtues?

One noteworthy characteristic of contemporary political discourse is that this type of argument has come to be viewed as quite problematic, especially in western liberal democracies. It is clear that promotion of virtues *has been* a politically persuasive rationale at various times in human history. Speaking specifically about soils, native lands and soils have been claimed to have special significance for fixing the identity and spirituality of a nation, as will be discussed at greater length. Thomas Jefferson famously favored policies that promoted the growth of farming on the grounds that farmers make the best citizens (Thompson 2000). Yet the idea that governments go too far when they base policy on a particular characterization of the type of life that an individual should lead is also a principle that many contemporary historians and political theorists trace to Jefferson, as well as, to many figures in the modern social contract tradition of political thought (Kloppenberg 1987; Nussbaum 2006).

More extensive development of the relationship between ethics and public policy must await a venue that affords more opportunity for expansive discussion than the present chapter. It must suffice to emphasize two points in closing this section. First, the rubric of duties, virtues, and payoffs continues to be a handy way to frame the array of moral arguments available for advocating and specifying an ethic of soil stewardship. Political theories of the state's role have in fact drawn upon each of these three traditions throughout human history. As such, people coming to the discussion of soil ethics without the benefit of extensive background in ethical theory will find it useful to think with this three-way scheme as they summarize moral arguments on soils, whether the argument applies to personal actions undertaken by individuals, common poll resource management schemes, or public policies. Second, it is important to be aware that linking soils to virtue and notions of community has been exceeding problematic within the domain of political philosophy. An expanded discussion of the philosophy behind this tradition follows, yet within the domain of political theory, the idea of soil as a contributor to national identity has become difficult to defend. The title of a recent book by Ben Kiernan says it all: *Blood and Soil: A World History of Genocide and Extermination from Sparta to Darfur* (2007).

3.5 Instrumental Values of Soil

Given the significance attached to the rubric of duties, virtues, and payoffs, it will be useful to take a second look at the way that soils might be characterized as having ethical significance in each approach, irrespective of the situation in which agency or action is motivated. Soil is a medium that is material to, and in many cases, essential for, obtaining and securing access to a plenitude of things that have been alleged to have moral significance. A full map of this plenitude promises to retrace the entire history human civilization, so any succinct inventory is necessarily selective and open to further elaboration. In constructing such a selective mapping, it may be useful to do so by emphasizing the distinct ways that valuable things have been understood to be of ethical significance. Perhaps the most obvious starting point here is the role of soil in agriculture. Humans have long understood that, along with climate and landscape properties, soil types determine whether a given plot of is useful for planting crops or grazing animals. Civilizations that have depended on agriculture thus come rapidly to have somewhat sophisticated understanding of soil capabilities simply because they recognize the contribution of soil to their ability to obtain food.

Food is ethically significant because it is necessary for human survival. Humans engaged in active pursuit of their survival have not generally paused to peruse the abstract philosophical question of whether their survival is ethically significant. Yet human survival has been recognized as ethically significant, even in circumstances in which particular individuals or groups sacrifice their own survival or threaten that of others. However, there are different ways to express the importance of survival. One is to see survival as a component of overall welfare, and goods such as food and in turn soil are understood to be seen as deriving their ethical significance in terms of their ability to make positive contributions to welfare. The notion of welfare can itself be unpacked and specified in various ways, and there has been a recent and important shift away from indicators of welfare that stress economic indicators such as gross domestic product and toward indicators organized around human capabilities.

This shift was inaugurated by the work of Nobel laureate Amartya Sen (1999). Sen's emphasis on capabilities has been described as an important modification of the utilitarian tradition in ethics. Classical utilitarian ethics understood welfare narrowly in terms of human satisfaction, an idea that Jeremy Bentham, one of its most influential proponents, formulated in terms of pleasure and pain. On this utilitarian view, food is important because having it yields satisfaction, whereas not having it results in the pain of hunger and deprivation. Food itself is of instrumental value in this utilitarian view, but soil follows along quickly in virtue of the fact that soils are, in many civilizations, of direct relevance to obtaining food.

Critiques of utilitarianism emphasized the importance of freedom. Utilitarians conceded the point that having certain political and economic freedoms was important, but they believed that their importance was grounded in instrumental considerations not unlike those just outlined in connection with food and soil. That is, freedom is ethically important because people who have political and economic freedoms are better able to secure their own satisfaction and avoid pain. Opponents of utilitarianism challenged this claim for reasons that, although extremely important, are less germane to the ethics soil than is the simple fact that they took freedom to be a more fundamental articulation of the ground for ethical value than welfare. This led them to conclude that sacrificing the freedom of one person for an improvement in the welfare of another person was ethically unacceptable (Nussbaum 2000).

In the West, opponents of utilitarianism tended to formulate ethical norms in the language of rights. Thus, the moral significance of food would be articulated as a right to food, a right that is, indeed, included in the Universal Declaration of Human Rights. Sen's work has created something of a watershed in recent thinking on international development because he has succeeded in convincing many that a focus on achieving human capabilities successfully negotiates much of the tension between utilitarian conceptions of development ethics that focus on welfare and conceptions that focus on rights. Sen conceived of the ethical importance of food as an entitlement that might be satisfied either by having the ability to produce food or by having the economic or political capability to ensure access by other means (Sen 1999; Crocker 2008).

These points become important in the present context because in a world in which 98% of the population secures food by subsistence hunting, fishing, farming, or animal husbandry, direct access to the biologically productive capacity of nature is critical. One way to articulate this criticality is to emphasize a notion of property or property rights. Here, the idea of a right to food is taken a step further, and the important rights claim would be expressed as a right to access or use the basic productive capacity inherent in soils. This has been more traditionally expressed in various agrarian reform movements as a right to land. The new focus on capability may be helpful in turning our attention to what is of underlying ethical significance in these claims, which is each human being's ability to secure basic needs in a self-reliant manner. Some means of material self-reliance is important for freedom because a person who relies on others in a subservient way is not really free.

The upshot is that multiple ways of articulating the moral significance of food extend naturally to soil. The capabilities approach may well be the most sophisticated way to adjudicate this moral complexity. Nonetheless, it is important to recognize two things. The first is that ideas such as property rights, welfare, and rights to food or land do not disappear overnight. These ways of conceptualizing the ethical significance of the human species' dependence on the biological productivity inherent in soil will be with us for some time, however promising the turn to capabilities might be for articulating these ethical terms in more appropriate language. The second is that for all of these notions, welfare, freedom, property rights, or capabilities, soils are of ethical significance because they are seen as an indispensable means to achieving or securing an underlying ethical good of importance to human beings.

This does not exhaust the sense in which soils can be understood to have instrumental value. Many would assert that the Earth is not of value solely in virtue of its capacity to serve the needs of human beings. It is clear, for example, that many other animals are capable of experiencing satisfaction as well as suffering or pain. It is thus logically straightforward to extend much of the argumentation just sketched so that soils are of instrumental value to nonhuman animals. It is also possible to argue that life itself is what is of ethical significance, whether we understand life in terms of individual organisms, colonies of diverse organisms, or larger assemblages such as species or ecosystems. As the properties of soil contribute to the maintenance of life at all these levels, soils can be understood to have instrumental significance in terms of the role that they play in supporting life. Thus, soil can be understood to have one kind of instrumental significance in ethical systems that are anthropocentric (that is focused on benefit to human beings), although this significance can be considerably broadened when ethical ideals are understood to articulate nonanthropocentric concerns.

3.6 Beyond Instrumental Value

When it is the life process that is understood to have moral value, it is only a short step to valuing soils in something other than a strictly instrumental sense. An ethic that understands the preservation or continuance of the life process as embodied not simply by individual organisms but also in the ensembles represented by breeding populations of organisms or the interaction of multiple populations in specific regions begins to challenge the instrumental conceptualization of value. Because soils are essential components of terrestrial ecosystems, they can be understood to have value as functional components of these systems. To the extent that soils are critical to maintaining the functional integrity of a local, regional, or planetary ecosystem, one can understand them as constituting elements in the identity of the ecosystem. As such, they seem less to serve as means for a logically independent and well-defined notion of value and come to be seen as having value in themselves.

It is notoriously difficult to defend such a conceptualization of value. Some of the difficulties have nothing to do with environmental values or soils. They reside in the way that we articulate and defend value judgments. For example, when we say that an individual human life has intrinsic value, do we deny that the person's life is instrumental to his or her having pleasurable or rewarding experiences? And what of experience itself? Are the satisfying experiences valuable in themselves or only insofar as they contribute to the development or a personality or integrated self? In asking such questions, we find ourselves embroiled in philosophical conundrums that have occupied humanity for millennia. The point here is simply to note that detailed attempts to apply a distinction between instrumental and noninstrumental value rapidly become embroiled in puzzles and the logical problems of infinite regress. This has not deterred humanity from asserting that some things have value not simply in virtue of their function as means but in ways that terminate means-end inquiry through the assertion of intrinsic value.

A great deal of ink has been spilled debating notions of intrinsic value in environmental ethics of the last 40 years. The assertion that nonhuman animals, plants, species, or ecosystems have intrinsic value is in every case intended to state that the value humans derive from using these items is not the sole source of their moral significance. Most assertions of intrinsic value are also intended to imply that humans have moral obligations to respect or preserve whatever has been said to have intrinsic value. These obligations are not typically understood to have absolute overriding significance. That is, there will be cases in which intrinsic values must be sacrificed, although an advocate of intrinsic value will assert that this sacrifice must be justified through moral deliberation and that there are some cases in which these intrinsic values override uses that human beings might make of organisms or ecosystems as natural resources.

However, the array of arguments and descriptions of how we should understand and identify intrinsic values in nature is overwhelming. Some point to features, such as sentience or life, shared by individual human beings, whereas others stress complexity or autopoesis. The philosopher Wilfrid Sellars argued that intrinsic values mark the boundaries of community. To say that a value is intrinsic is simply to say that it determines or informs aims and purposes in ways that would not be subjected to challenge or question by members of the community in question. To challenge such a value is to mark oneself as outside the community. Adapting the thought of Immanuel Kant, Sellars believed that language itself pointed toward a notion of community among all human beings, but this does not exclude the possibility of constructing shared commitments that extend beyond other human beings through discourses of shared memory, hope, and fate (Sellars 1980). The environmental philosopher Mark Sagoff (2008) has argued that this approach allows us to see conversations and debates that are committed to an articulation and defense of environmental aims and purposes as contributing to the community building needed for political action in pursuit of environmental aims. Sagoff's approach provides a "big tent" for including many proposals for articulating the intrinsic value of nature, while acknowledging the need for further clarification and defense of any particular proposal.

Sagoff's approach to intrinsic value is particularly useful in the present context because it allows us to both acknowledge and then move beyond an exceedingly abstract philosophical debate about the ethical significance of living processes and ecosystems in general and to consider briefly how soils in particular might be said to have more than instrumental value. As examined at length in Clarence Glacken's classic text, *Traces on the Rhodian Shore* (1967), soils have long been thought to play a role in the constitution of human cultures and associated notions of identity. People around the world have understood themselves and their cultures to have sprung from the soil. They express indebtedness to their lands not simply for the provisions that are brought forth but for endowing them with their peculiar character and bestowing upon them the way of life that gives meaning to their daily activities. The spiritual quality of such language may or may not be intertwined with the language of divinity and religious faith.

As noted, modes for expressing indebtedness or fealty to native soil are diverse. The often poetic language can be brought somewhat in line with more conventional ethical discourse by stressing the way that conditions of material production shape the routines of daily life. The German philosopher G. W. F. Hegel believed that the soils and topography of the Peloponnesian peninsula lent themselves to modes of production that were singularly conducive to a culture organized around the ideal of citizenship. The rough terrain was not amenable to the types of irrigated agriculture characteristic of Asia and the Nile Valley, but the sandy soils and Mediterranean climate were conducive for agricultures with tree and vine crops supplementing annual plantings of cereals. This farming system could be undertaken by a household-scale labor force. In contrast, irrigated agricultures of the ancient world required the coordinated activity of many slaves overseen by a managerial authority invested in the royal house or the priesthood. In contrast, farming in Ancient Greece created a society of semiautochthonous households, bound together into a local economy of craftwork and self-defense. As expressed by philosophers such as Xenophon and Aristotle, householders were bound to the polis through transparent mutuality of interest, making the family unit the foundation of Greek politics. Hegel argues that as a result of their farming systems, the Greeks were the first people to understand themselves as having a political identity capable of inspiring loyalty or concern for a shared fate. Once exemplified in Greek culture, the ideal of citizenship could spread elsewhere, but it required, in Hegel's view, the unique soils of Greece for its original emergence (Hegel 1900 [1956]).

Soils play complex roles in this philosophical account. First, because soils dictate a pattern of subsistence practice, they serve as a reinforcement mechanism for habits. Second they play a formative role in constituting the ideal of citizenship in Hegel's account of history. Third, farmers working in this system come to see citizenship as a moral virtue. Finally, because their habits of practice are fixed by their farming activity, citizen farmers cultivate a virtuous moral character at the same time that they cultivate their soils. The belief that a life of farming determines one to develop virtues and constrain vices is widespread throughout world cultures, having expression in Chinese thought (Fung 1997) as well as being strongly associated with Jefferson's understanding of democracy.

As noted previously, there are many qualifiers that must be added to these remarks. The ideal of native soil has been associated with xenophobia, whereas blood and soil visions of culture have been responsible for some of the most repressive political regimes in human history. Here as throughout all the remarks, to note that a particular value ideal is associated with soil does not mean that the ideal should be granted an unqualified endorsement. Any appropriation of the links between soil, virtue, and cultural identity would require considerable discussion and refinement. However, it is important to stress that in taking soil to play a constitutive role in the formation of personal or social identities, one undercuts the usual understanding of instrumental value. To say that a good has instrumental value is to say that it is useful in procuring some other aim that has been conceptualized as the end in view. This, in turn, implies that one acts out of an identity that is more or less well-formed. Constitutive values, in contrast, are the basis for identities. They cannot be chosen or desired because they are the foundation of the habits, preferences, and self-understanding that are the prerequisites of desire.

3.7 Conclusion and Next Steps

The two preceding sections show how the ethics of soil can be given a preliminary formulation by noting two broad categories. In the first, soil is thought to have ethical significance in virtue of its use in procuring or providing goods that are of more fundamental moral importance. Food for human populations is the most obvious such good, but soils are necessary to sustain life processes for nonhuman populations, as well. One might articulate a standard for soil ethics of the form: soils should be managed so as to promote the realization of human capabilities by all persons. Given such a standard, one could propose indicators informed by empirical science. But an alternative standard might require balancing human flourishing against the preservation of nonhuman populations or ecosystems. Such a standard would require different indicators and tests. How does one resolve the tension between these standards? Rather than answer this question directly, I would point out that it, too, is a question of the form: How should we act? It is a question that can be informed by philosophy, as well as by inclusive debate. At some point, one must act. Yet having worked through the philosophical questions will at least put agents in a position to learn collectively and cumulatively, if only because standards will have been articulated explicitly.

The second broad category of soil ethics includes ways in which soil might be seen as an integral component in systems that encompass the process of valuation, as opposed to being the object valued. Here, too, there are a number of ways to proceed. On one hand, one might stress the inequity of a local, regional, or even planetary ecosystem. On the other, one might note how soils are thought to function as constitutional components of human personality or culture. Either approach might lead one to a precautionary ethic in that the standing ecosystem or traditional practices would be endorsed for having made us who we are as moral agents. Even those who would press forward with an ethic more oriented to what we might become would be advised to acknowledge the way that constitutional values create special burdens of proof for those who would advocate change.

These two approaches to the ethics of soil can be interwoven with the previous discussion of stewardship and the motivation of ethical behavior. Within the context of personal action in which an individual regards himself or herself as having moral authority to undertake choices, a decision maker will generally understand ethics as informing possible goals or aspirations beyond those of pure self-interest and as placing constraints or brakes upon his or her pursuit of self-interest. Within this context, ethical norms may be formulated in terms of duties, virtues, or outcomes understood as "payoffs" or effects upon the health, wealth, and well-being of oneself and others. Soils will most frequently be seen as instrumental to securing goods such as food or imposing harms such as in the case of downstream impact from erosion. The benefits and harms of soil use are easily integrated into the payoff assessment and may also be conceptualized as material to the execution of key moral duties. The activities of producing these goods may also be reflected in a given conceptualization of virtue.

This overall structure remains intact as one moves into the consideration of common pool resource management and public policy. Duties and virtues are, in fact, brought more clearly into focus when soil usage is conducted under a common pool resource management scheme because the identity of the people to whom duties or loyalties are owed becomes more clearly fixed. Common pool resource schemes reinforce payoffs to individuals by adding social sanctions to inappropriate resource use. As one shifts to a public policy context, the instrumental use of soil can be readily integrated into duty/rights based political frameworks, as well as into the cost-benefit style of public policy evaluation associated with utilitarian philosophy. Virtue arguments that appeal to the intrinsic values of soil are widely viewed as problematic in political philosophy, especially in light of the abuse that these argument forms have suffered during the twentieth century. Nonetheless, these arguments may still have persuasive power, especially for individuals who see their own traditions and identity closely tied to farming and soil stewardship.

Every particular of the foregoing discussion can and should be subjected to significant elaboration and debate. It is, in fact, through public discussion and debate of ethical rationales that a critical dimension can be attached to the inventory of moral concepts surveyed. The most humbling lesson to be taken from a review of the ways that soil might be thought to have ethical significance is to be found in the care and attention that was lavished on this question by sages of the past. Although we should not suppose that they have the final word on soil conservation and management, the relative lack of attention to the ethical dimension of our own approach to preservation or utilization is evident by comparison. Scholars and technocrats alike require a more subtle and more complete inquiry into the ethics of soil than any single event can hope to provide. Let us hope this is only the first step.

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4 Aldo Leopold and the Land Ethic

An Argument for Sustaining Soils

Susan L. Flader

4.1 Introduction

Aldo Leopold (1887–1948) is best known for his concept of a land ethic—a conviction of personal responsibility for the health of the biotic community, including soils, waters, plants, and animals as well as people. But what has not been widely recognized is the extent to which his conviction of the need for a land ethic grew out of his scientific interest in soil systems and his concern about the integrity of watersheds.

This chapter explores the relationship between Leopold's lifelong observations and reflections on the problems of soil erosion and soil productivity and the evolution of his land ethic philosophy. It considers also the role of his thinking about climate change, landscape ecology, and ethics in the shaping of his ideas about public policy. With his remarkably integrated contributions to scientific analysis, land management, public policy, and environmental ethics, all grounded in his concern about the sustainability of soils, Leopold is a lodestar for the twenty-first century.

4.2 The Shaping of a Progressive

Leopold began his career at the height of the Progressive Era in the United States (Minteer 2006). The eldest son of a civic-minded German family in Burlington, Iowa, he was educated at Yale University during the administration of Theodore Roosevelt, whose presidency best exemplified the progressive ideals of order, efficiency, control, and administration by scientifically trained professionals. "The first duty of the human race is to control the earth it lives upon," wrote Roosevelt's friend Gifford Pinchot (1910), under whose leadership the US Forest Service was established in 1905 and became the quintessential progressive federal agency (Hays 1959). On earning his master's degree from the Pinchot-endowed Yale Forest School in 1909, Leopold joined the fledgling service as one of its early elite professionals, already fully imbued with progressive ideals.

He was assigned to lead a reconnaissance crew mapping and cruising timber along the route of a proposed logging road through the remote Blue Range of the Apache National Forest in eastern Arizona Territory (Fig. 4.1). "This fool mountain road" he called it in a letter home to his mother, saying he was eager to handle "the big 15-million timber sales" but he had some figures on the road that would make his superiors "squirm" (Leopold 1909). The road would have to clamber up and over the precipitous Mogollon Rim, where it would be passable only

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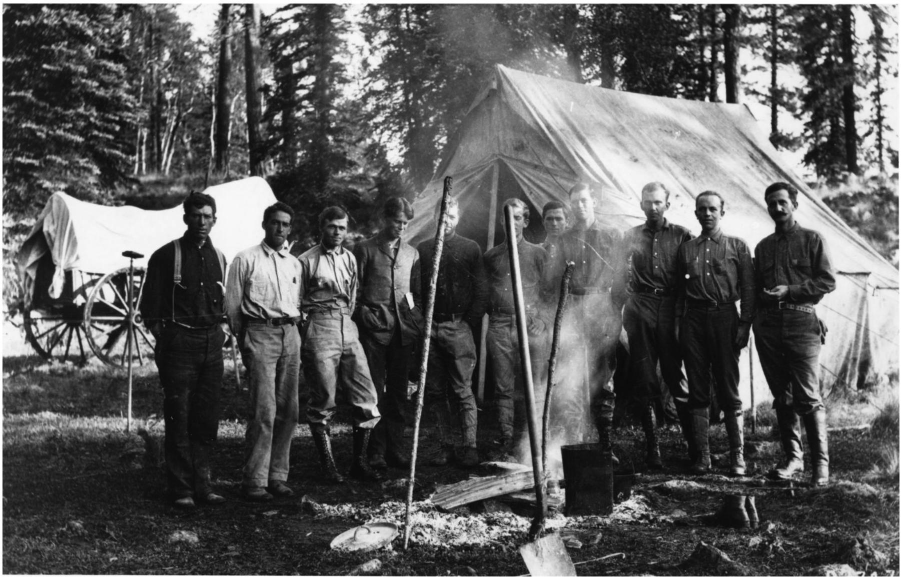

Figure 4.1 Aldo Leopold (*second from right*) and his reconnaissance crew on the Apache National Forest in Arizona Territory.
Courtesy of Aldo Leopold Papers, University of Wisconsin Archives, with permission of the Aldo Leopold Foundation.

a few months of the year because erosion and repeated flooding had torn out the more logical route up the valley of Blue River, which Coronado had likely followed. Leopold and his colleagues recommended against the road (Adams 1909). But less than a decade later, it would be the first road in the nation funded under the Federal Aid Road Act of 1916, and from its completion in 1926 it would be known, ironically, as the Coronado Trail (Bates 1978).

By then, Leopold had had an array of new experiences and ample time for reflection. He had been assigned to a new forest, the Carson in northern New Mexico, where he achieved by age 25 his life's ambition to be a forest supervisor. He had married Estella Bergere of a prominent Hispanic family in Santa Fe, then fell critically ill from exposure during a long horseback trip to examine disputes on the degraded ranges of the Carson, and spent 18 months recuperating back home in Iowa. During this time he could do little but read and think. A letter (Leopold 1913) to his fellow officers of the Carson suggests he was beginning to question simple reliance on the uniform regulations and procedures prescribed in Pinchot's little green *Use Book*. He argued instead for measuring the success of forest management by "the effect on the forest" as determined by careful observation and monitoring of conditions on the ground.

When he was able to return to the Southwest, his health was still so precarious that he had to settle for a succession of desk jobs at the district headquarters in Albuquerque, first in grazing, then in the new field of planning recreational uses, and the even newer field of game management, which he is credited with having established on the model of professional forestry (Flader 1974; Meine 1988). His efforts to organize citizen-based game protective associations in communities throughout the Southwest even won an enthusiastic letter of commendation from his hero Theodore Roosevelt (1917). During World War I he left the service for a time to become the first full-time executive secretary of the Albuquerque Chamber of Commerce, where he led a number of progressive civic endeavors. But after the war he returned to the

Forest Service as assistant district forester in charge of operations, with responsibility for business organization, personnel, finance, roads and trails, and fire control on 20 million acres of national forests in the Southwest. In this role he would make frequent inspections of forests and ponder the implications of what he was seeing on the ground.

4.3 Erosion as a Menace

Although Leopold's initial inspections tended to focus on the efficiency—and the *imagination*—of personnel, and on plans for fire control and other administrative matters, by the time he revisited forests along the Mogollon Rim, where he had begun his career, his attention was drawn increasingly to the condition of ranges and watersheds. The rim extended from the Prescott Forest north of Phoenix southeasterly through the Tonto, Coconino, Sitgreaves, and Apache forests of Arizona to the Gila in southwestern New Mexico. From the Prescott, he wrote to his mother, "I have a new hobby. I am seriously thinking of specializing in erosion control. The problem is perfectly tremendous here in the Southwest, and I seem to be the only one who has any faith in the possibilities of tackling it successfully" (1920a). His report (1920b) advocated starting "*actual work* on erosion" rather than waiting for further studies, and he outlined several demonstration projects.

In January 1921, he spoke on "Erosion and Prosperity" at the University of Arizona, arguing that soil was fundamental to prosperity: "All natural resources, except only subterranean minerals, are soil or derivatives of soil. Farms, ranges, crops and livestock, forests, irrigation water, and even water power resolve themselves into questions of soil. Soil is therefore the basic natural resource" (Leopold 1921a). And in March he published his first article on the subject, "A Plea for Recognition of Artificial Works in Forest Erosion Control Policy." Here he argued that the standard approach of redistributing livestock numbers was not adequate: "Our function is not to prove the infallibility of our initial forest policies, but to conserve the Forests" (1921b).

When he inspected the Apache later that spring, he noted with dismay the degradation that had occurred since he rode the ranges in 1909–1910. Formerly grassy parks were now bare or mostly weeds, and he described the contrast along the Apache Indian Reservation fence line as "painful and humiliating." He calculated in detail the losses in acreage and economic value from bank erosion along Blue River, where less than 15% of the formerly cultivable land remained (1921c, pp. 29–30, 33). As he knew only too well from his years on the Apache, the arable land in the small valleys was absolutely critical for sustaining families and livestock year-round throughout the forest and its high country ranges.

In other speeches and articles at the time, most notably a 1922 address to the New Mexico Association for Science on "Erosion as a Menace to the Social and Economic Future of the Southwest," Leopold presented the results of his ongoing tally of the status of erosion in tillable mountain valleys in the national forests, many of which were already ruined or partly ruined (of 30 valleys tallied, only 3 remained undamaged). In each he focused in particular on the Apache where he had begun his career:

> We the community have "developed" Blue River by overgrazing the range, washing out half-a-million in land, taking the profits out of the livestock industry, cutting the ranch homes by two-thirds, destroying conditions necessary for keeping families in the other third, leaving the timber without an outlet to the place where it is needed, and now we are spending half-a-million to build a road [the new Coronado Trail] around this place of desolation which we have created. And to replace this smiling valley which nature gave us free, we are spending another half-a-million to reclaim an

> equal acreage of desert in some place where we do not need it nearly as badly nor can use it nearly so well. This, fellow-citizens, is Nordic genius for reducing to possession the wilderness (Leopold 1946, p. 629).

As before, he advocated Forest Service demonstration projects, but here he noted especially the responsibility of private landowners to install erosion control on their own land. "The day will come," he forecast, "when the ownership of land will carry with it the obligation to use and protect it from erosion so that it is not a menace to other landowners and the public" (1946, p. 631). He also decried "the competitive overgrazing of the unreserved public domain," arguing that such land must either "pass into private control and be fenced and decently used, or it must be regulated by its present owner, the national government" (1946, p. 632). The speech was not published at the time, but in 1946 it was submitted to the *Journal of Forestry* by Leopold's former Yale professor H. H. Chapman, who called it "the first statement by a member of the profession of forestry, so far as known, which called attention to the magnitude and seriousness of soil erosion in the … fertile valleys in the arid Southwest" (Leopold 1946, p. 627).

4.4 Standards of Conservation

Leopold had demonstrated the reality and the economic consequences of erosion as well as some techniques to address it, but he still did not fully understand the *processes* at work. Then during the summer of 1922, he spent six weeks studying fire problems on the Gila (and, incidentally, developing his celebrated proposal for management of a half million acres as a roadless wilderness area) and another month again inspecting the Prescott, during which he rode for weeks through remote country, discussed observations with other foresters, and ruminated at length on the problem. Prescott supervisor Basil Wales and his rangers thought the grass cover had always been thin on the forest's granitic soils and assumed that continued heavy grazing was necessary to reduce the fire hazard of the encroaching brush, but Leopold saw evidence in the fire scars of scattered ancient juniper stumps to conclude that fire had been a recurring feature of the virgin landscape; from this he surmised that the grass cover had once been much heavier and the brush thinner, as in fact described by old-timers. In his view, it was overgrazing and trampling by cattle that had thinned the grass, thus inhibiting fires and initiating both brush encroachment and destructive erosion. His interpretation (1922a), particularly as to the benign role of fire and the value of grass over brush or trees in holding soil, flew in the face of virtually the entire corpus of scientific dogma in the Forest Service of his day.

Even more important, the differences in interpretations made him question how to determine the objectives of management on a particular forest (what he termed "standards of conservation"). As he explained, "If the prime objective is wood products, we may continue to overgraze, letting in the woodland and sacrificing watershed values. If on the other hand the prime objective is watersheds [the purported objective on forests along the Mogollon Rim], we should restore the grass" (1922a, p. 27).

In a handwritten fragment titled "Standards of Conservation" (1922b), he noted that standards were nothing new to the service, but they had heretofore been "machinery standards" applied to administrative procedures rather than addressing what he had years previously called "the effect on the forest." Who and how to determine the desired future condition, of course, was the problem. Leopold recognized that certain unlettered individuals seemed to possess "natural skill" in diagnosing conditions, but here he looked to "the highest order of skill … [by] only the highest authority." His paper ended in mid-sentence on the quandary, as if he realized he did not yet have a satisfactory answer. In retrospect, we can see that he was grappling with some of the very issues that would bedevil restoration ecology and ecosystem management three-quarters of a century later.

Nevertheless, he devised and implemented a detailed system to monitor and facilitate comparisons year by year of conditions on the ground, including the presence or absence of species that *should* grow there. His new system of inspection won high praise from his superiors in Washington, and Leopold himself considered it "one of the two or three points" in his US Forest Service career that gave him the most satisfaction (1924b). His commitment to restoring natural communities in the working forest through management, his willingness to experiment and learn from experience, and his insistence on systematically monitoring changes on the ground year to year are traits that would lead philosopher Bryan Norton (2005, p. xii) to call him "the first adaptive manager."

4.5 Conservation as a Moral Issue

Leopold would devote much of the remainder of his career to working on the objectives of conservation, a quest that would involve philosophical as well as scientific and policy issues. In each of his key efforts to articulate his thinking, he would begin with the problem of sustaining soils and soil productivity. His philosophical exploration began with a paper found in his desk after his death, "Some Fundamentals of Conservation in the Southwest," in which he analyzed the deterioration of organic resources in the Southwest, especially soils (Fig. 4.2). In his search for causes he considered at some length "whether we are dealing with an 'act of God,' or merely with the consequences of unwise use by man" (1923a, p. 89). After reviewing the evidence from tree rings, archaeology, and vegetation distribution, he concluded that the climate in the region had been generally stable for the past 3,000 years. Droughts and floods were recorded in the rings, but he saw no evidence of long-term climate change, so he concluded that the recent disequilibrium in the delicately balanced arid environment resulted from unwise use. This led him to discuss "conservation as a moral issue." Some three-quarters of a century later, scientists would indeed find evidence of climate change, which many would interpret as anthropogenic—something unthinkable in Leopold's day; but if he had foreseen the future direction of climate science, his moral argument would still have been appropriate.

Having previously written about "the forestry of the prophets," Leopold began his discussion of morals with the prophet Ezekiel's scorn for human-induced pollution and erosion, concluding "it is possible that Ezekiel respected the soil, not only as a craftsman respects his material, but as a moral being respects a living thing." "Many of the world's most penetrating minds"—here he cited the Russian philosopher Ouspensky—"have regarded our so-called 'inanimate nature' as a living thing," he explained, then observed: "Possibly, in our intuitive perceptions, which may be truer than our science and less impeded by words than our philosophies, we realize the indivisibility of the earth—its soil, mountains, rivers, forests, climate, plants, and animals, and respect it collectively not only as a useful servant but as a living being." He would not dispute the anthropocentric religions or sciences, but "granting that the earth is for man–there is still a question: what man?" Cliff dwellers, Pueblos, and Spaniards had "left the earth alive, undamaged." In his view white Americans had a moral obligation to pass it to their successors unimpaired (1923a, pp. 94–97).

Leopold sent the paper to several colleagues for their critical review. Most were complimentary, but one, M. M. Cheney, probably spoke for many watershed specialists when he argued that Leopold had overdrawn the destructiveness of erosion. Cheney viewed erosion

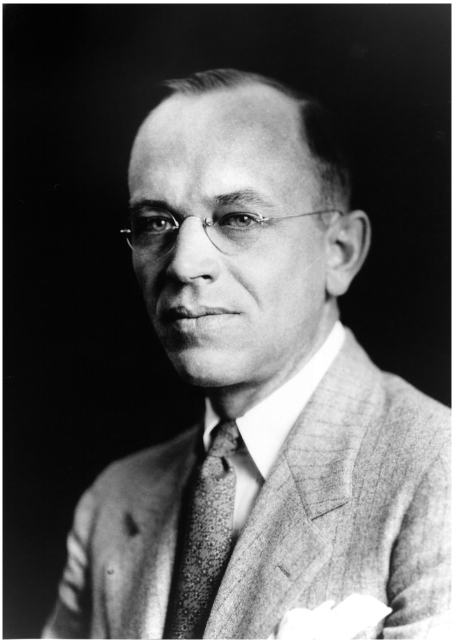

Figure 4.2 Aldo Leopold, 1920s.
Courtesy of Aldo Leopold Papers, University of Wisconsin Archives, with permission of the Aldo Leopold Foundation.

as an ongoing geologic process, "a world-building factor" that would ultimately smooth the rough uplands of the Southwest and create more agricultural land, and he questioned whether the white man had caused any great increase in erosion. This was in essence the classic geomorphological theory of William Morris Davis, who described the stages through which mountains are uplifted and eroded to peneplains. Leopold undoubtedly knew all that, but he also understood that there were other ecological processes involved, and there is evidence here and there in his writing that he was frustrated by the unwillingness of many of his colleagues to recognize any responsibility on the part of the Forest Service to deal with the problem (Flader 1979).

Later that spring, however, Leopold won a measure of support from Evan Kelley of the Washington office during an inspection of district operations. Where two years previously Kelley (1921) had said Leopold "moves along with his feet somewhat off the ground," he was now highly complimentary of Leopold's systematic attention to detail and thought he was on the right track with respect to erosion: "Leopold is not seeing bugaboos. He is not pointing out a vacant foreboding.... Now is the time for the Forest Service to open its eyes to facts and come out squarely and confess whatever responsibility the Service might have for present conditions due to injudicious range management" (Kelley 1923, p. 58).

For whatever reasons, Leopold decided not to publish "Some Fundamentals" and, indeed, it would be another decade before he would publish anything on conservation as a moral issue. But despite Cheney's criticism of his treatment of erosion—or perhaps because of it, coupled with Kelly's support—he turned later that year, after yet another illuminating inspection of the Tonto Forest near Phoenix, to preparation of a "Watershed Handbook" (1923b) for the Southwest. It was recognized by the Washington office as the first of its kind and a model for other districts. Although he had previously emphasized artificial controls, Leopold was now trying to teach personnel to focus on the overall condition of vegetation on the watershed—a significant step, in effect, toward development of standards of conservation. Where foresters typically focused on the commodity values of cattle and timber, Leopold was thinking of the whole system.

Then, in 1924, he drew together all he had learned from his studies of forests along the Mogollon Rim to publish one of the most penetrating analyses of his career, "Grass, Brush, Timber, and Fire in Southern Arizona," which is still recognized as an ecological landmark. "Fifteen years of forest administration were based on an incorrect interpretation of ecological facts," he boldly asserted, "and were therefore in part misdirected" (1924a, p. 119).

4.6 Wildlife and Soils

By the time "Grass, Brush, Timber and Fire" appeared, Leopold had left the Southwest for Madison, Wisconsin, to become associate director of the Forest Products Laboratory, then the principal research arm of the Forest Service, with the expectation that he would soon become director. He was offered the post owing to his intense interest in scientific research, but he must surely have felt constrained dealing with industrial products when everything about him made him interested in the forest as a living community.

In his spare time he continued work on "Southwestern Game Fields," a book he had begun with two friends while in New Mexico. He considered it "a new kind of natural history" that went beyond description and cataloguing of species and even beyond "avowal of a moral responsibility for the perpetuation of wild life" to a search for principles and techniques of game management, much along the lines of the already well-advanced profession of forestry. By early 1927, he had a first draft of five chapters, including a lyrical account of "The Virgin Southwest and What the White Man has Done to It." This time he used the accounts of early explorers as well as his own personal observations across the length and breadth of New Mexico and Arizona to analyze landscape changes and discuss their impact on wildlife.

He drew on the personal narrative of James Ohio Pattie to contrast the heavily grassed borders and clear waters of the Rio Grande, Gila, Colorado, and other streams when Pattie trapped beaver in the 1820s with the situation a century later, when "we now have scant grass, much erosion, and a river [the Rio Grande] so choked with silt that it bogs its own bottoms with seepage and poisons their fertility with alkali" (1927b, p. 5). He described the old Santa Fe Trail winding for miles across the foothills on the north flank of Mount Taylor but now cut at the bottom of every hollow by "a steep-banked arroyo that no wagon could possibly cross" (pp. 6–9). He acknowledged that quail, ducks, and smaller birds had benefitted from the extension of reclamation ditches, lakes, and crop stubble to what once was desert, but it is clear that he thought the costs outweighed the gains, especially for the long-term support of human communities.

Four years after he left the Southwest for the Forest Products Laboratory, Leopold left the lab and the Forest Service to venture full-time into what had become his consuming passion, game management. He accepted a position funded by the Sporting Arms and Ammunition Manufacturers' Institute to conduct a national survey of game conditions on the ground, assess potential for restoration, and recommend and oversee needed research. Using the skills of observation and analysis he had honed as a forest inspector in the Southwest, he came to a focus on eight states in his new environment, the north central Midwest. And not surprisingly in view of his previous interests, he paid special attention to the condition of watersheds and the relationship between wildlife and soils. This was especially the case in his surveys of his home state of Iowa, his adopted state of Wisconsin, and his grandparents' state of Missouri.

A major theme of his report on the survey was that "Game went with rich soils, and there displayed its greatest tenacity in the face of settlement. Likewise, game restoration will be easier on rich soils, other things being equal" (1931, p. 15). After 7 years of schooling on the East Coast and 15 years of experience in the Southwest, he saw the greatest opportunity for early success in game management in his home region. But even within the region there were differences in richness. He began the book with maps and tables classifying the region by types of game range based on original vegetation, present land use and trends, physiography (including soil origin and occurrence of lakes and swamps), topography, and land values. "Contrary to common belief," he concluded, "the cream of its game country was the prairie type, which is now the poorest." The broad belt of agricultural lands on deep, rich, black prairie soils was richer in game than either the forest belt to the north or the Ozark hill belt to the south with their poorer soils. The region presented a gamut of opportunities for answering the question: "Can wild game be produced in a motorized and moneyed democracy? Here, if anywhere," he concluded, "is the place to seek the answer" (1931, p. 21).

In his chapter on waterfowl, Leopold compared the productivity of duck breeding lakes in the forest belt of Wisconsin with that of lakes in the prairie pothole country of Minnesota, finding the prairie lakes vastly more productive. Yet they were increasingly being drained. In his discussion of Bobwhite, he devoted four full pages, complete with maps and tables, to the effect of intensified agriculture on quail in less than a decade on a single Missouri farm; quail declined from about 210 to 90 as the manager, a recent agricultural college graduate, rebuilt the farm "to fit the standards of modern agriculture" (Leopold 1931, pp. 26–30). He included photos of gullies in Iowa and Wisconsin. "There is something almost absurd," he concluded, "in the expenditure of hundreds of millions for navigation in the large rivers which drain from the north central region, without even an attempt to influence agricultural practices on their watersheds" (1931, p. 250).

Leopold's funding from the arms manufacturers dried up by 1931, in the depths of the Great Depression, leaving him largely unemployed with five children to support, three of them in college. Yet, except for a bit of consulting, he devoted himself during this bleak period to writing the first textbook for the new field, *Game Management* (1933g). The new project was spurred in part by his intended publisher having found his previous manuscript on the Southwest too regionally limited, but even more by his extensive fieldwork on the game survey, including discussions with more than 600 state and local officials, scientists, and sportsmen, and his leadership of a successful effort to initiate research and to craft an American game policy. But because the new book dealt with management theory, concepts, and techniques rather than with game populations in particular locales, there was relatively little regarding soils and watersheds. The direction of his thinking, nevertheless, was clear in his central thesis: "Game can be restored by the *creative use* of the same tools which have heretofore destroyed it—axe, plow, cow, fire, and gun" (1931, p. vii).

4.7 The Conservation Ethic

Just as *Game Management* was about to be published in the opening months of Franklin Roosevelt's New Deal, Leopold accepted a position supervising erosion control work in newly established Civilian Conservation Corps (CCC) camps on national forests in the Southwest. Shortly after arriving back in New Mexico he presented four lectures that reflected both his previous preoccupation with southwestern watersheds and his more recent work on game. In Las Cruces he spoke on "Wildlife and Soils" (1933a), using examples from throughout the Midwest as well as the Southwest to make the case for the fundamental role of soil fertility and integrity—and, he suggested, perhaps even soil chemistry and bacteriology—in restoring wildlife abundance and diversity. In Albuquerque, he discussed "Ecology as an Applied Science," arguing that concerns about overgrazing and arroyos that a decade previously could be dismissed as "seeing spooks" were now being substantiated by game management demonstrations. In Santa Fe, he finally presented his paper on "The Virgin Southwest" with its lyrical descriptions from the early explorers. But by far the most consequential was "The Conservation Ethic," delivered as the John Wesley Powell Lecture of the Southwestern Division of the American Association for the Advancement of Science. It was a completely new approach to the problem of conservation as a moral issue, on which he had first written a decade previously but never published.

He began with the image of Odysseus punishing his slave girls by hanging (they were his private property, after all), which would become so familiar to readers of his later "Land Ethic," and then made the case for the gradual extension of ethics to all human beings and ultimately, he predicted, to the relation of humans to land. As he put it, "Civilization is not … the enslavement of a stable and constant earth. It is a state of *mutual and interdependent cooperation* between human animals, other animals, plants, and soils, which may be disrupted at any moment by the failure of any of them" (1933b, p. 635). As he had done a decade previously, he led from the problem of soils, contrasting the cane-lands of Kentucky, which reverted under heavy human use to the relatively hardy and nutritious bluegrass, with the cienegas of the Southwest, which under similar use reverted through a succession of more and more worthless vegetation and gullies that cut the heart out of the country—both equally unforeseen.

There were three ways to approach the problem of soil conservation as he saw it: legislation, self-interest, and ethics. Self-interest or legislative compulsion might work on the best soils but hardly on the poorer, especially in the midst of a depression. "By all the accepted tenets of current economics and science we ought to say 'let her wash' "—staple crops were already overproduced, science was still raising yields, government was spending millions to retire unneeded acreage, "and here is nature offering to do the same thing free of charge; why not let her do it?" This was economic reasoning. "*Yet no man has so spoken*," Leopold observed, and in that fact he saw the embryo of a conservation ethic (1933b, p. 640). He viewed such an ethic as "a mode of guidance for meeting ecological situations so new or intricate, or involving such deferred reactions, that the path of social expediency is not discernible to the average individual." He saw the conservation movement as a nascent affirmation of a duty to restore the land. At this stage in his thinking he called it "this idea of controlled wild culture":

> I will not belabor the pipe-dream. It is no prediction, but merely an assertion that the idea of controlled environment contains colors and brushes wherewith society may some day paint a new and possibly a better picture of itself (p. 642).

Leopold's faith in controlled environment, his confidence that scientific intelligence could learn enough about the system to exert control—a confidence that also permeates *Game Management*—carried over from the Progressive-era tradition of Gifford Pinchot in which he was schooled. It was an assumption that Leopold's invocation of an ecological attitude was even then beginning to challenge, but the resolution would await yet another stage in the evolution of his land ethic. Nevertheless, "The Conservation Ethic," which was slated for publication even as he spoke, would stamp him as a philosophical as well as scientific and policy leader in US conservation.

With his new emphasis on restoring vegetation on disturbed lands, Leopold worked out an arrangement with the Boyce-Thompson Arboretum at Superior, Arizona, to grow native species in paper pots that could be planted whole (Leopold 1933d). Described as "the world's first nursery for the production of erosion control plants," it would produce some 300,000 plants per year of 25 species of native shrubs and grasses locally exterminated by grazing, from seed gathered by CCC crews as close as possible to the planting localities to ensure acclimated stock (Forest Service 1933). Leopold also worked with the University of New Mexico to develop a test for the ability of check dams of various designs to fit the physical properties of the varied sediments they were to hold; with the Santa Rita Range Reserve on installation of "vegetable dams" in washes to force flood waters to throw down their silt and allow clarified water to sink (in the process providing mini-refuges for quail); and with CCC camps to install experimental check dams and plantings. An ardent fisherman, he also helped devise techniques to minimize sediment from roads near trout streams. But he was vexed by the inability of Forest Service CCC camps to work on adjacent private lands, where the problems were often even greater than on federal land. On the Carson, where he had been supervisor 20 years previously, he found vegetative cover on the forest better than he had ever seen it, but cover outside the forest was "much worse, and constitutes a threat to the whole Rio Grande Valley" (Leopold 1933c).

Before leaving the Southwest, he revised the watershed handbook he had originally prepared back in 1923. And he wrote a memorandum (1933e) for the regional forester suggesting changes in national forest policy and regulations. In his view, range and watershed research had far outdistanced policy, which had been developed before there had been any analysis of the biological mechanisms of watersheds in various regions, and the regulatory structure now needed to be adjusted to the semiarid conditions of the region. After summarizing various aspects of his ecological interpretation a decade previously in "Grass, Brush, Timber and Fire" that were now "admitted facts" among watershed researchers, he made a case for giving grazing permittees the strongest possible incentives to restore their range, providing for acquisition of ranches on which grazing was inherently destructive, and making renewal of permits contingent on specified improvements in watershed conditions. He was pleased that range reconnaissance now recognized "the virgin condition as its standard" for measuring forage, as he had long advocated, but official regulations were often working at cross purposes to ecological understanding.

A few months after Leopold left the Southwest, Washington office erosion specialist E. W. Loveridge (1933, p. 1) noted that erosion control methods were being "studied, tested, and demonstrated in [the Southwest] on a scale that has not been approached in other Regions." He commented on the many different types of structures being developed and tested for different conditions and also, "of particular interest to the economist and taxpayer," on the effort to determine "how little work and how inexpensive the type of work may be to meet the erosion control requirements." It was a research emphasis and a cost consciousness that had been particularly evident in Leopold's reports that summer.

4.8 An Adventure in Cooperative Conservation

Leopold returned to Wisconsin to a job that he would hold for the rest of his life. In his absence, funding had been arranged through the Wisconsin Alumni Research Foundation for a chair of game management, the first in the nation, to be housed in the University of Wisconsin's noted Department of Agricultural Economics in anticipation of his efforts in the realm of land utilization—development of a productive game crop—on Wisconsin's cutover, eroded, and tax-reverted lands. He had spent the first half of his career working on public land; he was now committed to applying what he had learned on the much larger and even more troubled acreages of private land.

Within days of beginning his new job, Leopold accompanied M. E. Deters of the US Forest Service and program administrator Noble Clark of the university on an inspection of erosion control work by CCC flood control camps in the severely eroded "driftless area" of southwestern Wisconsin. Influenced perhaps by discussions with Leopold, Deters (1933, pp. 1, 3) reported that "the engineering point of view has completely dominated" the Wisconsin program, and that the resulting concrete and steel structures were too expensive and the program too narrowly conceived. "It is viewed entirely from the perspective of the gully," rather than dealing with causes of erosion. There was no effort to change land use practice or to use vegetative controls of the sort Leopold had explored in the Southwest. Even before Deters submitted his report, Leopold began visiting other farms in the region and noting potential for erosion control (Fig. 4.3), then prepared a more general paper on the use of vegetative controls in CCC camps (1933f). By October, Leopold, Clark, and R. H. Davis of the Upper Mississippi Valley Erosion Experiment Station at LaCrosse had conceptualized a new, broader, and more integrated program of comprehensive farm planning for soil conservation for the Coon Creek watershed in southwestern Wisconsin and traveled to Washington, D.C., to present it to Hugh Hammond Bennett, director of the Soil Erosion Service. Bennett approved Coon Valley as "Project No. 1," the nation's first soil conservation demonstration area (Clark 1967).

Though it would become perhaps the most celebrated soil conservation project in US history, the Coon Valley effort got off to a rocky start. The Forest Service withdrew its CCC camps from the area that fall; the Soil Erosion Service (SES) insisted on aerial mapping rather than field surveys of individual farms, thus delaying the signing of farm agreements (Clark 1934), and just as Leopold (1934b) got game management demonstrations underway in Coon Valley, Secretary of the Interior Harold Ickes terminated all such game work nationwide. But Leopold and his colleagues persisted: Coon Valley got its own CCC camp, Ickes reversed his decision (after a campaign orchestrated by Leopold), and more than 400 of the 800 farmers in the valley signed cooperative agreements, the number limited only by available funds. By 1935, Leopold would publish an article about the exciting give and take among farmers, government technicians, university experts, and CCC crews in their common enterprise under the title "Coon Valley: An Adventure in Cooperative Conservation" (1933b). H. H. Bennett ordered 500 reprints for distribution throughout the SES and its new successor, the Soil Conservation Service. The watershed has since become one of the most studied in the nation; a 1982 report by Trimble and Lund found that erosion in the watershed had been decreased more than 75% and sedimentation more than 98%. There was evidence of widespread adoption of contour plowing and other conservation practices on other farms in the region, though changes in ownership patterns, land use, and agricultural policies later in the century moderated some of the gains (Hawkins 2002; Heasley 2005). In 2005, Leopold and the subtitle and theme of his Coon Valley paper would repeatedly be invoked at the White House Conference on Cooperative Conservation.

For all his involvement with the New Deal, however, Leopold remained an incisive critic of it, nowhere moreso than in a speech and article on "Conservation Economics" (1934a, pp. 537, 544). "A mighty force, consisting of the pent-up desires and frustrated dreams of two generations of conservationists, passed near the national money-bags whilst opened wide for post-depression relief," he began. The result was an abundance of new alphabetical agencies, each on its own track, often working at cross-purposes with the others. To him there was an urgent need for integration of land uses and protection of the public interest on *all* land, private

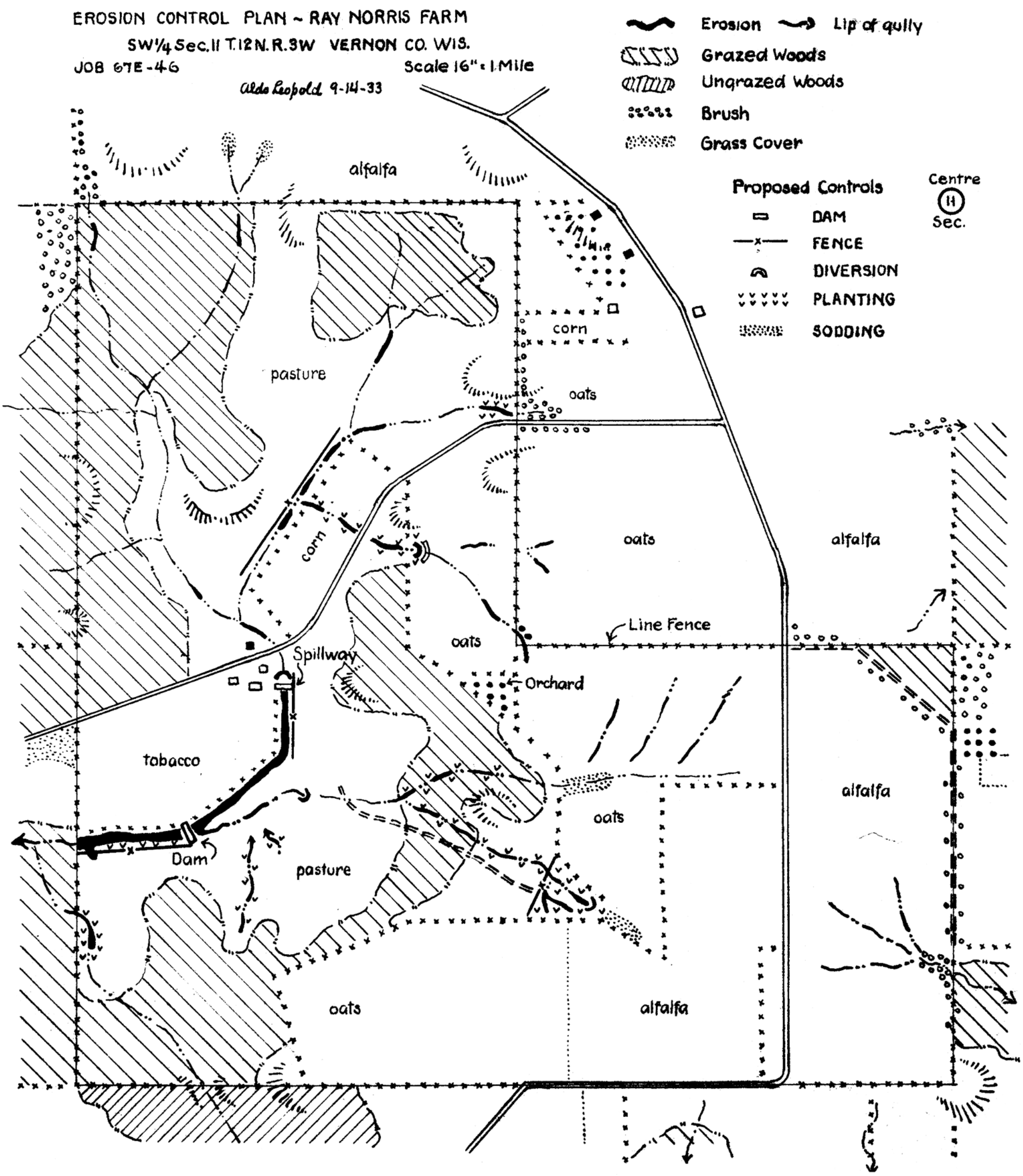

Figure 4.3 Erosion control plan prepared by Aldo Leopold for a farm in Vernon County, southwestern Wisconsin, 1933. Courtesy of Aldo Leopold Papers, University of Wisconsin Archives, with permission of the Aldo Leopold Foundation.

as well as public. To motivate it, he looked forward, as he had a decade previously, to some sort of *contingent possession* or a differential tax. "This paper forecasts that conservation will ultimately boil down to rewarding the private landowner," he wrote. "It pleads that our jurists and economists anticipate the need for vehicles to carry that reward." "Conservation Economics" and Leopold's other writings on economics and institutional mechanisms would be plumbed three-quarters of a century later by scholars and administrators concerned with implementing incentives for the protection of ecosystem services (Daily 1997; Collins 2009).

4.9 Land Pathology

The situation would get worse before it would get better. In April 1935, the day before Leopold was scheduled to speak to the scientific honorary society Sigma Xi, the dust storms plaguing the plains were the worst ever, and the day would become known as "Black Sunday." Leopold titled his talk "Land Pathology."

To the young scientists, he stressed the need for integration of land uses, both economic and esthetic, and hence also of the sciences, social and physical, that were needed to help point the way. The early phases of machine civilization, as well as the present legal and economic structure, he argued, developed in northwestern Europe on land especially resistant to abuse, so there evolved few mechanisms for protecting the public interest in private land. But the terrain in the United States was "in large part set on a hair-trigger," and the velocity and difficulty of subjugating such land "in turn created traditions which ignored esthetic land uses." The result was land pathology to which the dust bore witness. To effect any real change, Leopold looked for "the injection of some new and potent forces": mechanisms for protecting the public interest, "the revival of land esthetics in rural culture," and further refinement of remedial practices. And then the kicker: "Out of these three forces may eventually emerge a land ethic more potent than the sum of the three, but the breeding of ethics is as yet beyond our powers." It was the first time he had used the term *land ethic*—the concept for which he would become best known—in any of his writings. But on this day he was asking his scientific audience only to help "safeguard the environment in which ethical mutations might take place" (Flader & Callicott 1991, pp. 213–215).

The search for "practicable vehicles" to encourage landowners to conserve public values he saw as a research problem that called for a synthesis of biological, legal, and economic skills of the sort being sought by the university's "Science Inquiry," a new Depression-era effort to bring physical and social scientists together across disciplinary boundaries to assess research needs on problems of vital concern to the state and nation. Leopold contributed his analytical and writing skills to four of the working groups: erosion, forestry, wildlife, and water. He was principal author of the first report in series, *The University and the Erosion Problem* (Science Inquiry, c1935; Clark 1967), which lays out possible channels of advanced study and research. Leopold had already been discussing with H. H. Bennett, W. C. Lowdermilk, the National Research Council, and others the need for creation of a new profession to deal with the erosion problem; he considered it "exactly analogous to wildlife [the profession of which he is the acknowledged "father"] but basically more important" (Leopold 1934c).

In August 1935, Leopold took his first and only trip overseas on a Carl Schurz Foundation Fellowship to study forestry and wildlife management in Germany, the land of his ancestors. This was terrain he had previously described as resistant to abuse, but he was now confronted by a different type of land pathology—"soil sickness," he called it (Leopold 1936a). From records of state forests and private estates he pieced together the story. German foresters in a search for higher yields in the early 1800s began clear-cutting stands of mixed conifers and hardwoods to plant pure spruce. The "spruce mania" worked for a time, but soon both timber yields and wildlife began to decline. The result of this "wood-factory economics" was podsolization, "an accumulation of surface acids due to the lack of hardwoods to pump up bases from the subsoil" (Leopold 1936a, p. 347). Windfalls increased and so did insect epidemics. Deer could be maintained only by artificial feeding, fencing and predator control, leading to further impoverishment of flora and fauna. As they began to realize the problems, some foresters began shifting to a mixed forest with more natural reproduction, and *Dauerwald*, or permanent woods, became official government policy in 1934 (only to be abandoned in the Nazi quest for wood products a few years later). Though he approved the new *Dauerwald* policy, Leopold wrote in his usual critical way about problems in applying it. Under a photo in his German album he jotted "the Germans talk Dauerwald but plant spruce."

He returned to the United States profoundly sobered by the artificial management he witnessed in Germany and more than ever determined to avoid it at home. He began advocating for rare and threatened species (1936b), including the wolves and mountain lions he had once sought to eradicate. And most importantly, he began rethinking the *objectives* of conservation. One of the most heavily edited pencil drafts of any of his essays is "Means and Ends in Wildlife Conservation" (1936c; Flader & Callicott 1991, pp. 236–237). Comparing his fledgling profession with agriculture and even forestry, range management, and erosion control, he argued that wildlife management "has already admitted its inability to replace natural equilibria with artificial ones, and its unwillingness to do so even if it could." So much for means, but as to ends he was obviously still struggling. Where as recently as *Game Management* and "The Conservation Ethic" three years previously he was still thinking in terms of "controlled environment" and profitable game crops, he now had to admit that the field's output could hardly be weighed in dollars but was "largely of the heart."

4.10 Land Health

It would require the jolt of conditions in yet another country for Leopold finally to grasp the end toward which he had been working for years. In September 1936, he went with friends on a deer hunting pack trip along the Rio Gavilan in the Sierra Madre of Chihuahua, Mexico (Fig. 4.4). It was a place that still retained the virgin stability of its soils and the integrity of its flora and fauna. The river ran clear between mossy banks, deer thrived in the midst of their natural predators, and the pines, grasses, and other flora did well despite evidence of repeated wildfires. "It is ironical that Chihuahua, with a history and a terrain so strikingly similar to southern New Mexico and Arizona, should present so lovely a picture of ecological health, whereas our own states, plastered as they are with National Forests, National Parks and all the other trappings of conservation, are so badly damaged that only tourists and others ecologically color-blind can look upon them without a feeling of sadness and regret" (1937c; Flader & Callicott 1991, p. 239). Ecological health, what he would come to call "land health," was the end toward which he had been groping, and it would be his guiding principle for the rest of his life. Years later, in an unpublished autobiographical foreword to *A Sand County Almanac*, he reflected on his experience in Mexico: "It was here that I first clearly realized that land is an organism, that all my life I had seen only sick land, whereas here was a biota still in perfect aboriginal health" (1947a).

Leopold returned from Mexico determined to initiate a study of the soil-water-streamflow relation in the Sierra Madre—or as he put it, "the lineaments and physiology of an unspoiled mountain landscape"—as compared with geologically similar terrain in Arizona or New Mexico. Several attempts to find funding and partners for the study fell through, but he encouraged his son Luna to explore aspects of the problem, even suggesting that he study at Harvard with the eminent geologist Kirk Bryan, who had been Aldo's most severe critic on matters of geologic history and climate change (Leopold 1937a; L. B. Leopold 1968, 2004). Luna completed his doctoral dissertation on "The Erosion Problem of Southwestern United States" and went on to become one of the most eminent geohydrologists of the twentieth century.

Figure 4.4 Leopold resting near the Rio Gavilan in Chihuahua, Mexico, during a bow-and-arrow hunting trip. Note evidence of wildfire.
Courtesy of Aldo Leopold Papers, University of Wisconsin Archives, with permission of the Aldo Leopold Foundation.

In 1939, Aldo pulled together all the strands of his new understanding of land health and soil productivity in a seminal paper, "A Biotic View of Land," for a joint session of the Society of American Foresters and the Ecological Society of America, in which he presented land as an energy system: "Land, then, is not merely soil; it is a fountain of energy flowing through a circuit of soils, plants, and animals" (Fig. 4.5). Unlike the old approach of economic biology, which sought sustained production of certain resources as commodities, the new approach recognized that long-term productivity requires normal cycling of nutrient energy in the system and that in turn is a function of the integrity and diversity of flora and fauna. "The upward flow of energy depends on the complex structure of the plant and animal community," a structure elaborated and diversified over eons of evolution. Fertility, a result of this complex structure, "is the ability of the soil to receive, store, and return energy" (1939, pp. 268–269).

Such a view, based on his admired friend Charles Elton's conceptualization of food chains and a "pyramid of numbers," could comport also with Lowdermilk's finding that soils rich in organic matter absorbed rainwater better and were resistant to erosion, William Albrecht's findings that soil fertility affected the nutrient qualities of plants and hence the welfare of animals, Walter P. Taylor and F. Fraser Darling's work on how animals affected plant communities and soils, John E. Weaver's research on how native prairie soils maintained granulation and moisture equilibrium but deteriorated under even the best agriculture, and his own observation-based supposition that rodents such as prairie dogs reached pest proportions only on degraded soils, all which were often cited by Leopold in articles and speeches at the time. A healthy system had a complex structure with multiple channels of energy flow and hence the capacity for self-adjustment and renewal following disturbance. Leopold's "biotic view," which drew on emerging research but was also deeply a product of his own experience

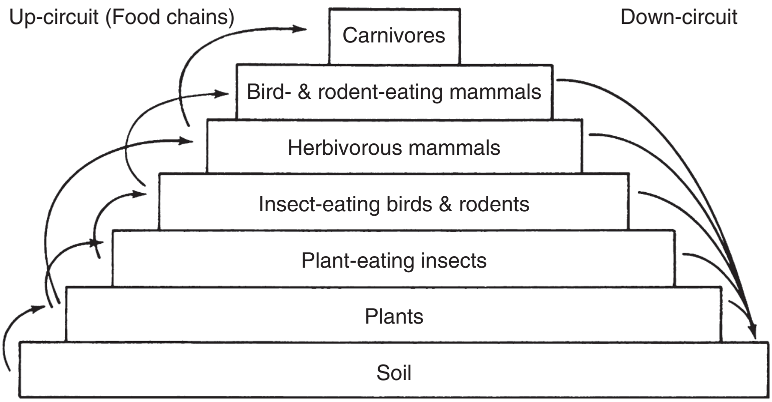

Figure 4.5 Leopold's drawing of a biotic pyramid, which accompanied his article "A Biotic View of Land" to illustrate the circulation of energy through the biotic system.
Courtesy of Aldo Leopold Papers, University of Wisconsin Archives, with permission of the Aldo Leopold Foundation.

and thought, was perhaps the earliest comprehensive expression for a general scientific audience in the United States of what would come to be called the ecosystem concept (Colinvaux, personal communication 1988; Newton 2006; cf. Worster 1994).

With his new energetic appreciation of land health as the objective of conservation, Leopold also found his voice as a writer. We can hear it in "The Thick-billed Parrot in Chihuahua" (1937b, *SCA*, p. 137), later more euphoniously titled "Guacamaja," in which he describes the bird as the *noumenon*—the imponderable essence or motive power—of the Sierra Madre, an exemplar of "the physics of beauty." And in "Song of the Gavilan" (1940a, *SCA*, p. 151), where "foods are the motive power which plants pump through that great organ called the fauna." In his own Wisconsin, we hear it in "Marshland Elegy" (1937d, *SCA*, p. 96), with its haunting image of sandhill cranes "standing on the sodden pages of their own history"—the peats that are the compressed remains of the mosses, the tamaracks, and the very bones of their progenitors over the eons. In a different way we see it at work in "Odyssey" (1942a, *SCA*, p. 107), where he recounts the adventures of atom X, sucked from a limestone ledge by a bur oak root to begin its journey through acorn, deer, Indian, and back to the soil, coursing on and on through a healthy system; and atom Y in its "dizzy annual trips through a new grass called wheat," then washing downhill through "over-wheated loam" to an impounded river and eventually to imprisonment in oily sludge. We see it in "Escudilla" (1940b) and "Thinking Like a Mountain" (1944b, *SCA*, p. 130), where he reaches back in memory more than three decades to his first year on the Apache when he shot a wolf and watched "a fierce green fire dying in her eyes," as well as in the more immediate vignettes of his experiences on his own sand country farm.

Though he acquired his sandy, worn out, abandoned farm with its manure-filled chicken coop of a shack along the Wisconsin River in 1935 as a base for hunting, he became enthused during his visit to Germany that fall about "building a little forest for ourselves up there" (1935c). Gradually over the years he came to realize he was engaged in an intimate experiment—a personal commitment to land health—by seeking to restore the place to ecological integrity (Fig. 4.6). It would be an experience in the slow sensitizing of people to land but also an exercise in humility. Each year he and his family planted thousands of pines and other trees and shrubs as well as prairie plants and wildflowers, burned the prairie, and put in food patches and grape tangles for the birds, but each year most of his plantings succumbed to drought or

Figure 4.6 Leopold and his wife Estella planting trees at the shack.
Courtesy of Aldo Leopold Papers, University of Wisconsin Archives, with permission of the Aldo Leopold Foundation.

flood or rabbits or weevils. All his knowledge did not suffice to control the system. As a further exercise in restraint he left a patch of bare sand on a hillside as a reminder of what had happened to the place when the soils were sucked of nutrients and wasted away; but gradually, long after his death, even his sand blow would be captured by exuberant new life. He wrote of his experiences in a series of columns for the *Wisconsin Agriculturist and Farmer* (Callicott & Freyfogle 1999), seeking to encourage farmers and other landowners in "the creative art of land beauty" with his homely examples. Then in the early 1940s, he began to conceive of combining his "shack sketches" with his recent essays from elsewhere on the continent into the book that would eventually become *A Sand County Almanac and Sketches Here and There* (1949).

4.11 The Land Ethic

As if he did not realize he was succeeding in expressing the land health concept and its ethical implications in his lyrical essays, Leopold struggled throughout the war years and beyond with more prosaic efforts to capture the import of his thinking about stability, diversity, beauty, health, and ethics under titles such as "Biotic Land Use," "What is a Weed?" "Conservation: In Whole or in Part?" "The Land Health Concept and Conservation," and some efforts too fragmentary even for a title. Each dealt in part with soils and land health, but each was still lodged in the "cooler" drawer of his desk at his death. He also tried out his ideas on his students, particularly in his new course on wildlife ecology for liberal arts majors, in which he mused in his concluding lecture on "Motives for Conservation" (c. 1940s, p. 3). After analyzing the inadequacy of economics as a motive, he traced the evolution of ethics from primitive taboos to the "monastic" stage, in which ethics were relegated to protected places. "Our parks and sanctuaries are the monastic stage of the land ethic," he observed, but he looked forward to a time when people would not be content to "delegate their ethics" to specialists and special places but would recognize their own obligations to the land community where they lived and worked.

He ventured into print twice in the pages of *Audubon Magazine* during World War II with articles that touched on land health and moral obligation. In "Land Use and Democracy" (1942b), he argued that "we must prove that democracy can use its land decently." He ventured beyond the ethical obligations of the private land owner to argue for the moral responsibility for conservation that we all bear as consumers; here he visualized some system that would give people an opportunity to select "conservation milk" or "honest boards" that had been sustainably produced, anticipating by half a century certification systems that have gained ground worldwide in recent years. In another essay, "Post-War Prospects" (1944a, p. 49), full of grave misgivings about the impending industrialization of the world and the globalization of conservation problems, he found a glimmer of hope in the discovery that the fertility of the soil affects the nutritional value of plants grown in it. "He who erodes his field," he argued, "now erodes the health of his children and his neighbors. It is ironical that chemistry, the most materialistic of sciences, has thus unwittingly synthesized a conscience for land-use." Though one imagines he may have written this with tongue in cheek, historians have observed that Leopold's concepts of land health and a land ethic cut across the human/nature divide (Cronon 1996; Mitman 2005).

In 1947, when he addressed the Garden Club of America on "The Ecological Conscience," he argued the need for a sense of responsibility for the health of the land community on the part of ordinary citizens: "No important change in human conduct is ever accomplished without an internal change in our intellectual emphases, our loyalties, our affections, and our convictions," he insisted. "The proof that conservation has not yet touched these foundations of conduct lies in the fact that philosophy, ethics, and religion have not yet heard of it" (1947b; Flader & Callicott 1991, p. 338). The first of four case histories he discussed to show the need for a change in values was the failure of soil conservation districts to achieve more than a few remedial practices profitable to the individual farmer; the case came directly from a policy study he and a graduate student had made of problem farms in southwestern Wisconsin for the Wisconsin Soil Conservation Committee (Leopold & Hickey 1943). The speech was noteworthy also for his explicit invocation of esthetic values among the criteria for an ecological conscience—"The practice of conservation must spring from a conviction of what is ethically and esthetically right, as well as what is economically expedient"—and for his initial version of what has been called the *summum bonum* of the land ethic.

Leopold devoted the month following his Garden Club address to recasting his proposed collection of essays yet again, the book having several times been rejected by publishers. He drafted his autobiographical foreword (1947a) and, most importantly, pulled together the reflections of a lifetime on ecology, land health, esthetics, and ethics into his celebrated essay, "The Land Ethic," as the volume's capstone. He began his foreword to what he called "this philosophy of land" with a bald fact: "In my lifetime, more land has been destroyed or damaged than ever before in recorded history." Indeed, his life had spanned the most intense period in the urbanization of the United States and the beginnings of the industrialization of agriculture (Fitzgerald 2003). He had also lived through and contributed to the genesis of the professions and sciences of land management and to the growth of the national conservation movement, but science and conservation, he noted ruefully, had been unable to stem "the juggernaut of land-abuse." He then discussed in terms of his own career the circumstances and subsequent reflections that inspired the various essays. Some months later he would jettison this somewhat bleak and dated approach in favor of a new foreword that would present the essence of his philosophy as embodied in the three parts of the book—the almanac of the seasons on his Wisconsin farm, his mature reflections on certain episodes at other times and places that taught him, "gradually and sometimes painfully, that the company was out of step," and a cluster of more philosophical essays that dealt with how we may "get back in step" (*SCA*, p. viii).

For his new capstone, "The Land Ethic," he drew the opening passages about Odysseus and the gradual extension of ethics from his 1933 "Conservation Ethic," his ecological explanation of the land pyramid from his 1939 "Biotic View of Land," and his challenge to individuals to develop an ecological conscience, as illustrated by the problem of soil conservation, from his Garden Club address. All were carefully edited, refocused, and integrated into the final essay with an equal quantity of wholly new material on the community concept, land health, and the outlook for the social evolution of a land ethic. Here, in the most oft-quoted passage from the entire Leopold lexicon, he states his criteria or *summum bonum* for a land ethic: "A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it tends otherwise" (1949, pp. 224–225).

Though he does not here explicate these criteria, we may understand from the larger context of the essay and the book that integrity refers to the wholeness or diversity of the community: the precept to retain or restore the full complement of species characteristic of a particular biota. Stability—although Leopold knew even at the time that its relationship to diversity was a subject of debate—almost certainly is meant to convey his concept of land health: the complex structure of the biotic system that yields its capacity for sustained functioning and recovery from disturbance. It is what C. S. Holling and Gary Meffe (1996), leaders of adaptive ecosystem management and conservation biology, who acknowledge how Leopold anticipated their ideas, now term *resilience*. And beauty, we know from other essays in the *Almanac,* is what Leopold regards as the motive power of a land ethic: the assertion of values beyond the merely economic, and probably also an allowance for the subjective tastes of the individual.

Leopold articulated his ethical philosophy out of a profound conviction of the need for acceptance of moral obligation in dealing with the dissolution of watersheds in the Southwest, and each reformulation of his philosophy was stimulated at least in part by his continuing concern about erosion elsewhere in the country and by advances in his understanding of soils as the fundamental basis of productivity in the entire biotic community. Remarkably, it was his compelling concern about soil, which was never a major professional responsibility, rather than his lifelong interest in wildlife, which became his profession, that led him to his conviction of the need for a land ethic and his understanding of ecosystem health in which it was grounded. But once he had grasped these concepts and their relationships, it was his sensitivity to the esthetics of wildlife that would enable him to evoke a sense of love and respect for the land community and a commitment to a land ethic in others. He would motivate not by inciting fear of ecological catastrophe or indignation about abused watersheds but rather by leading people from esthetic appreciation through ecological understanding to love and respect. *A Sand County Almanac* is the case in point.

4.12 Epilogue

Oxford University Press notified Leopold by telephone that it would publish his book just as he was about to leave for his annual spring planting week at his shack in April 1948 and sent him a letter the same day. Leopold never saw the letter because he suffered a heart attack and died while helping to fight a fire on a neighbor's land. After some initial consternation, the book was published in fall 1949 substantially as he had left it. It was well received and began a period of slow but steady sales during the 1950s and 1960s, just as, paradoxically, his reputation within the resource management professions was suffering a decline. In retrospect we can attribute a certain disparagement of Leopold within the professions to the fact that forestry, wildlife management, and virtually all of agricultural science, management and policy in the decades following World War II were moving strongly in a direction opposite to what he had envisioned (Berry 1978; Gottlieb 1993; Steinberg 2002). With the appearance of a mass-market paperback edition of the *Almanac* in 1970 during the environmental awakening of the first Earth Day, sales skyrocketed and Leopold was eagerly embraced by college students and environmentalists nationwide, further deepening the rift with the natural resource and agricultural professions.

His work, especially the *Almanac*, became an inspiration for the new fields of environmental history and environmental ethics in the 1970s, although many mainstream academic philosophers, particularly in English-speaking countries abroad, dismissed or impugned his “Land Ethic” (Callicott 1987, pp. 186–187). It was not until the late 1980s, with the rise of conservation biology, restoration ecology, and adaptive management, each of which took inspiration from Leopold (Holling & Meffe 1996; Rapport et al. 1998; Norton 2005), that younger professionals in virtually all the natural resource fields began nudging their professions toward directions Leopold had pointed half a century previously. Much recent biological research in soil systems (Uphoff et al. 2006) would also seem consonant with Leopold’s general approach. By the early 1990s, Leopold’s community-based philosophy was identified by the chief of the Forest Service (Robertson 1992) as a guide for ecosystem management in the twenty-first century, just as Pinchot’s idea of sustained yield had guided the agency in the twentieth century, and Leopold was viewed also as an inspiration for the work of the Natural Resources Conservation Service, the Fish and Wildlife Service, and other federal and state agencies.

More significant even than his influence on natural resource professions and agencies has been the inspiration his career and writings have provided for the burgeoning movement in recent decades for grassroots conservation at the community level, what Paul Hawken (2007) has called “blessed unrest” and considers “the largest movement in the world.” Some efforts such as the Malpai Borderlands Group (Sayre 2005) and the Quivira Coalition (White 2008) of ranchers and scientists in the Southwest, the urban restorationists of the Chicago Wilderness, and farmers in Wisconsin’s Organic Valley have taken inspiration directly from Leopold. The establishment of the Leopold Center for Sustainable Agriculture at Iowa State University in 1987, work on perennial grains and natural systems agriculture at the Land Institute in Salina, Kansas, and the growing movements for organic agriculture and local foods brought more attention to the significance of Leopold’s work and land ethic philosophy for sustainable agriculture, soils, and food systems (Jackson 1980; Thompson 1995; Nabhan 2002; Carroll 2005; Kirschenmann 2010). Countless other groups and individuals worldwide may never have heard of him, yet are working in the spirit of his land ethic philosophy. The largest gathering of such community-based groups in the United States was undoubtedly at the 2005 White House Conference on Cooperative Conservation, at which virtually every plenary speaker quoted or discussed Leopold. Citations to his writings continue to grow, greatly outpacing Carson, Muir, or similar US writers, and *A Sand County Almanac* recently was ranked number one among the world’s top fifty sustainability books as voted by alumni of the University of Cambridge Programme for Sustainability Leadership around the world (Visser 2009). The *Almanac* has been translated into 11 languages, and the March essay on geese appears in the Chinese national middle school textbook on literature, where it may be read by nearly every schoolchild in China.

With Leopold’s land ethic philosophy beginning to penetrate the grassroots worldwide, it is worth remembering that it was itself rooted in his concern about the sustainability of soils. It was a product of his quest for scientific understanding of watersheds and soil systems, better techniques of land management, and more responsible public policy. In his integration of science, policy, ethics, and community action throughout his career, Leopold exemplifies the conclusion of the UNESCO working group on the ethical implications of global climate change (Hattingh et al. 2009, p. 34) that ethics cannot be just an add-on but must be "a constitutive part" of all aspects of the problem and the response. It is also worth reflecting that Leopold did not consider the land ethic *his* ethic or a finished product but still in process of social evolution. "Nothing so important as an ethic is ever written," he reminds us. It evolves "in the minds of a thinking community" (1949, p. 225).

References

Notes: This chapter is grounded in the entire corpus of the Aldo Leopold Papers at the University of Wisconsin Archives, available online at http://digital.library.wisc.edu/1711.dl/AldoLeopold (hereafter cited LP). For items reprinted in *River of the Mother of God* (*RMG*) or *Sand County Almanac* (*SCA*), page numbers cited are in those volumes because they will be easier for most readers to find, even though for historical accuracy the original date and location of each item has been cited.

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5 Rural Response to Climate Change in Poor Countries

Ethics, Policies, and Scientific Support Systems in Their Agricultural Environment

C. J. (Kees) Stigter

5.1 Introduction

In the second half of the past century—in less than 50 years—East Asian countries managed to climb out of extreme poverty and chart a path toward shared economic growth. Much of discussions and debate on this phenomenon have focused on the kinds of policies that these countries adopted or the nature of political regimes that spawned it. Although policies and regimes have indeed been important ingredients, they obscure the key lesson from this experience; due in part to historical circumstances, leadership in these countries recognized the vital importance of managing the politics of change, which invariably would come with economic growth, and fashioned institutions to address this challenge. From this emerged strategies to promote shared growth (Campos 2009).

Mapolu (1990) described the situation for the mid-1980s in Tanzania, in the words of my then-colleague Professor Mascarenhas (University of Dar es Salaam), as one of a peaceful peasant revolt, an unwillingness to produce, or to become part of the wider system. There was a turning back to the small farm/small plot for survival-level farming. The peasantry of Tanzania, among the poorest in Africa, was described as "uncaptured" (Hyden 1980). Instead of linking the state with rural society, politics after independence aided in increasing the distance between them (Van Cranenburgh 1990). This is the opposite of what was said about change in East Asia. Officials in Tanzania tried to force change on farmers, and the farmers refused it.

The lessons learned are about the importance of managing the politics of change and of establishing institutions to address this challenge. It definitely also applies to climate change. Scientists are supposed to propose and prepare policies, so in agricultural sciences scientists should—among others—care for policies of managing the rural response to climate change and of institutionalization of that response.

5.1.1 Sustaining Production

Sustaining production has many agrometeorological aspects, some of which are related to soil productivity. Stigter Jr. (T. Stigter 2010) reviewed that commercial fertilizer nitrogen (N) accounts for approximately half of all nitrogen reaching global croplands today and supplies basic food needs for at least 40% of the population. Because of the continuous economic expansion of some farming systems in some developing countries, the global application of nitrogen fertilizer is currently on the rise again. Fertilization is the principal source of nitrate contamination of groundwater on a regional

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scale. However, the application of commercial fertilizers in many developing countries is presently limited by unavailability or economic constraints, resulting in soil nutrient losses and a land-use efficiency far too low to sustain present and future food production needs.

Soil carbon sequestration has recently been considered a higher mitigation potential than emission reductions in agriculture, although both are important. These are best achieved under management systems with higher carbon density, as well as improved soil conservation. Also, enhanced soil carbon pools provide numerous agronomic and environmental benefits and stabilize global nutrient cycles, with the resultant long-term enhancement of the resilience of agricultural systems to climate change (Dumanski et al. 2010).

This chapter comes back to these issues under the heading of "Policies" because that is what is needed: to use knowledge properly. But first assisting colleagues and farmers in developing countries, if, only for ethical reasons(Stigter 2010a) will be considered. But on what basis should that help be?

5.2 Ethics

Ethics, such as the choice for a "farmer first" paradigm (to be discussed), should come first, followed by policies derived in accordance with these ethics, and then science following with choices in research and application supporting the policies. But why does the world not work like that? If ethics are the moral principles governing or influencing people's conduct, why are internal ethics of conduct in science discussed more than external ones by scientists themselves (Stigter 2010a)?

5.2.1 Values

Research priorities and research agendas incorporate values of what is seen by research managers as worthwhile. Research priorities and research agendas determine the future of research by selecting scientific and technological pathways that often cannot easily be changed.

Even in the selection of materials and methods, the products of science are incorporated values, especially as they relate to the impact on society. In general the research priorities of scientists are now criticized by many (e.g. see Fossey 2008; Logar 2010), and often it is expected of science to reduce the gap between poor and rich countries (Korthals 2008). So external ethics are a thoroughly accepted reason to decide to work in, and for, developing countries in Africa, Asia, and Latin America. However, that is only a first step.

5.2.2 Two Basic Lessons Learned

When at the University of Dar es Salaam (1975–1984),some basics were learned (Stigter 2010b), including that field quantification in the tropics needed special attention because (a) such work had hardly been done in the tropics and either existing equipment had to be made suitable for tropical conditions or suitable equipment had to be designed and (b) modeling could not be an important issue in many cases because of the inhomogeneity of tropical agricultural field conditions and the absence of reliable basic data. Locally, there was no place for studying processes in the tropical environment, however studies of phenomena relevant to the local agricultural production environment are needed and should be undertaken, preferably on farm (Stigter & Weiss 1986).

Secondly, to assist farmers in decision making, little could be learned from the situation in developed countries because in the early 1980s management-oriented weather services were generally not available to farmers there, and any advisories available had little practical utility and therefore were not often incorporated into the management decision-making processes (Stigter 1984). This conclusion meant that agrometeorology had to look at the local agricultural extension situation for contact with farmers. However, by the early 1980s there was, if anything, a top-down structure in which little useful information reached farmers. Farmers' conditions were not understood at all, and the extension approach, if any, was one of "modernization," which completely out of tune with the reality of agricultural production of peasant farming. Peasants were seen as backward and uneducated.

However, in what started as an ethical countermovement, in the 1970s genuine interest was shown in indigenous knowledge still in use and traditional techniques developed by peasant communities. Stigter et al. (1983, 1987, 1994) were the first to work into that direction in agricultural meteorology.

5.2.3 A Third Lesson

A third lesson may be added here, that was also partly worked out elsewhere (Stigter 2006). Neither my colleagues nor I, were at that time, connected to decision makers, policy makers, or anybody representing farmers or farming that could be taken serious. There were no nongovernmental organizations (NGOs); there were no farmers in our lives as scientists in Tanzania. The closest one could come were plantation owners who occasionally showed interest in what was being done, but they were just outside mainstream agriculture.

There was no way that science could play a role; there were no institutions anywhere linking scientists to the reality of peasant farming. Ethics could therefore play no role through science. It could, however, through education: fighting for the development of a different role of science under different policies and different institutional behavior, starting at the universities (Stigter 1982). It is interesting to note that during my work in the Sudan (1984–2001), the local situation was basically conducive to such a role of science, but institutional extension bottlenecks limited successes to initial target groups (Stigter 2006).

5.3 Policies

What *has* been learned is that general policies have to be developed to manage change. It can also be derived from previous experiences that policies in basic data taking would help to understand the tropical environment better and that policies on understanding traditional techniques and indigenous knowledge used in rural areas should be established. A final consequence from the preceding discussing and field research is the need for new educational and extension commitments. Let us now consider more closely where sustained soil productivity, agrometeorology, and climate change touch on policy grounds in poor counties.

5.3.1 Nitrogen Use

Often the only available nitrogen source in the poorer parts of countries is manure with relatively high losses to atmosphere and water because of its inherent properties, but it is often good for soil structure. Full organic agriculture or a combination with relatively low inputs of chemical fertilizers should be practiced. On the other hand, China and India are currently the largest nitrogen fertilizer consumers in the world. As a result, groundwater contamination by nitrates has occurred in several regions of both countries (T. Stigter 2010). Policies are needed to develop balanced and sustainable use of fertilizers.

5.3.2 Fighting Land Degradation

Climate change is having serious negative effects on sustained and already subsustainable production through higher rainfall intensities (leaching and water erosion) and floods (Stigter et al. 2003) as well as drought conditions, in which the uptake of nutrients is limited by lack of water, wind erosion, and fire (e.g. Breman & Kessler 1995). The roles of water, water-use efficiency, and nutrients, among others, in adopting efficient organic farming, are widely discussed in the work of Stigter et al. (2010b). Policies and institutions are needed to fight this change caused by degradation.

5.3.3 Carbon Sequestration

The opportunities for enhanced carbon sequestration in soils arise because of the degraded carbon stocks in most cultivated soils. However, the sequestration potentials vary according to soil type, ecosystems, and management practices, and soil carbon sequestration will continue only to the point where a new carbon equilibrium is reached. In all probability, this new level will be lower than the original carbon stock. To a large extent it will be highly controlled by specific land management practices and inputs, operating within specific soil types and local environments. Although soil carbon sequestration has considerable potential to mitigate climate change, increases in soil organic carbon are often associated with increases in nitrous oxide (N_2O) emissions, which act to counterbalance the sequestration benefits (Dumanski et al. 2010).

There are lingering uncertainties on the permanence of the sequestered carbon and on the potentials for leakage, but permanence can be assured by promoting land management philosophies, such as sustainable land management that enhance economic viability while also sequestering carbon. It can also be assured through agronomic practices that “inject” more carbon at depth, using more deep rooting cultivars (Dumanski et al. 2010).

5.3.4 Greenhouse Mitigation

On a global scale, grassland management, agroforestry, integrated zero tillage technologies (conservation agriculture), and reduced greenhouse gas emissions from animal production have emerged as the strategies with the highest potentials for greenhouse mitigation in agriculture (Dumanski et al. 2010).

It is on all these matters that (changes in) policies will be needed as well as (in) related institutions.

5.3.5 Afforestation and the Biotic Pump

Another important issue is that of deforestation, which is leaving soils bare or with degraded vegetation from a carbon point of view, and the traditional belief of forests generating rainfall. Sheil and Murdiyarso (2009) recently drew attention to new scientific evidence brought forward by Makarieva et al. (2006) and by Makarieva and Gorshkov (2007). Pressure gradients driven by temperature and convection are considered to be principal drivers of air flows in conventional meteorological science. Makarieva and Gorshkov argued that the importance of evaporation and condensation have been overlooked. At the global average lapse rate, water vapor rises and condenses. The reduction in atmospheric volume that takes place during this gas-to-liquid phase change causes a reduction in air pressure. This drop in pressure has routinely been overlooked. Atmospheric volume reduces at a higher rate over areas with more intensive evaporation. The resulting low pressure draws in additional moist air from areas with weaker evaporation. This leads to a net transfer of atmospheric moisture to the areas with the highest evaporation.

Sheil and Murdiyarso (2009) discuss various local consequences of this biotic pump theory. Forest loss and diminished evaporation can, for example, reduce the penetration of monsoon rains and reduce the duration of the wet season. Clearing enough forest within a larger forest zone may switch net moisture transport "from ocean to land" into "from land to ocean," leaving forest remnants to be dessicated. Clearing a band of forest near the coast may suffice to dry out a wet continental interior. Makarieva and Gorshkov's hypothesis (2007) suggests that forest loss will be associated with a loss of stabilizing feedbacks and with increased climatic instability. There is scope for self-stabilizing interactions to arise. The feedback processes and thresholds that operate spatially at different scales, and the influences that act upon them, need to be unraveled.

Acceptance of the biotic pump would add to the values that society places on forest cover. By raising regional concerns about water, acceptance of the biotic pump demands attention from diverse local actors, including many who may otherwise care little for maintaining forest cover (Sheil & Murdiyarso 2009).

5.3.6 New Educational and Extension Commitments

For some important fields where sustainable production, agrometeorology, and climate change come together, important changes in policies and in insitutions dealing with such policies are needed. This must include new educational and extension commitments. The latter have recently been reviewed by the World Meteorological Organization (WMO 2010).

A most important issue in the context of this book is the establishment and follow up of climate field schools (e.g. Winarto et al. 2008) and other farmer-related educational commitments in the rural areas (e.g. field days, on-farm training exercises, roving seminars to train the trainers, farmer facilitators), that could become important institutionalizations related to new policies in the rural response to climate change. New developments are, for example, taking place within WMO and in Africa, China, India, and Indonesia (WMO 2010).

5.4 Scientific Support Systems

Scientists believe that science can be used to make this world a better place, including the rural areas of developing countries and with conditions of a changing climate. It has been argued that most existing scientific support systems (i.e. data, research, education/training/extension, policies) are insufficiently geared to rural services (Stigter 2007, 2008, 2009; Stigter et al. 2010a). Subjects are being determined from within these systems and are not guided by farmers' problems from outside those systems. Indeed, as discussed when dealing with ethical issues, in the selection of the products of sciences, their materials and methods are incorporated values, especially as they relate to the impact of scientific support systems on society.

5.4.1 Applied Agrometeorology

In *Applied Agrometeorology* (2010c), Stigter et al. explain, historically and as an unavoidable and lasting development, the establishment of agrometeorological services in rural areas; this is illustrated with 30 case studies.

There are, and will be, no agrometeorological services and no agrometeorological action support systems without supportive scientific methodologies as workable tools and approaches. Modern assessments of climatic resources, water resources, soil resources, and biomass resources are unthinkable without such technologies (Stigter et al. 2010a). In *Applied Agrometeorology* (Stigter et al. 2010c), it is not about an explanatory approach to these methodologies but about exemplifying how these methods are supportively applied as tools and approaches, that is, to get operational results in problem solving in the agricultural environment that is the livelihood of farmers. How the scientific methodologies guide certain fields toward the operational applications and other applications, as well as, how they contribute to derive the examples and make them work, including the related educational commitments, are fully discussed.

5.4.2 Services and the Livelihood of Farmers

Belonging to agrometeorological services, all agrometeorological and agroclimatological information are considered that can be directly applied (i.e. operationally) in trying to improve or protect the livelihood of farmers. This means protection of yield quantity and quality and income, while safeguarding the agricultural resource base from degradation. Ten fields of such services may be distinguished (Stigter 2007; WMO 2010). However, examples for developing countries under these 10 headings as collected (WMO 2010) teach us that almost all products developed with focused scientific support are no services. They are only seeds sown for the development of actual agrometeorological services in an extension approach.

Although scientists want to get to a situation that is a farmer-first paradigm (e.g. Chambers et al. 1989), livelihood problems and farmer decision-making needs can guide the bottom-up design of actual services. Services should be based on products generated by operational support systems in which understanding of farmer livelihood conditions and innovations have been used (Stigter 2008). NGOs (e.g. unions, nonprofit organizations) are popular in western countries and in Bangladesh, India, and Sri Lanka (e.g. grassroots movements). Governments and NGOs should work complementary to each other. Governments must be able to leave certain interests to those concerned, organized in or by NGOs (KNMI 2009).

In the last decade a good idea of what is needed to establish such agrometeorological services from scientific products generated by National Meteorological and Hydrological Services (NMHSs), research institutes, and universities has been developed (KNMI 2009). But what is needed is institutionalization of science supported establishment and validation of such services as part of a rural response to climate change (Box 5.1). This must be carried out through the new education/extension commitments.

Box 5.1 Examples of Institutionalized Agrometeorological Services with Scientific Support

According to WMO (2010), in almost 20 examples had no institutionalization or had any validation had taken place, although scientific support had, in some cases, been strong. But these were products developed as agrometeorological services for specific target groups without follow-ups. The 10 examples of (just as a start to fully) institutionalized agrometeorological services, for which scientific support and validation could be discussed, follow (Stigter 2009).

- The Mali agrometeorological pilot projects, now 25 years old and still expanding, in which a team of applied scientists of the NMHS gives response farming advice over the growing season on cultural practices to farmers that send rainfall and soil moisture data and other relevant information to the team (*Assistance meteorologique operationnelle* 2005; Helmuth et al. 2007; Diarra & Stigter 2008; WMO 2010). The actual scientific support is unclear, but the team makes use of what is available nationally and internationally as research products. However, this needs considerable improvement and the same applies to actual field extension (Helmuth et al. 2007). It is nevertheless clear from validation exercises that this is a project from which much can be learned by others, particularly regarding involvement of farmers.
- In India, there is a growing list of weather-based pest and disease models of which a slowly growing number is used to provide warnings (e.g. Stigter with Rathore 2008; WMO 2010). The scientific support comes from agricultural meteorological forecasting units under the Indian Meteorological Department, which also make use of results from research institutes and universities. A validation of this work has not yet taken place.
- In Cuba, the “SAT” agrometeorological service of drought forecasting and early warning is operational in the Camaguey provincial weather service since 1994. Governmental institutions rely heavily on the existence of this agrometeorological service. The scientific support came and comes from scientists from the provincial weather service. Validation has shown existing problems of direct communication with farmers (International Society for Agricultural Meteorology [INSAM] 2005).
- In northeast Brazil, drought forecasts have been directed toward small-scale rainfed agriculturists as well as state and local level policymakers in the areas of agriculture, water management, and emergency drought relief. Most farmers in Cereá are so vulnerable to climatic variability that they are unable to respond to raw climatic predictions, irrespective of the quality and the precision of the forecast. The researchers have now changed their focus from items around the start of the rainy season to studies of dry spells and preseason weather and climate patterns (i.e. response farming, easing preparations). The limits of the use of climate information in policy making derive in part from the levels of skill and direct usefulness of the science products themselves and in part from the necessity for a policy making apparatus to learn how to apply it usefully. In comparison to farming communities, validation gave a more positive outlook for success with the use of forecasting products for “intermediate” organizations (Lemos et al. 2002; Stigter 2004).
- In India, at a local university, Murthy (2008) has started to use the previous 30 days’ worth of newspaper cuttings with risk information on weather, a traditional almanac locally followed by the farmers, and local relevant information on effect of weather/climate

on crops, agricultural operations, and animals to serve farmers in understanding connections between agriculture, daily weather, and climate (WMO 2010). Virtually in each village where this was tried out, the farmers had questions or got advice on microclimate issues, which shows the importance of such issues as agrometeorological services in their livelihood (WMO 2010). Further institutionalization needs funds, the scientific support comes from the university and farmer innovations, and a validation is something for a faraway future.

- In Portugal, to combat drought and to assist water use efficiency, an Operational and Technological Irrigation Centre takes advantage of ICT potential for information services to support farmers in their irrigation decisions since 1999. They provide as an agrometeorological service a web-decision support system based on weather stations, the region most common soils, crops, and technologies, and users data (INSAM 2005). This is well institutionalized and validation by users is positive. Another institutionalized agrometeorological service of this kind by the provincial meteorological services in Villa Clara (Cuba) since 2005 helps producers to achieve proper use of water resources for irrigation and aims to allow users to manage that water efficiently. The agrometeorological forecasts are constructed from weather forecasts in the short and medium term and the expected trends in climate forecasting of monthly rainfall and temperatures, taking into account the local history of the behavior of the elements predicted (INSAM 2008). Validation has not yet taken place.
- In Sudan a local university, in collaboration with a Dutch university in a research education project, got the request to study the mechanism by which a Eucalyptus shelterbelt traditionally used in Egypt was most efficiently keeping disastrous wind blown sand out of parts of the Gezira irrigation scheme where it buried crops and prevented irrigation canals to carry water. This led to the institutional design of improved shelterbelts that were subsequently applied there (INSAM 2007). External evaluation was positive. Such a design of microclimate improvements for wind protection and settlement of wind blown sand is an agrometeorological service (Stigter et al. 2002). Various other research results to fight land degradation were obtained in that same project (Stigter et al. 2005). They could all be considered agrometeorological services for specific target groups of users, but an institutionalization phase was never reached.
- In Nairobi, Kenya, IGAD Climate Prediction and Applications Centre (ICPAC) provides the recent past climate over this part of eastern Africa through decadal, monthly, and seasonal summaries of rainfall and drought severity and monthly temperature anomalies. The current state of climate is monitored and assessed using climate diagnostics and modeling techniques. These are derived from information on the state of the sea surface temperature anomalies over all the major ocean basins, surface and upper air anomalies of pressure, winds, and other climate parameters. Scientific support systems are strong. The prediction products are provided through outlooks for a decade, month, and season. Consensus preseason climate outlook are also organized in conjunction with the major climate centers worldwide to derive a single consensus forecast for the region. An assessment of the vulnerability together with the current and potential socioeconomic conditions and impacts (both negative and positive) associated with the observed and projected climate anomalies is also made in decadal, monthly, and seasonal time frames. These products are disseminated to all NMHSs of the participating countries to serve as early warning information and can be used to establish local agrometeorological services (WMO 2006, 2010). No validation was reported.

- In the Philippines, PAGASA (the local NMHS) is of the opinion that the productivity of a region in a particular farming operation may be increased by the reduction of many kinds of losses resulting from unfavorable climate and weather and also by the more rational use of labor and equipment. Greater economy of efforts is largely achieved on farm by the reduction of activities that have little value or are potentially harmful. This is what they are trying to provide institutionally, so as to assist farmers in their day-to-day operations. There is still much to be done and to develop, not only in the accuracy of forecasts and advisories but also in the effectiveness of such services. This also pertains to making sure that climate information and advisories reach the farmers and are understood by them (WMO 2010). No validation has been reported.
- In China, Stigter et al. (2008a; 2008b; 2008c; 2008d; 2008e) have provided information on ten recently identified agrometeorological services in five provinces. In inner Mongolia autonomous region, this is about crop and variety planning as well as on spring wheat sowing advices in melting frozen soils. In Ningxia autonomous region, they are about improving microclimate for water melon in a dry mountainous area and fungus disease forecasting in wolfberries. In Jiangxi province, planning the growing of navel oranges and their protection is dealt with, together with relay cropping of late rice into lotus. In Henan province, services deal with more accurate determination of water saving supplementary irrigation of wheat and the forecasting of peony flowering for commercial activities. Whereas in Hebei province winter straw mulching of wheat and early warning of less sunshine and related low temperatures for winter vegetables in simple but popular plastic greenhouses are the subjects. All these examples have been institutionalized by the provincial meteorological administrations concerned. Several of these agrometeorological services have locally had recent scientific support but others are in high need of much more supportive research. Validation is being prepared.

5.5 Conclusions

In managing the politics of change that appear to be a condition for rural responding to climate change in poor countries, institutionalization is crucial. This must be done through extension that may belong to the organizations that delivers the scientific support (NMHSs, research institutes, universities) or through an extension service established for that purpose or given the mandate to do so. Indonesian scientists recently demanded that scientists not in the extension wings should assist in running help desks to assist in the training of solving farmers' problems.

Governments must develop general and specific educational commitments to rural areas. The farmers as end users of services need to be trained by extension staff in the establishment of agrometeorological and other related services. And the extension officers as intermediaries need training themselves in better communication with farmers on their needs, in the role of farmer innovations, and in the consequences of climate change for the livelihood of farmers, among other topics. This is presently often the weakest link in the chain in getting agrometeorological services established and validated (Stigter 2009).

Backing rural response to climate change has ethical starting points; it needs policies derived and proposed by scientists and science managers from the politics of change. But it also needs scientific support systems encouraging the development of policies based on products generated by operational support systems in which understanding of farmer livelihood conditions and innovations have been used.

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6 Soil and Human Health

Eiliv Steinnes

6.1 Introduction

Soil can adversely affect human health in several ways. People can be affected directly by soil ingestion or inhalation of soil particles or by contact through wounds. Moreover the soil may contain chemical elements and substances, either naturally or through pollution, that are toxic to humans and animals when their intake is excessive. On the other hand, the quantities of essential elements in plant—available form in many types of soil may be too small to provide an adequate supply to plants, animals, and ultimately, humans.

For any essential element there is a range of safe and adequate human intake. Any supply in excess of this may be toxic. On the other hand, intake below this range is likely to cause deficiency resulting in health problems, and in extreme cases, death. This range of optimal intake varies among the essential elements and may be considerably narrower for some elements than for others.

There is a vast literature on soil pollution with toxic substances and the risk to human health. The most severe case worldwide is probably the excessive contamination of urban soils by lead, mainly from leaded petrol. This has been shown to affect children's blood lead levels significantly (Mielke et al. 1997). Most probably, however, problems related to natural imbalances in mineral elements are generally more important to human health than those associated with pollution. In some areas, people are affected by excessive concentrations of naturally occurring toxic elements in drinking water. The best known example is probably fluorine. Moderate amounts of fluorine are beneficial to dental structure, whereas chronic intake of large amounts may lead to the development of dental fluorosis, and in extreme cases, skeletal fluorosis. Deficiency in fluorine has long been linked to dental caries, and fluoride has been added to drinking water in some countries to augment naturally low fluoride concentrations. The range of fluoride concentrations that is safe and adequate appears, however, to be narrow. More than 200 million people worldwide, including about 70 million in India and 45 million in China, are thought to be exposed to drinking water with fluoride levels that may be detrimental to health (Edmunds & Smedley 2005). In Sri Lanka, where the incidence of dental fluorosis among children is high, it is apparent that the fluoride exposure may depend not only on the natural fluoride content of the bedrock but also on the climate (Dissanayake 1991). In the dry zone in the east of the country, dental fluorosis is prevalent, whereas in the wet zone in the southwest, the problem is much less abundant.

In recent years a problem of catastrophic dimensions related to arsenic poisoning has become evident in Bangladesh and adjacent areas of India. When the water of the large rivers in the region

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became too polluted for use as drinking water, people started to drill deep wells to access groundwater. Unfortunately that water has a high arsenic concentration, and it is estimated that as many as 40 million people are currently at risk from arsenic poisoning in the Bengal Basin (Smedley & Kinniburgh 2002).

Although the preceding examples show that toxicity related to naturally occurring trace elements may severely influence human health, problems related to deficiencies in mineral elements are much more widespread, possibly affecting perhaps as much as one third of the population in the world. These problems are generally most prevalent in developing countries where people depend largely on locally grown food, often in combination with a general food shortage. Such problems are expected to continue and will probably become more serious because a rapidly increasing world population depends on food produced from a steadily decreasing agricultural area.

The major mineral elements needed by living organisms, namely sodium, magnesium, phosphorus, sulfur, and chlorine, rarely cause any problem of deficiency in humans. However, humans and livestock also depend on a several elements that are present only in trace concentrations in both the body and soil but are necessary to support essential functions in the body. If these elements are not supplied in sufficient amounts through food and drinking water, serious health problems may become evident. This chapter, therefore, concentrates on the essential trace elements.

Problems of deficiency related to trace elements are also relatively common in agricultural crops. Only exceptionally are these elements added to commercial fertilizers. A soil deficient in one or more essential trace elements may not only reduce the yield of agricultural crops growing on it but also lead to less transfer of the elements to humans or livestock. Trace elements that are essential to plants but not to humans may also affect human health indirectly by reducing the yield of important food crops.

6.2 Essential Trace Elements

The elements present only in trace concentrations in the human body but having a well-defined biochemical function are shown in Figure 6.1. The same elements are also essential to mammals, including most domestic animals. Trace elements essential to plants are also shown in the figure. Some additional elements have been reported to stimulate plant growth without necessarily having a defined essential function.

The nine elements essential to man and mammals are discussed briefly with respect to their biological functions and the problems associated with intake outside the limits referring to essentiality.

6.2.1 Chromium

Chromium (III) is essential to man and animals, and it plays a role in carbohydrate metabolism as a glucose tolerance factor (Anderson 1981). The function of chromium in the human body seems to be closely associated with that of insulin, and most chromium-stimulated reactions depend on insulin. It plays a role in carbohydrate and lipid metabolism and in the utilization of amino acids. On the other hand, chromium (VI) is mutagenic, and epidemiological studies have shown an association between occupational exposure through the inhalation to chromium (VI) and mortality due to lung cancer. No problems in human health connected to naturally high or low levels of chromium in the soil seem to have been reported.

H																	He
Li	Be											**B**	C	N	O	F	Ne
Na	Mg											Al	**Si**	P	S	Cl	Ar
K	Ca	Sc	Ti	V	*Cr*	***Mn***	***Fe***	*Co*	Ni	***Cu***	***Zn***	Ga	Ge	As	*Se*	Br	Kr
Rb	Sr	Y	Zr	Nb	***Mo***	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	*I*	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															
		Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu		
		Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr		

Figure 6.1 Periodic table with essential trace elements enhanced.
Italic, Essential to humans and domestic animals; **bold**, Essential only to plants; ***bold italic***, Essential both to plants and humans/domestic animals.

6.2.2 Cobalt

Among the trace elements essential to humans and animals, cobalt is unique in that the requirement of cobalt is not for the element per se, but for a preformed cobalt compound, cobalamin (vitamin B_{12}), produced by microorganisms. This occurs, for example, in ruminants where cobalamin produced by rumen microorganisms is absorbed further down the gastrointestinal tract of the animal. Cobalt deficiency is frequently observed in sheep, and sometimes also in cattle; it is widespread in New Zealand, Australia, Great Britain, and parts of Scandinavia (Frøslie 1990). Endemic problems in humans related to cobalt are not known with certainty.

6.2.3 Copper

Copper deficiency is widespread all over the world. Copper deficiency in plants is common with high soil pH, high organic carbon content, and excessive drainage conditions. Copper plays an essential role in the human body as part of some metalloproteins (e.g. hemoglobin). The main sources of copper in food are meat, mainly liver, followed by fish, nuts, and seeds. Zinc and iron are strong antagonists to copper, and a large intake of these elements can lead to copper deficiency (Oliver 1997). Copper deficiency in humans may lead to typical disease symptoms such as anemia, deformities of the skeleton, neural disorders, change in hair color, degeneration of the heart muscle, reduced elasticity of arteries, and loss of pigment in the skin. Copper deficiency, however, is relatively rare in adults but is involved in several diseases in children, particularly in situations of malnutrition. In animals, in particular in sheep, problems of both copper deficiency and copper poisoning related to natural pastures are quite common(Frøslie 1990). In both cases, the condition may be influenced by the antagonistic effect on copper exerted by molybdenum. Thus, the copper-to-molybdenum ratio in the animal feed is important, in particular with ruminants. Excess molybdenum can cause copper deficiency at copper concentrations that would otherwise be sufficient (molybdenosis), whereas poisoning may occur at relatively moderate copper levels if the molybdenum intake is too low.

6.2.4 Iodine

Iodine concentrations in soil range from about 15 mg kg^{-1} in organic-rich soil near the coast (Låg & Steinnes 1976) to less than 1 mg kg^{-1} in areas far inland. The major mechanism of iodine transfer from the ocean to land reflects preferential volatilization of seawater iodine into the atmosphere (Fuge 2005), and the most likely source seems to be the release of volatile methyl iodide by marine organisms (Yoshida & Muramatsu 1995). The relative role of wet and dry deposition of iodine on land surfaces is not clear (Fuge 2005) and little is known about the quantities of marine iodine transported to areas remote from the sea.

Iodine has long been known as an essential element for humans and mammals as a component of the thyroid hormone thyroxine. An insufficient supply of iodine may lead to a series of iodine deficiency disorders (IDD), the most common of which is endemic goiter. Iodine deficiency during prenatal development and the first year of life can result in endemic creatinism, a disease that causes stunted growth and general development together with brain damage. This brain damage may occur even when there is no obvious physical effect, and probably represents the most widespread current geomedical problem on Earth with as many as 1.6 billion people at risk (Dissanayake 2005). Areas of the world currently most affected by IDD are largely in the developing countries of Africa, Asia, and Latin America (Fuge 2005) and mainly in areas located far from the ocean. Also in some affluent countries of Western Europe it has been suggested that as many as 50 to 100 million people may be at risk (Delange 1994).

6.2.5 Iron

Iron is a key component of hemoglobin, myoglobin, and several enzymes. Iron deficiency is a common problem in human populations. In several studies of infants in the United States, the incidence of iron deficiency anemia is reported to vary from less than 5% to 64%; differences in socioeconomic status are probably an important factor in this (Morris 1987). In the adult population, iron deficiency is much more common in women during their fertile years than in men because of their iron losses in menstruation, pregnancy, parturition, and lactation. In developing countries, where the population relies heavily on vegetables and where infections and extensive sweating are common, the incidence of iron deficiency anemia is generally higher than elsewhere.

6.2.6 Manganese

Manganese occurs in some metalloenzymes and is involved in many biochemical processes in the organism. Some epidemiological studies have linked manganese deficiency to human health problems (Deckers & Steinnes 2004), but the evidence does not appear to be strong. Manganese deficiency is known in several animal species including sheep, goats, and cattle (Frøslie 1990), but it does not appear to be of great practical importance in livestock farming.

6.2.7 *Molybdenum*

Molybdenum is a constituent of several enzymes in human and animal organisms. It has a relatively small window of optimal concentration and is involved in several problems in sheep and cattle associated with toxicity. These are mainly related to the copper-to-mylybdenum ratio in feed (Frøslie 1990). Corresponding problems in humans have not been reported.

6.2.8 *Selenium*

Selenium concentrations in soils are highly variable geographically. This, together with a narrow range of safe and adequate intake means that problems have been identified in humans and livestock both in relation to selenium deficiency and excess. In the United States, there are large areas in the Great Plains where the soil has high concentrations of selenium, and selenium in some plants that may reach levels toxic to livestock. On the other hand, white muscle disease in animals, a disorder related to selenium deficiency, has been frequently observed in several US northeastern and northwestern states (Muth & Allaway 1963).

China is another country where the soil has extremely variable selenium contents geographically (Fordyce 2005) and where significant problems in humans are evident both in low-selenium and high-selenium districts. Geographically widespread endemic diseases such as Kashin-Beck disease, an endemic osteoarthropathy resulting in chronic arthritis and deformity of the joints, and Keshan disease, a cardiomyopathy whereby the heart muscle is damaged, are both associated with selenium deficiency (Tan & Hou 1989). Rice appears to concentrate selenium more efficiently from the soil in these areas than other local food crops, and people on a diet rich in rice diet showed fewer symptoms of selenium deficiency that people with other eating habits. Recently selenium supplementation to the affected populations has reduced these health problems substantially. It has been suggested that certain iodine deficiency and selenium deficiency problems in humans may be interconnected (Kohrle 1999; Fordyce 2005).

The selenium status in developed countries also varies considerably among different populations, depending on the composition of the diet. Around 1970 the incidence of cardiovascular disease in Finland was among the highest in the world, and it was hypothesized that low selenium might be one of the reasons. Therefore, a large-scale experiment adding selenium to fertilizer was initiated. This led to increased selenium content in bread grain and milk, and eventually an increase in serum selenium concentration in the population to the level assumed to be optimal (Hartikainen 2005).

Låg and Steinnes (1974, 1978) found that selenium in forest soils of Norway decreased regularly with distance from the ocean from around 1.0 mg kg^{-1} near the coast to <0.2 mg kg^{-1} in areas shielded from marine influence, suggesting that the marine environment might be a significant source of selenium to coastal terrestrial areas. This seemed surprising considering the very low concentration of selenium in seawater (0.1 µg L^{-1}). Cooke and Bruland (1987) studied the chemical speciation of dissolved selenium in surface water and observed the formation of volatile organo-selenium compounds, mainly dimethyl selenide, $(CH_3)_2Se$. They suggested that transfer of dimethyl selenide from the ocean to the atmosphere might be an important mechanism for the removal of dissolved selenium from aquatic systems. Thus, in a similar way as for iodine, it seems that atmospheric transport from the ocean to continental areas that are naturally low in selenium may be a significant factor alleviating selenium deficiency problems.

6.2.9 Zinc

Zinc is an essential trace element required by all living organisms because of its critical roles both as a structural component of proteins and as a cofactor in enzyme catalysis (Leigh Ackland & Michalczyk, 2006). According to Alloway (2005), zinc deficiency is the most widespread essential trace element deficiency in the world, perhaps affecting as much as one third of the world's human population. Large areas of the world have soil that is unable to supply staple crops, such as rice, maize, and wheat, with sufficient zinc. In several countries large proportions of the arable soil is affected by zinc deficiency, such as in India where around 45% of the soil is deficient in zinc (Singh 2001). Zinc deficiency in humans was first observed and reported among rural inhabitants of the Middle East in the early 1960's (Nauss & Newberne 1982). Dietary zinc deficiencies are also found in industrialized countries such as the United States (Nauss & Newberne 1982) and Sweden (Abdulla et al. 1982). Moderate zinc deficiency has been cited as a major etiological factor in the adolescent nutritional dwarfism syndrome in the Middle East, the cardinal features of which are severe delay of sexual maturation and dwarfism (Hambidge et al. 1987). Recently it was suggested that fetal zinc deficiency contributes to the pathogenesis in adults (Maret & Sandstead 2008).

6.3 Concerns for the Future

Regional differences in chromium, copper, iron, iodine, selenium, and zinc in the human diet occur in both developed and developing countries, but their effects are usually more evident in the latter, largely because of malnutrition and reliance on local food products (Oliver 1997). Moreover, the effects of infectious diseases are likely to be more serious in a population already suffering from imbalances in the diet. The total extent of problems related to trace element deficiencies in developing countries is potentially very large, and further work is required to identify the full scale of these problems and eventually solve them.

The main problem in the twenty-first century related to human nutrition, however, is the rapidly increasing population worldwide. At the same time, the area of agricultural land is decreasing, due to factors such as urbanization, desertification, and increased soil erosion. During the last few decades the global growth of human population has been supported by a dramatic increase in the amount of food produced per area of land. This has been made possible by the use of high-yielding crop varieties, chemical fertilizers and pesticides, irrigation, and mechanization (Matson et al. 1997). The intensification of agriculture, however, has also had several negative effects worldwide (Foley et al. 2005), and the potential productivity of existing agricultural land has been affected by reduced soil fertility in many areas. This development may also have depleted the soil with respect to plant-available forms of essential trace elements.

The climate change expected for the next decades is likely to result in more weather extremes, which may lead to more frequent and severe floods and droughts. These conditions may well affect not only the quantity of food produced but also the quantity of essential trace elements in that food. The effects of such a development would be particularly severe in developing countries where a large part of the population is already deficient in some of these elements.

To secure the food supply of the next generations it may be necessary to change land-management strategies, for example by increasing agricultural production, fertilizer, and water input per unit land area. This might be possible by changing the diversity of crop species and further genetic improvement of key species. There are reasons to believe that the success of such changes in food production may be measured mainly in quantitative terms (i.e. in produced tons or calories). It is important however that the quality of the product (i.e. the concentrations of essential nutrients) be given appropriate weight. This also includes the essential trace elements discussed and appears to be particularly important in future projects related to improvement of food production in developing countries.

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7 Agroecological Approaches to Help "Climate Proof" Agriculture While Raising Productivity in the Twenty-First Century

Norman Uphoff

7.1 Introduction

Much of the scientific and public debate about climate change in recent decades has focused on issues relating to global warming. However, cropping systems can often be adjusted to accommodate gradual shifts in temperature by changing varieties, schedules, cropping mixes, and other elements (although there are limits to how much change is economically or physically feasible).

Agriculture as an economic sector is particularly vulnerable to what are classified as extreme events: storms, flooding, droughts, hot spells, and cold snaps. Large variations or fluctuations in the amount and distribution of rainfall, as well as temperature, can cause inordinate crop and livestock losses, affecting the production of many millions of farmers.

Adding to the impact of these abiotic stresses on crops and livestock is the frequent emergence of greater biotic stress from pests and diseases. In the decades ahead, dealing with climate change will require the rethinking and refashioning of agriculture to make it more robust and resilient in the face of adverse climatic influences, as well as in response to other economic, demographic, and environmental pressures and trends.

Some of the vulnerabilities associated with climate dynamics derive from the way that so-called modern agricultural production has become structured, with its greater homogeneity, financial requirements, and environmental impacts:

- Although larger-scale units of production can absorb financial losses more readily than can smaller farms, this advantage is offset by their practice of *monoculture*. This sets up larger farms for more extensive crop failures or livestock diseases because they lack the resilience that diversity confers.
- In their search for higher rates of profit, farmers who rely exclusively on selected modern cultivars of crops or breeds of livestock are promoting *genetic uniformity* within agricultural production systems. This can be another source for losses from climate-related biotic and abiotic stresses.
- Heavily capitalized agricultural production units using the most current technologies create greater *indebtedness*, so that price fluctuations induced by swings in climate can have larger and more serious financial impacts.
- Production that depends on extensive mechanization and on agrochemical inputs contributes to the *degradation of soil systems*. Soil compaction, loss of soil organic matter, and reduced subsurface biodiversity all contribute to diminished soil fertility (Magdoff & Weil 2004).

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> As soil systems' capacities for absorption and retention of water are reduced, this has adverse effects on the functioning of hydrological cycles, making undesirable climatic trends more disruptive of agriculture.

These and other considerations suggest that scientists, policy makers, and practitioners should think about possible directions and strategies for postmodern agriculture (Uphoff 2007a).

Economic and technological factors are already making this a relevant concern. Declining per capita amounts (and quality) of soil and water resources, plus higher costs of energy, will make less sustainable the *extensive* strategies that were promoted for agriculture in the past century.

These trends will make *intensive* resource management more economically competitive, that is, using soil and water resources more productively by protecting and building up the productivity of the soil systems on which agriculture depends. Higher energy costs in the twenty-first century are likely to change the economics of large-scale mechanized production and of long-distance transportation of food. Restructuring of farming systems and trade patterns is likely to become economically efficient.

Fortunately, it appears that future gains in agricultural productivity can be achieved in environmentally benign ways that involve reduced rather than increased costs. This will be done by capitalizing more fully on processes and potentials that exist in plant-soil-microbial dynamics.

Specifically with regard to rice, the world's most widely produced and consumed staple food, in some three dozen countries farmers have found it possible to produce more of this grain with reduced inputs of seed, water, fertilizer and other agrochemicals, and sometimes even labor, using practices that together are called the System of Rice Intensification (SRI).

Although this may sound infeasible, evidence from China, Gambia, India, Indonesia, Myanmar, Sri Lanka, and Thailand published in the peer-reviewed literature supports this claim (Ceesay et al. 2006; Kabir & Uphoff 2007; Mishra & Salokhe 2008, 2010; Namara et al. 2008; Sato & Uphoff 2007; Sinha & Talati 2007; Thakur et al. 2009, 2010; Zhao et al. 2009).

To benefit from SRI methods, farmers need only to make changes in the ways that they manage their rice plants, soil, water, and nutrients. These alternative management practices with appropriate adaptations are also reported to raise the productivity of wheat, sugarcane, and other crops in various countries. Of relevance here, these changes in crop management are found to buffer crops from many weather extremes, making the methods relevant for coping with climate change.

SRI is an expression of principles and practices referred to often as *agroecology*. This approach does not rely on making modifications in genotypes and on exogenous chemical inputs to boost production, which uses more water. Those modifications were the basis for what is known as the Green Revolution.

Agroecology instead uses existing, available resources differently to increase their productivity. Already, economic incentives and environmental pressures are laying the groundwork for its wider acceptance. Taking account of climate change considerations makes the case for rethinking and revising agricultural strategies stronger.

7.2 Agroecological Approaches

Agroecology has become increasingly recognized and accepted as a multidisciplinary, scientifically based subject over the past 25 years (Altieri 1995; Carrol et al. 1990; Gliessman 2007). Its basic principles have been summarized by Altieri (2002) as follows:

- *Enhance the recycling of biomass*, so as to optimize nutrient availability in the soil and to balance nutrient flows within the soil and biosphere over time.
- *Provide the most favorable soil conditions for plant growth*, enhancing the structure and functioning of soil systems, in particular by managing organic matter so as to enhance soil biotic activity.
- *Minimize losses of energy and other growth factors* within plants' microenvironments, both above- and belowground.
- *Diversify the species and genetic resources* within agroecosystems over time and over space.
- *Enhance beneficial biological interactions and synergies* among the various components of agrobiodiversity, thereby promoting key ecological processes and services.

Agroecological approaches are not some "backward" kind of agriculture, as some skeptics might suggest. The effectiveness of its practices can be explained in terms of well-established agronomic knowledge about plant-soil-microbial interactions and the functioning of soil systems (Coleman et al. 2004; Uphoff et al. 2006). Agroecological practices are driven and confirmed by scientific knowledge in soil biology, ecology, microbiology, and epigenetics, so they can become the *most modern* agriculture.

Research findings are documenting the contributions made by bacterial and fungal symbionts to plant success, not only in, on, and around the roots (the rhizosphere) but also in, on, and around plant leaves (the phyllosphere), and even in rice seeds.[1]

Such findings suggest that humans' view of plants is due for revision. Crop plants are not biological versions of "food machines," amenable to being redesigned, and dependent largely on external inputs and control. Animals too, including humans, coexist with and benefit from microorganisms and even viruses (Ryan 2004; Costello et al. 2009). Thus, we are coming to see that plants, as well as animals, are thoroughly interdependent with microbes and function more as *systems* than as isolated organisms (Margulis & Sagan 1987; Margulis 1998). Ecological concepts and theories, usually seen as applying to large-scale ecosystems, should be taken down to microbiological and even molecular biological levels.

This perspective is timely for the climate-challenged twenty-first century because the twentieth-century's capital-intensive, chemical-dependent, high-energy strategies for raising agricultural production are due for some revisionist thinking and practice. As will be seen, appreciating and using ecological strategies could help farming systems become more resilient as well as productive.

Newer thinking and practice will not totally displace present production systems, of course. Large-scale change always proceeds with more compromise and adaptation than competing conceptual models imply. But there are reasons to expect that demonstrable economic trends and environmental dynamics, compounded now by climate considerations, will expand the incentives and opportunities for rethinking and redesigning agricultural production strategies. This process should proceed with empirical grounding, not limited by commercial interests, even if these cannot be ignored.

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[1] Feng et al. (2005) have documented with replicated trials and five strains of rhizobia how soil bacteria migrate from the rhizosphere up through the roots and stems of rice into the phyllosphere. Their inhabiting of rice plants' *leaves* increases the plants' levels of chlorophyll, their rate of photosynthesis, water-use efficiency, and resulting yield, by 20% to 70%. Rodriguez et al. (2009) have found that rice seeds inoculated with a certain fungus (*Fusarium culmorum*) had five times greater root growth in their emergent seedlings and earlier emergence of root hairs, which confer growth advantages on the "infected" seedlings. Studies of plant-microbial symbiosis are beginning to explain some of the observed effects of agroecological practice.

7.3 The System of Rice Intensification

The SRI was developed in Madagascar in the 1980s by Fr. Henri de Laulanié, SJ, after he had spent 20 years working with Malagasy farmers and on his own trial plots to learn how rice could be grown with less reliance on external inputs. The resource-limited farmers with whom Laulanié worked were not able to benefit from Green Revolution technologies that required purchase of new seeds and chemical fertilizer (Laulanié 1993; Uphoff 2006).

The Malagasy nongovernmental organization (NGO) that Laulanié established with Malagasy friends in 1990, *Association Tefy Saina*, worked with the Cornell International Institute for Food, Agriculture and Development (CIIFAD) from 1994 to 1998, helping to implement a conservation and development project funded by the US Agency for International Development. The challenge was to give farmers living around the rain forest within Ranomafana National Park some attractive alternative to their slash-and-burn rice cultivation, which was reducing the remaining biodiversity. An evaluation of soils in the peripheral zone concluded that these were extremely unfavorable in terms of acidity, cation exchange capacity, and available phosphorus.[2]

Yet on these soils, farmers using the SRI methods recommended by Tefy Saina field staff, over three successive seasons, averaged 8 t ha^{-1} yields of paddy rice where previously they had obtained only 2 t ha^{-1}. This increase was achieved without their adopting new, improved varieties; without relying on chemical fertilizer, just applying compost made from available biomass; and with less irrigation because paddy fields were not kept flooded, just moist with intermittent water applications and drainage.[3]

These results were achieved with methods that contradicted the prescriptions of the Green Revolution: no new or improved varieties were involved, and requirements for seed, water, and fertilizer were *reduced* rather than increased.

SRI benefits have now been seen across a wide range of ecosystems, in all of the major rice-producing countries in Asia, and from coastal West Africa (Ceesay et al. 2006) to the dry interior climate of Mali's Timbuktu region on the edge of the Sahara Desert (Styger et al. 2010).

SRI practices have the two basic effects of:

- Promoting the growth and continuous health and functioning of *plant root systems*, and
- Nurturing the abundance, diversity and activity of the *soil biota*.

These morphological, physiological, and ecological effects make rice plants more resilient when confronted with climatic and biotic stresses as will be discussed.

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[2] Johnson (1994, 8) concluded: "The two principal soil fertility constraints [low nutrient levels and soil acidity] … cannot be realistically managed by low-input technologies such as composting or even manuring…. The only viable strategies for producing sufficient agricultural yields are to use man-made fertilizers or to continue slash-and-burn practices."

[3] The results obtained by farmers around Ranomafana were consistent with other evaluations done in the 1990s for the French development assistance agency in Madagascar, finding that SRI methods raised farmers' yields from 2 to 3 t ha^{-1} up to an average of about 8 t ha^{-1} (Bilger 1996; Hirsch 2000). Such results were also confirmed by large-scale factorial trials, with random block design and six replications of the treatment combinations evaluated, conducted for agronomy theses at the University of Antananarivo in 2000 ($N = 288$) and in 2001 ($N = 240$), analyzed in Randriamiharisoa and Uphoff (2002). On good soil with a local variety where conventional practice yielded 3 t ha^{-1} SRI methods produced 10.35 t ha^{-1}.

7.3.1 Results of SRI Practice

The impacts that SRI methods can have on rice productivity are summarized here from eleven evaluations of SRI done by a variety of institutions in eight countries (Uphoff 2007b).

- *Increased yield* (t ha^{-1}) of 50% to 100%, and often more if farmers' present yields are low.
- *Reduced irrigation water requirements* by 25% to 50%; note that adaptations of SRI methods to nonirrigated rainfed production in upland areas are achieving similar results.
- *Lower costs of production* by 10% to 20% because no purchases of fertilizer and agrochemicals are necessary if sufficient organic matter is added to the soil. Cost reduction, coupled with higher output, leads to:
    - *Increased net income* from rice production, often by 100% or more.
    - *Higher milling outturn*, giving about 15% more edible rice per bushel of unmilled paddy rice, due to fewer unfilled grains (less chaff) and less breakage during milling (fewer broken grains). This is a bonus with SRI beyond increases in the amount of paddy rice harvested.

7.3.2 Requirements for SRI Dissemination

Any innovation is likely to have some costs or limitations. These are the constraints or difficulties observed so far.

- *Labor requirements*: Whenever farmers are learning new methods, more time and effort is initially needed. With SRI, farmers are transplanting small seedlings, keeping their unflooded fields free of weeds, and applying a minimum amount of water, all new practices. SRI has been characterized as "labor-intensive," indeed, too labor-intensive to be widely adopted (Moser & Barrett 2003). However, once farmers gain skill and confidence in the methods, SRI can become labor-neutral or even labor-saving (Barrett et al. 2004; Sato & Uphoff 2007; Sinha & Talati 2007).
- *Water control*: Maintaining paddy fields in moist but unflooded condition, so that soil systems can support abundant and diverse aerobic bacteria, fungi, and other organisms requires some degree of water control. This requires some appropriate combination of "hardware" (structures) and "software" (organization). Where these are not adequate, they become worth investing in because of the profitability of SRI cultivation. Some low-lying areas and some heavy soils that are perpetually waterlogged will not be suitable for SRI practice, although the cost of installing drainage facilities may be justified in such areas.
- *Crop protection*: SRI crops are generally less susceptible to losses from rice pests and diseases, as will be discussed. However, having both more grain, leaves, and stalks, SRI fields are a good target, especially for vertebrates (i.e. rats, birds). SRI farmers need to be prepared to protect their crops. Although greater losses compared with conventional cultivation methods are rare, they are possible and may need to be guarded against. Usually integrated pest management (IPM) practices, with little or no chemical application, will suffice.
- *Skill and motivation of farmers*: This is the most essential and pervasive requirement because SRI is a knowledge-based innovation that does not rely on material inputs of new seeds, fertilizer, etc. Farmers who already know how to grow rice can learn the alternative techniques fairly easily if motivated. Farmers are not expected to be "adopters" but rather

are enlisted as "partners," being encouraged to *adapt* SRI concepts and practices to their own local conditions. The human resource development that is part of the SRI methodology is considered as a benefit of SRI rather than as (only) a cost.

- *Overcoming skepticism*: One constraint has been opposition to SRI from some within the international scientific community (e.g., Dobermann 2004; Sheehy et al. 2004; Sinclair & Cassman 2004; McDonald et al. 2006). One critic even objected to any effort to evaluate SRI (Sinclair 2004). However, national rice research institutions in China, India, Indonesia, and Vietnam, where two thirds of the world's rice is grown, having done their own evaluations of SRI have confirmed its ability to raise productivity in their rice sectors. Opposition appears to be diminishing as donor agencies are increasingly involved in SRI dissemination.[4]

Farmers are themselves finding ways to reduce SRI labor requirements with new or better implements and crop management practices, and they also are finding ways to cooperatively manage irrigation water. There is considerable farmer-to-farmer spread of the new methods because many farmers who benefit from SRI are motivated to spread this opportunity to others like themselves. This means that SRI is a more dynamic innovation than most in the agricultural sector, but it is definitely still a work in progress.

7.3.3 Environmental Implications of SRI Practice

That SRI is an environmentally friendly innovation is an additional benefit which is hard to quantify.

- *Reduction in water requirements* reduces the competition between meeting food needs and the needs of natural ecosystems, which is why the Worldwide Fund for Nature (WWF) has become involved in SRI evaluation and dissemination. Irrigated rice production is the single largest consumer of freshwater extracted from natural flows and reserves, surface and subsurface (Barker et al. 1999). Thus, SRI methods can reduce water demand if more widely used. At the rice plant level, there is evidence that SRI-grown rice plants are physiologically more efficient in their use of water (Thakur et al. 2010; Zhao et al. 2009).
- *Fewer toxic agrochemicals* are required to protect rice crops because SRI plants are more resistant to pests and diseases. Reduced use of agrochemicals means that there will be less accumulation of these substances in water and in soil systems, which should be a boon for both human and ecosystem health.

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[4] Nongovernmental organization support comes from Oxfam America (Cambodia and Vietnam), Oxfam Great Britain (Bangladesh), and Oxfam Australia (Laos and Sri Lanka); bilateral support includes GTZ (Cambodia), and USAID (Mali). A World Bank irrigation improvement project in India is extending SRI cultivation to 250,000 ha in Tamil Nadu (http://web.worldbank.org/WBSITE/EXTERNAL/COUNTRIES/SOUTHASIAEXT/0,contentMDK:21789689~pagePK:2865106~piPK:2865128~theSitePK:223547,00.html), and the World Bank Institute has produced DVDs on SRI to inform policy makers, project managers and farmers (http://siteresources.worldbank.org/WBIWATER/Resources/SRIbrochure.pdf). The President of the World Bank has endorsed SRI (*Hindustan Times*, Dec. 2, 2009), and the International Fund for Agricultural Development (IFAD), having seen SRI methods raise yields in Rwanda by 50 to 75%, is encouraging use of SRI in other projects (http://ciifad.cornell.edu/sri/countries/rwanda/RwandaIFADSRIflyerJan09.pdf). The Japanese consulting firm Nippon Koei, having had success with SRI methods in eastern Indonesia (Sato & Uphoff 2007), is introducing them in other projects in Asia and Africa. In India, the WWF has given support to SRI evaluation and dissemination and encourages SRI use elsewhere (http://www.panda.org/wwf_news/?uNewsID=114481).

- With more reliance on organic means for maintaining soil fertility and with less dependence on inorganic materials, there will be improved water quality—less build-up of nitrate in groundwater supplies—and more biodiversity in soil systems.
- With SRI management of rice paddies, there could be some net *reduction in greenhouse gas* (GHG) *emissions*. Methane (CH_4) should be reduced by SRI management when rice paddies are no longer kept flooded as anaerobic soil conditions favor microbes producing methane. Possibly, however, nitrous oxide (N_2O) emissions could be increased when soil systems are managed more aerobically, creating offsetting adverse effects. So far, the initial evidence on the net effects of SRI practice on GHGs is encouraging, as discussed in the next section.

7.4 Effects of SRI Practices on Agriculture Affected by Climate Change

The enhancement of crop production through SRI agroecological management practices is impressive. But what effect, if any, do they have on the climatic challenges facing world agriculture? These methods evidently can make rice production more resilient under a variety of adverse climatic conditions that are foreseeable in connection with projected future climate change, and they may countervail to some extent the drivers of climate change (V&A Program, 2009).

7.4.1 Drought Resistance

Although experimental evaluations have not been done on this, farmers widely report that SRI crops withstand considerable water stress if the crops can be sustained through their first 3 to 4 weeks of growth.

In the summer season of 2009, much of India was affected by failure of the monsoon rains, causing widespread crop loss. Farmers who used SRI methods in the state of Orissa reported little or no loss of yield due to low rainfall or pest damage (“SRI method to deal with erratic monsoon” 2009). In Tamil Nadu state, the minister of agriculture attributed its increased rice production, despite reduced crop area due to lower and erratic rainfall, to the spread of SRI methods (“Rice intensification project a boon to farmers” 2009). Buffering of drought impacts was seen also in northern India (Sen & Goswami 2010).

Similarly, villages and rural areas in Sichuan province in China have been hit by drought. By complementing SRI methods of crop management with plastic mulching on raised beds, farmers have been able to increase their paddy yields while reducing water requirements. In Hehe village, SRI yield increases of 30% were accompanied by 70% water reduction. The drought resistance conferred by SRI methods had led farmers in the village to use them on 200 ha (3,000 mu) in 2009, with plans to extend SRI to 6,666.66 ha (100,000 mu) in 2010 (Zhou 2009). In Xiangshui village, farmers reported that instead of yields previously averaging 4.5 t ha^{-1}, they are getting 7.7–9.0 t ha^{-1} with SRI methods in a water-short season, and some yields are as high as 12 t ha^{-1}. Farmers’ reduced costs of production for weeding, land preparation, fertilizer, and irrigation more than offset their cost of mulching (Sheng 2009).

Surprisingly, SRI methods were reported to offer greater benefits in drought years than in normal years (Lv et al. 2009). With normal rainfall, SRI methods add 2.25^{-3} t ha^{-1} beyond usual yields, while in a drought year SRI management increased yields by 3 t ha^{-1} or even more compared to usual methods. In terms of economic impacts, the authors reported that average net income ha^{-1} with usual methods was US$220; with SRI methods in a normal

Figure 7.1 Farmer in Dông Trù village, Hanoi province, Vietnam, holding up an SRI rice plant on left, and a conventionally grown rice plant on right, in front of the fields in which the respective plants were grown, after a typhoon had passed over the village. Note extensive lodging in conventionally grown field.
Courtesy of Elske van de Fliert.

rainfall year, this could be raised up to US$1,500. In a drought year, it was calculated that farmers' net income were increased from a *loss* of US$550 ha^{-1} with usual practices to a *profit* of US$880 ha^{-1} with SRI (Lv et al. 2009).

Such improvement is explainable at least in part because SRI plant roots grow deeper and continue to function right to the end of the crop cycle, whereas rice that is continuously flooded loses about three fourths of its root system by the flowering stage, when grain formation is beginning (Kar et al. 1974).

7.4.2 Resistance to Storm Damage

Farmers also report that SRI plants can withstand the effects of heavy wind and rain from storms, even typhoons and hurricanes (Fig. 7.1). I have seen this effect in China and Pakistan, where "normal" fields of rice plants had become lodged by the force of the storm, whereas SRI fields continued to stand upright so no harvest was lost.

Having stronger root systems could explain this resistance to lodging, but the tillers (stalks) on SRI plants are thicker and stronger, which could be due to a greater uptake of silicon facilitated in aerobic soil and a lower planting density. Controlled trials have shown that the% of rice plant lodging is reduced by intermittent, as opposed to continuous, flooding, younger seedings (14 versus 21 days), and wider spacing (Chapagain & Yamaji 2009).

7.4.3 Tolerance of Abnormal Temperatures

SRI crops' ability to withstand temperature stress has also been reported by farmers, although experimental evaluations have not been done yet. In 2006, researchers at the state agricultural university in Andhra Pradesh, India, serendipitously generated data on this effect while monitoring comparison plots of SRI and regular rice to assess pest damage (Sudhakar & Reddy 2007).

During a five-day period, 16 to 21 December, 2006, average mean temperature dropped to between 9.2 and 9.8°C, badly affecting most of the rice crop in the region. Average paddy yield from the conventionally grown trial plots in that season was just 0.21 t ha^{-1} whereas the yield on nearby SRI plots averaged 4.16 t ha^{-1}. In the preceding season, when temperatures were normal, the average yield on these plots with usual practice was 2.25 t ha^{-1}, and 3.47 t ha^{-1} with SRI methods, a 54-percent increase. Ability to withstand the effects of abnormal temperatures is also likely to become more important in the future.

7.4.4 Pest and Disease Resistance

With global warming, many insect pests and microbial pathogens are likely to become more widespread (Rosenzweig et al. 2004). SRI farmers have reported frequently that they do not need to apply agrochemical protection to their crop. They find this either unnecessary or uneconomic, as damage is not great enough to justify the cost of chemicals and labor.

This effect has been assessed by the National Integrated Pest Management (IPM) Program of the Ministry of Agriculture and Rural Development in Vietnam. Based on frequency or severity counts for the main rice pests and diseases on comparison plots in eight provinces, for two seasons, the program reported that the average for four pests or diseases was 55% lower in the spring season and 70% less in summer (Table 7.1). This quantifies less formal assessments in other countries.

7.4.5 Shorter Crop Cycle

Although it has been claimed by critics that SRI crops take longer to mature (Surridge 2004), the opposite is more common because SRI rice crops mature usually 1 to 2 weeks sooner than the same variety when grown with older seedlings, close spacing, and continuous flooding.

The most detailed assessment of this has been done by the District Agricultural Development Office in Morang, Nepal. It found that eight rice varieties when grown with SRI methods on average matured 16 days sooner (Table 7.2). The average SRI yield for these 413 farmers was 6.3 t ha^{-1} compared with rice yields in the area with conventional methods of 3.1 t ha^{-1}. Getting doubled yield in less time reflects a marked change in plant phenotype.

Shorter crop cycles have many economic advantages. The same field can then be used for a short-season crop, such as a vegetable, or a following crop, such as wheat, can be planted sooner to get higher yield. There is also the environmental benefit of further reducing crop water requirements.

This phenotypical change in SRI rice is relevant for coping with climate change in that a shorter growing period reduces the crop's exposure to abiotic and biotic stresses, which are likely to increase with global warming. This will likely increase also extreme weather events. Many of the most agriculturally damaging storms and droughts come toward the end of the growing season. So being able to harvest a crop 1 or 2 weeks earlier can reduce the climatic hazards that a crop must face.

Table 7.1 Reduction in incidence of major rice pests and diseases with SRI production methods, average for trials in eight provinces of Vietnam, 2005–2006 crop year.

	Season	No. of provinces	Units	Farmer practice	SRI methods	Difference (%)
Sheath blight	Spring	9	Percent	18.1	6.7	63.0
	Summer	9	"	19.8	5.2	73.7
Leaf blight	Summer	6	"	36.3	8.55	76.5
Small leaf folder	Spring	6	Insects/m^2	107.7	63.4	41.1
	Summer	6	"	122.3	61.8	49.5
Brown plant hopper	Spring	8	"	1,440	542	62.4
	Summer	8	"	3,214	545	83.0

Source: National IPM Program (2007).

Table 7.2 Crop duration, in days, of rice varieties grown with SRI versus conventional methods (ranges are shown in brackets), Morang district, Nepal, 2005 main season.

Variety	(N)	Standard duration[1]	SRI duration	Difference
Mansuli	(48)	155	136 [126–146]	19 [9–29]
Swarna	(40)	155	139 [126–150]	16 [5–29]
Radha 12	(12)	155	138 [125–144]	17 [11–30]
Bansdhan/Kanchhi	(248)	145	127 [117–144]	18 [11–28]
Barse 2014/3017	(14)	135	126 [116–125]	9 [10–19]
Hardinath 1	(39)	120	107 [98–112]	13 [8–22]
Sughanda	(12)	120	106 [98–112]	14 [8–22]
Average (total)	(413)	141	126 [115–133]	16 [9–25]

[1] Period of time, in days, reported by rice breeders for this variety to reach maturity.

Source: Records of Morang District Agricultural Development Office, Biratnagar, Nepal, provided by Rajendra Uprety.

7.4.6 Greater Plant Water-Use Efficiency

Research on plant physiological parameters of SRI rice plants is only beginning. A three-year evaluation of SRI practices conducted at the Water Technology Center for the Eastern Region at Bhubaneswar, India, compared the functioning and performance of the most recommended rice variety in Orissa state when it was grown with either SRI practices or those recommended as best management practices by the Central Rice Research Institute for India, coincidentally 30 miles away (Thakur et al. 2010).

Among other things, this research showed that the *ratio* of photosynthesis to transpiration was much higher in SRI rice plants than in the same variety of rice grown according to rice scientists' recommended practices. This ratio indicated a significantly higher—more than doubled—efficiency of plant water use. This will be an important characteristic in the decades ahead as water becomes an increasingly constraining factor of agricultural production.

Physiological changes in rice plants induced by SRI management raise their water use efficiency, by 75% according to an analysis done in China (Zhao et al. 2009). Getting more yield per unit of water was in part due to delayed senescence of roots and leaves. Experiments in India have calculated that SRI plants fixed more than twice as much carbon dioxide per unit of water transpired; 3.6 μ mol CO_2 per millimol H_2O versus 1.6 μ mol fixed by conventionally grown rice plants (Thakur et al. 2010). An evaluation done in Gambia measured six times more rice yield per unit of water consumed by plants (Ceesay et al. 2006). Such considerations will become more important as water becomes scarcer as an agricultural input.

7.4.7 Possible Reduction in Greenhouse Gases

Rice paddy fields are presently one of the agricultural sector's main producers of methane (CH_4) given that methanogenic bacteria thrive in flooded soil conditions. Converting paddy soils from anaerobic to aerobic status will substantially reduce methane emissions.

On the other hand, a switch to aerobic soil conditions could increase the production of nitrous oxide (N_2O) by aerobic bacteria, and this is a more deleterious greenhouse gas. A N_2O molecule contributes 12 times more to global warming than its CH_4 counterpart. We have thus been cautious about proposing SRI rice production as a way to help curb global warming because small increases in N_2O emissions could offset much larger reductions in methane.

A recent evaluation in China of two of the main SRI practices has concluded, however, that the projected gains in methane reduction from (a) increasing organic fertilization of rice soils and (b) reducing the continuous flooding of paddy fields are considerably greater than any offset from generation of more nitrous oxide (Yan et al. 2009). This evaluation was done according to guidelines of the Intergovernmental Panel on Climate Change (IPCC) and considered much smaller changes in conventional irrigated rice production than are made with SRI. So it appears that SRI could indeed make a net contribution to the reduction of greenhouse gas emissions. The modest changes that the Chinese researchers evaluated, which were less extensive than those recommended for SRI, reduced the methane production from paddy fields by almost 30%.[5] Thesis research in the Nepal terai, measuring methane and nitrous oxide emissions in comparable paddy fields with SRI or conventional management, found that CH_4 was reduced fourfold in SRI fields, whereas N_2O was reduced even more, fivefold, apparently due to the reduction in inorganic nitrogen for aerobic soil organisms to alter and due to SRI rhizospheres being more effective "sinks" for nitrogen in the soil (Karki 2010).

7.5 Applications to Crops Other than Rice

The relationships and capabilities observed in rice under SRI management are not unique to this crop. Here we can only note that there are accumulating reports and evidence that SRI concepts and methods give similar benefits for other crops in terms of yield, economic returns, and resistance to biotic and abiotic stresses.

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[5] Yan et al. (2009) concluded: "We estimated that if all of the continuously flooded rice fields were drained at least once during the growing season, the CH_4 emissions would be reduced by 4.1 Tg a^{-1} [million metric tons per annum]. Furthermore, we estimated that applying rice straw off-season wherever and whenever possible would result in a further reduction in emissions of 4.1 Tg a^{-1} globally…. if both of these mitigation options were adopted, the global CH_4 emission from rice paddies could be reduced by 7.6 Tg a^{-1}. Although draining continuously flooded rice fields may lead to an increase in nitrous oxide (N_2O) emission, the global warming potential resulting from this increase is negligible when compared to the reduction in global warming potential that would result from the CH_4 reduction associated with draining the fields." Globally, emissions from rice fields in the year 2000 were estimated to be 25.6 Tg a^{-1}.

7.5.1 Wheat

In India, adaptations of SRI starting with transplanting young, widely spaced seedlings have given yield improvements in Uttarakhand and Himachal Pradesh states in the north, in Madhya Pradesh state in the center, and in Bihar in the east. Some farmers have even tripled their wheat yields with SRI methods (Prasad 2008).

In the Timbuktu region of Mali, farmers adapting SRI concepts found that direct-seeded wheat with wide spacing did better under the harsh sun and wind conditions on the edge of the Sahara than did transplanted wheat (Styger & Ibrahim 2009). Their direct-seeded wheat adapting SRI concepts and practices gave 13% higher yields than the broadcasted control plots, with 26% less water and a 50% reduction in labor inputs.

The Center for Agroecology and Farming Systems of the China Academy of Agricultural Sciences has been adapting SRI concepts and methods to the *wheat-rice rotational farming system* that is used on 22 million hectares in China and South Asia. Three years of experimentation have shown 30-percent to 70-percent increases in combined annual grain yield from wheat and rice over the present 10 t ha^{-1} level with reduced costs (http://ciifad.cornell.edu/sri/countries/china/chSWRIwheatriceCAAS08.pdf).

7.5.2 Sugarcane

Soon after learning about SRI for rice production, farmers in Andhra Pradesh state of India began adapting its ideas to their sugarcane. Farmers in other states also began working with these concepts, and by April 2009, enough experience and knowledge was accumulated for the Worldwide Fund for Nature (WWF) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) to launch a Sustainable Sugarcane Initiative (SSI). This adaptation of SRI to sugar production improves yield by at least 20%, reducing water applications by 30% and chemical fertilizer use by 25%, with also less agrochemical crop protection. A manual on SSI has been posted on the web at http://assets.panda.org/downloads/ssi_manual.pdf.

7.5.3 Other Crops

Work is beginning with other crops using SRI principles with reports of the same kinds of benefits for finger millet, maize, pulses, cotton, and even teff in Ethiopia (Berhe & Zena 2009; Sen & Goswami 2010). These results are associated with evident increases in root growth and functioning, as well as promotion of greater biological activity in the soil, not adequately studied and evaluated thus far. Although such changes are beneficial for crop performance, we can see ways in which they can mitigate climate-change impacts and even make some contributions to improving climate trends.

7.6 Climate-Proofing Agriculture

Much work remains to be done with alternative crop management methods to assess how much such revisions can contribute to the agricultural sector as a whole. There is reason to think that the climate-proofing seen when SRI methods are used with rice could, with appropriate adaptations, be beneficial for crops beyond rice. Rather than rely so heavily on external inputs, agroecological approaches focus on and mobilize endogenous potentials and processes within existing genomes and better-managed soil systems.

This does not reject genetic research or improvements in genotypes. But genetic potentials already available are not being fully realized because of assumptions about best management. Crop breeders could become more successful by paying more attention to plant-microbial interactions and interdependencies, working more on belowground factors in growth and efficiency rather than focus so much aboveground. Because crops in the coming decades will need to adapt to and accommodate climate change and to larger variations in temperature and rainfall, the significance of roots will surely increase.

There will need to be more consideration of soil systems as homeostatic systems with remarkable capacities for self-regulation and self-restoration, provided that they can function within certain ranges of humidity/moisture, temperature, nutrient availability, and circulation and diffusion of gases, particularly O_2 and CO_2. Management of soil systems to facilitate the abundance, diversity, and activity of soil organisms should become more intrinsic to crop management. It should also become more *continuous*, rather than regarding soil management as largely *preparatory* for crop production. To the extent that plants have large and robust root systems, they are better able to withstand aboveground stresses—heat, cold, drought, rainstorms, insect predation, and other adverse conditions.

A key part of any management strategy for crop and soil systems is to promote soil biological activity that will *improve soil structure*, creating optimum sizes and mixes of soil particles and permeation of the soil with pore spaces. These circulate oxygen and water to sustain large populations of soil organisms and create a better growing environment for roots, as well as venting gases like H_2S that can impede root health.

Falkenmark and Rockström (2006) have suggested a useful distinction. Water that exists in bodies such as lakes, rivers, reservoirs, irrigation channels, and even that pumped from aquifers, able to reflect the color of the sky, they consider as "blue water." "Green water," on the other hand, is diffused throughout the biosphere, including particularly water absorbed and moving through soil systems, in or near plant rhizospheres, where it can be used by plants directly. It does not need to be conveyed, as in classical irrigation processes, from some point of collection or acquisition to some distant point of use. Being embedded in natural systems, it is designated "green."

If agriculture is going to be successful in the remainder of the twenty-first century, with rainfall patterns changing and less predictable, soil systems will need to absorb and retain as much water as possible from hydrological cycling. Physical structures can be built to store runoff and convey it long distances, but this solution to providing water for agricultural production is likely to have physical losses through seepage and evaporation, and it entails substantial economic as well as often environmental costs.

Whether current agricultural practices are contributing to climate change directly, by disruption of hydrological cycles and by impacts on soil carbon and nitrogen, remains a matter of controversy. There are demonstrable negative effects of heavy mechanization of production (compaction of soil), heavy use of chemical fertilizers (loss of soil biodiversity, and adverse impacts on soil structure), and large-scale monoculture (reducing crop genetic diversity). The latter contributes to greater vulnerability of crops to pests and diseases at the same time that climate change adds to abiotic stresses on crops.

A more stressful physical environment leads to intensified application of agrochemical protection, which exacerbates the biotic stresses on crops (Chaboussou 2004). Such effects are particularly destabilizing in tropical ecosystems for reasons reviewed by Primavesi (2006). But in more temperate systems also, we see how heavy inorganic fertilization of crops can lead to chemical pollution of water bodies, even affecting parts of the ocean where heavy loads of nitrates and phosphorus are discharged from river drainage systems, compromising the survival of some marine regions. Such long-distance effects derive from the production strategies chosen to feed our large, still-growing populations. Large-scale effects are shaped by what is done at the field level and even at micro (microbial) levels to nurture crop growth, and in parallel, animal growth.

The industrial-engineering strategy for agriculture which served humankind reasonably well in the twentieth century is due for reconsideration in the twenty-first century, if only because economics (e.g. energy costs) and natural resource limitations (e.g. arable land per capita and water availability) are different from preceding decades. Climate pressures are adding to the urgency for modifying our agricultural production systems.

Fortunately, agroecological approaches may be able to help meet the multiple and often conflicting objectives of food production, economic viability, and environmental sustainability. External inputs will not be entirely displaced, but they could become more supplementary and remedial than the predominant driving force for raising production as we proceed in this climate-challenged century. Such a reorientation of production methods will be positive for most ecosystems.

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8 Ecological Integrity and Biological Integrity

The Right to Food

Laura Westra

8.1 Introduction

People can kill one another with bombs and machetes, but economic arrangements are often quite as effective. Millions were killed this way in the Irish potato famine, in Joseph Stalin's forced collectivization, in Mao Zedong's Great Leap Forward, in contemporary North Korea, as well as in many other spatiotemporally limited human-made disasters. The ongoing catastrophe of world hunger is of the same kind—but it is also different—by being less confined in space and time, even more devastating, and less recognized. It claims a third of all human deaths (Pogge 2008).

The question of public health and grave threats to life and health that result from disintegrity have been addressed elsewhere (Westra 2006). The lack of food is certainly one of the most obvious ways to produce grave attacks on life, health, and normal development. Malnutrition's effects are worse for children 0 to 5 years of age.

> Two out of five children in the developing world are stunted, one in three is underweight and one in ten is wasted (FAO 1999; Westra 2006; www.fao.org/news/1999/img/sofi99-e.pdf).

Pogge (2002) justly emphasizes the centrality of global poverty, and that is certainly the most important issue demanding concerted action by global society and international law; some of the many aspects of the interface between poverty and starvation will be considered in this chapter. However, starvation and malnutrition are not only the product of the lack of countries will to give aid, but are also, increasingly due to the way the wealthy countries conduct themselves within their own borders, quite aside from the interaction they might have with developing countries on this issue. In fact, a recent major work of the World Health Organization (WHO) is titled "Social Determinants of Health" (March 2008), and it proposes "Closing the Gap in One Generation" between the rich and the poor of the world to implement equity in the world.

Aside from imposing conditions of life based on extreme poverty (Pogge 2008), there are several other ways in which food availability is affected in developing countries. Pogge speaks eloquently about ways of eradicating poverty: by spending money in ways that will enable "poor people to buy more and better foodstuffs and shelter," as well as for the provision of other social services (Pogge 2008, p. 8). Yet there is far more than aid that is owed to impoverished people who need food to survive. It is a matter of justice (Pogge 2001).

Hence western citizens of democratic countries must effect serious changes in their lifestyles, as the results of their ongoing "normal" habits have consequences so grave that it might be argued that they result in crimes (Westra 2004). The normal activities that have such grave

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results can be listed under two major headings, both of which contribute in important ways to the hunger and starvation in the world:

1. Ecological disintegrity and biotic impoverishment;
2. Western diets and other lifestyle preferences;

   In fact, (1) can also be divided into two further subheadings,

   1a. ecological disintegrity caused by polluting activities, including those caused by industrial operations, including the emissions that result in or contribute to climate change;

   1b. the primacy of trade over ecological safety, an example of which is the ongoing support for GMOs and other inappropriate agricultural practices and subsidies.

In the rest of this chapter some of these issues, starting with the primacy of ecological integrity—because that issue remains basic to the two categories and the two subcategories listed—will be considered. In each case, the basis will be the primacy of integrity because the difference between sustainability and integrity was discussed elsewhere (Westra 1994, 2004). As far as the provision of food is concerned, the way agriculture is practiced, promoted, and regulated is central to its relation to integrity. Hence, the first listed category will begin the discussion. We will turn now to the primacy of trade over ecological safety because present-day agricultural practices represent the clearest connection between disintegrity and the deprivation of food in developing countries.

8.2 Ecological Integrity and Food Production Today

To obtain food, humans manipulate natural ecosystems and alter their biodiversity. In altering the natural systems to produce vegetation or animal types (livestock) different from that typical of the natural systems, a certain amount of human and fossil energy input is necessary. In principle, the greater the change required in the natural ecosystem to produce crops and livestock, the greater the energy and labor that must be expended; that is, the more closely the agricultural system resembles the original natural ecosystem, the fewer the inputs of energy and other factors that will be required in an agricultural ecosystem (Pimentel 1995).

The underlying principle is simple enough: natural systems and any food production that is compatible with naturally evolving systems require the least possible amount of energy to ensure production; hence they are environmentally "better" in two separate ways. Limiting the amount of energy used is less hazardous from the standpoint of global warming and far more important, the more ecointegrity is retained by a system, the better chance there is that some ecosystem services will be retained (Daily 1997).

Yet the question that has primacy at this time is not the preservation of ecointegrity (such as the establishment of protected areas), but the efforts to retain as much integrity as possible in cultivated areas, while increasing the amount of food available to feed the world's hungry. The question of "livestock," although it is extremely relevant, can be set aside for now because it is a major factor in the question of "lifestyles" on issue number 2 in the list. What is left is the problem spelled out in two major issues debated today: industrial agriculture with all the hazardous pesticides and overuse of energy that the practice entails today in contrast with small farming practices and traditional agriculture versus agriculture that involves genetically modified organisms.

The extravagant industrial claims of "feeding the world" have brought at least as much hazardous material, especially carcinogenic substances, into food production as they have provided safe nutrition. Integrated Pest Management may be of slight help (Boardman 1986; Oyer 1986). The important thing is that

> Soil fertility depletion, erosion, and soil regeneration rates are of paramount importance.... Services from biodiversity (pollination, recycling, natural pest control) should not be impaired (Goodland & Pimentel 2000).

Essentially, although it is necessary to produce food, it should be produced in a sustainable, fair and nonhazardous way. Environmental sustainability can be defined as follows (Goodland & Pimentel 2000; Box 8.1):

Box 8.1 Definition of Environmental Sustainability

Output Rule

Waste emissions from a project or action being considered should be kept within the assimilative capacity of the local environment without unacceptable degradation of its future waste-absorptive capacity or other important services.

Input Rule

Renewables Harvest rates of renewable resource inputs must be kept within regenerative capacities of the natural system that generates them.
Nonrenewables Depletion rates of nonrenewable resource inputs should be set below the historical rate at which renewable substitutes were developed by human invention and investment according to the Serafian quasi-sustainability rule. An easily calculable portion of the proceeds from liquidating nonrenewables should be allocated to the attainment of sustainable substitutes (Daly& Cobb 1989; Goodland & Daly 1991; Daly 1996).

Another major problem facing agriculture today in relation to ecointegrity is the question of "extensification versus intensification":

> Extensification, the cultivation of hitherto uncultivated lands, creates massive environmental impacts, not the least of which is biodiversity loss (Goodland & Pimentel 2000, p. 124).

Much of the land used for extensification has been reclaimed from forests with severe consequences for global warming. In contrast, "intensification," although it appears to be the better alternative, is problematic as well, as its sustainability depends on availability of water, of fertilizer and other energy and raw materials, a steady climate (Goodland & Pimentel 2000, p. 124), but, most of all, it depends on the appropriate fertilizer and pest controls being used. Goodland and Pimentel estimate that "12% of the earth's total land area" (Goodland & Pimentel 2000, p. 127) is used this way, and the land presently used for agricultural purposes is threatened by various forms of degradation because the required conditions are not met.

> The major types of degradation include rainfall and wind erosion, and the salinization and waterlogging of irrigated soils (Kendall & Pimentel 1994).

Soil erosion by wind and water cause the ongoing desertification, especially in sub-Saharan Africa, where the rate of soil loss "has increased 20 times during the past 30 years," whereas topsoil grows slowly.

> Thus, topsoil is being lost 13 to 40 times faster than it is being replaced or 13 to 40 times above the sustainable rate (Goodland & Pimentel 2000, p. 128).

The intensive practices and chemical additives as well as pesticides are touted to be necessary to feed the world are—without a doubt—a major factor in the exponential growth of diseases fostered by various products of chemical companies, ranging from the death of field workers in developing countries (Westra et al. 1991) and exacerbated by regular famines.

The results of ongoing exposure to industrial products and processes manifest a direct relation between present-day agricultural practices, environmental conditions, and human rights to health. From the standpoint of integrity, earlier work by Soulé and Piper puts it well:

> Farmers in the present industrial agriculture must play the role of ecosystem simplifiers. By applying various biocides they attempt to eliminate such complicating factors as weeds, insect herbivores, and fungal pathogens from their fields. By applying synthetic nutrients they attempt to short-circuit biologically driven nutrient cycles and control soil fertility. What remains of the biotic community they direct to a solo peak performance to maximize short-term yield of products for human use. This single species star performance comes at the expense of other ecosystem components (Soulé & Piper 1992).

Because of the steady biotic impoverishment of our natural systems, agriculture is now just another industrial operation, with no regard for regional conditions, social issues, or climate problems (Shiva 1988). As well as energy intensive and ecologically harmful practices, including the use of chemicals, the all-pervasive use of genetically modified organisms (GMOs), especially in North and South America, are increasingly eliminating the biological integrity of natural systems and organisms, while they put human health and human rights at risk.

The presence of GMOs has been an insidious threat to health and well-being, both directly and indirectly. Direct harm occurs when unlabelled GMOs are consumed by people in most countries where labeling of these products is not allowed (only Europe has labeling laws so far), hence people are forced to consume unlabeled products that (a) may cause unexpected allergic reactionsor (b) may contain material that is contrary to their religious faith. These two possibilities entail two breaches of human rights: for (a) the right to know what one is eating and feeding one's children, as well as one's right to health/life and for (b) the right to practice one's religion. These are both moral rights as well as legal rights. Hence, before discussing the legal status of GMOs and the present legal implication of their use, a moral assessment of the issue will be discussed.

8.2.1 Introduction to Biotechnology: A Moral Assessment

When we face moral and social questions about the commercial uses of biotechnology and transgenics, we need to ask ourselves two important questions *before* consenting to their use: (1) Are these technologies equal to the task they are intended to accomplish; and (2) even if it can be shown that they are the means to some common good, can it also be argued that they are right in themselves, or a morally defensible means to a morally right goal? Biotechnologies and transgenics are proposed as means to the universal good of alleviating hunger worldwide. Hence, in relation to food production the multinational corporations that push to develop, patent, and commercially distribute technologically altered organisms do so for profit; at the same time, however, they claim that their products are environmentally sounder than those produced by present practices, and in fact, that they provide the only solution to hunger in the Third World in the face of exploding populations.

Increasing scientific evidence about the problems arising out of the high-tech approach to agriculture, such as soil erosion and increased use of pesticides (with its accompaniments, pesticide-resistant insects and contaminated food), all point to reduced productivity in the near future and foster poor long-term prospects as well. On one hand, these pressing concerns suggest the need for new agricultural techniques, on the other, public unease in regard to the widespread use of toxic chemicals also appears to point to the need for new solutions to the hunger problem. Hence, there is a drive to quickly introduce new products and technologies, ostensibly to solve the previous problems and to produce better results.

The newly engineered plants, animals, and fish look as they always did, but they are different in specific ways. A plant may have been bred with a virus so that the new creation is both animal and vegetal (an “aniplant,” perhaps?), and it possesses traits the predecessor plant did not. These traits are desirable from the standpoint of economics and production; on the positive side, they increase yield and thus promise to feed more people more efficiently and on the negative side, the new plant has now evolved into one with an inbred resistance to a specific herbicide. The result is that the bioengineered species—heralded as a step forward for environmental safety and a step away from chemicals—actually represents a permanent, inescapable link to chemicals because the new creation has a built-in tolerance for a specific herbicide.

Therefore, the corporation gains twice: once when it sells the biotechnology, and again, when it ensures the product’s permanent addiction to its own patented herbicide. At the same time, however, the people and the environment lose twice: once because the proposed “safe” product ultimately is not, and again when other possibly safer, organic, and sustainable choices are preempted. The producers’ strategy entails appealing to shared principles of the good for the majority to defend their aggressive pursuit of these novel technologies and their intensive marketing. Despite this side of their operations, corporations could still operate according to shared moral principles.

But these so-called shared principles of justice, fairness, and the pursuit of the common good are not necessarily present once both the technologies and their dissemination are scrutinized more closely. If the expected consequences are either nonexistent or vastly different from the results envisioned, then the “countervailing benefits” may not be overwhelming enough to justify neglecting the problems and risks involved (Shrader-Frechette 1991).

Therefore, the questions posed at the outset need to be reexamined. Is the claim advanced on behalf of new biotechnologies and their superior capacity in regard to food production a correct one? Is it true that these new products are not only instrumental in resolving the problem of world hunger, but that they also represent the *only* possible solution to that problem? It would be easier to dismiss the whole enterprise as nothing but another corporate money-making scheme if these questions could be answered with some degree of certainty. To feed the hungry is a morally worthwhile goal, and if it could be shown that the achievement of that goal depends on the use of biotechnology, then we would need to attempt to mitigate its negative effects, and to find ways to control and modify the way engineered products are manufactured, marketed, and distributed, but not to question their very existence.

In contrast, if a careful examination were to indicate that the widely touted benefits of biotechnology are doubtful, or simply outweighed by their negative effects, then its moral status as a means to a desirable end would be seriously in doubt. The next sections will discuss the claims made on behalf of biotechnology and the use of transgenics in the areas of agriculture and aquaculture and carefully examine their negative impacts. These negatives will not only be practical and ecological, but will also include problems that might be raised by their use in regard to traditional moral theories as well as from a holistic environmental perspective. I will conclude that once the impact of these technologies is unmasked, the principle of integrity provides the strictest criterion on which to base our assessment of their moral viability.

8.2.2 Agricultural Food Production, Biodiversity, and Biotechnology: The "Perils Amidst the Promise"

What are "transgenic plants," and what is their application and use in commercial agriculture? "Transgenic plants are crops that have been genetically engineered to contain traits from unrelated organisms." (Rissler & Mellon 1993; Mellon, 1994) In practice, "Adding novel genes to crops means adding new traits and abilities. Genetic engineers can move genes from any biological source—animal, plants or bacteria—into almost any crop," and it is this novelty that ensures that these "aliens" will simply not fit in with the rest of the system's naturally evolved biota. Traditional breeding techniques have a built-in safety net because they will fail unless the organisms that are joined are similar (in the sense of coming from similar species) in ways that are relevant to their function within their joint habitats. If they were incompatible for some reason, they could not be successfully joined. In this sense then, previous traditional techniques ensure that the breeding's result will fit within the natural habitat of both organisms used. From this perspective, therefore, traditional breeding is different *in kind* from genetic engineering.

In the past, food scarcity, the desire for new products, or the presence of agricultural problems have been mitigated by the importation of alien species (e.g. the introduction of the potato in Europe). From this perspective, there is a difference in degree between biotechnology and this occasional introduction of nonnative species. Biotechnologies are many, uncontrolled, widespread, and ubiquitous in many areas without any attempt to coordinate and study the effects of their presence as a whole. They are added to complex systems already subjected to multiple anthropogenic stresses under hazardous conditions of global change.

Thus, the introduction of biotechnologies gives rise to a number of environmental problems. These problems affect the claims about increased agricultural productivity on which biotechnology's manufacturers rely to justify their enterprise.

The environmental problems—major as they are, as we shall see—inspire only one set of questions that need to be raised in this regard, and although many of the problems raised by biotechnology are related, a list of problem clusters may help to understand the concerns many express in their regard:

a. The introduction of novel organisms into natural ecosystems, with unpredictable effects on both humans and nonhumans
b. The lack of controls comparable to those imposed on the manufacture of new drugs, cosmetics, and medications
c. The lack of labeling, hence the denial of the public's right to know
d. The absence of independent professional interventions, to ensure safety to humans

e. The lack of support for our right to choose, to consent, and to freely practice a chosen religion, which follows upon the denial in (c)
f. The increase of threats to biodiversity and to natural systems

A brief discussion of some of these points as examples will place us in a better position to reconsider the claims about increased productivity and the industry's right to be viewed as the only answer to world hunger.

The major point at issue is the introduction of *novel* organisms (a) into natural systems, in the senses discussed previously. Corporate manufacturers respond that by combining what is already available in nature, transgenics are neither novel nor alien in the sense intended by this objection. This response ignores the fact that each natural systems is geared to function optimally through and for certain species that are appropriate and native to it. The evolutionary unfolding of various systems through almost two thousand years has ensured that certain processes will support a diversity of life appropriate to each landscape. Any change is at least a risk. The introduction of novelty represents a risk without precedent, leading to unpredictable, effects that are unlikely to be benign. We are learning, by trial and error, the results of these new anthropogenic stresses on natural systems, but we do so only at the cost of using all the earth's biota (including ourselves) as the nonconsenting subjects of giant experiments.

Another point worthy of note is that (b) like the pharmaceutical industry, biotechnology is research intensive. It tends to cover research costs by selling expensive products at premium prices (Rissler & Mellon 1993; Mellon, 1994). But unlike the drug industry, biotechnology is (1) under no tight controls similar to those imposed by the medical establishment upon new drugs and medications; (2) not forced to label its products clearly for content, indications, and possible side effects; and (3) such that as it targets global mass markets without the intervention of a medical professional to protect the public free to examine the industry claims and to tailor the use of a product to the specific requirements of each individual patient.

In other words, the introduction of alien substances may produce different effects in different natural systems; similarly, both the medication and its quantity must fit specific patients. One example will illustrate this problem and the related issue of the right to knowledge and consent. In the late 1980s, an amino acid—tryptophan—was produced and sold through health food stores as a sleep medication. Eventually a Japanese firm, Showa Denko Company, changed the process and started to produce it with genetically engineered bacteria with disastrous results. Particularly in the United States, where, in contrast with Canada, it was sold as food, and thus not subject to testing, regulations, and labeling; people started to sicken and die from eosinophilia-myalgia syndrome. After 31 deaths, injuries to over a thousand people, and a rash of lawsuits, Showa Denko closed for business. This made it impossible to test either the substance or the manufacturing/engineering process. Nevertheless, as the substance was over 99% pure, the procedure involving genetic engineering appears to be the most likely cause of the terrible toll of death and suffering (National Wildlife Federation 1992; Mayeno & Gleich 1994; Mellon 1994).

Even if absolute proof is not available of the direct causal connection between genetic engineering and this case's morbidity and mortality, several points emerge (1) there was no required labeling to alert the public to the changed processes and the genetic engineering involved in the manufacture of the product; (2) the product was sold as food, rather than as drug, and therefore neither testing nor medical advice was required for its use; and (3) the US government itself was "unaware of the introduction of tryptophan made by genetically engineered bacteria" so that, under present regulations, the tragedy was unavoidable, even in principle (Mellon 1994).

It can be argued that the *institutional* setting of biotechnology is hostile to any concern for the public interest, beyond public relation efforts designed to allay public fears without, however, imparting information about the manufacture of products (because of the legal protection of trade secrets) or about possible effects (because of the lack of available research, scientific imprecision and the lack of time to develop appropriate research projects).

8.3 The Legal Status of Genetically Modified Organisms

In recent years a heated international debate has developed regarding the production and consumption of food made for or with GMOs. Among the key players in this debate, the United States, supported by many companies who have developed GMO-based products, has pushed for their acceptance; by contrast, the European Communities (EC) and its members states, backed by consumer groups and other activists, have tried to restrict their use through various regulations (WTO 2006).

The WTO ruled against the EC's regulatory regimes and their position against biotech products (i.e. products that contain or are made from or with GMOs). The European Union (EU) has mandatory "labeling of food containing genetically modified organisms" since April 2004 (Keane 2006). In fact,

> Legal support for the regulations is found in the 1997 Amsterdam Treaty, which expressly promotes the right to consumer information as separate and distinct from the right to health and safety interests(Treaty 1997; Keane 2006).

In fact, even the United States, despite its strong opposition to labeling on purely economic grounds, has a strong history of supporting the right to know of consumers. In 1962, then-president, John F. Kennedy sent a "Special Message" to Congress, wherein he declared four "basic consumer rights": "The right to safety, the right to be *informed*, the right to choose; and the right to be heard" (Kennedy 1962; Keane 2006, p. 301). In fact, the right to know is basic to both morality and law regarding contracts of any sort (Kant 1981).

Public support for the right to know was certainly spurred by the bovine spongiform encephalopathy (BSE) scare of the 1990s (McCalman et al. 1998), where the right to know was closely tied to the right to life and health, given the lack of available treatment for the victims of BSE.

In the United States, in contrast, the main problem was perceived to be "safety," given the allergic reactions of many to altered food:

> This is a particular problem if the new gene is derived from food that commonly cause allergic reactions, such as milk, eggs, fish, crustacean, mollusk, tree nuts, wheat and legumes (especially peanuts and soy beans). These food account for some 90% of food-based allergic reactions (Bailey & Boldman 2001).

Hence, the issues appear to be clear, internationally, in the EU and the United States: the right to know and the connection with safety are taken to be primary. To some extent this is the most useful service that GMOs perform: the issue of safety/public health is raised in conjunction with the environment and viewed as one of the two major problems of GMOs. No other aspect of disintegrity has a clearly recognized position in regard to public health in the same way. The best known US case is *Alliance for Bio-Integrity* v. *Shalala* (2000), and it includes a variety of issues: some who thought that "allergens and toxins could emerge from GMOs, others who argued that their religious obligations were threatened. In fact, there were six separate challenges, but all were rejected by the Court (Bailey & Boldman 2001).

In contrast, GMO labeling in the EU is primarily focused on the consumer's right to know, but "the regulations are chock-full of language about protecting health and safety" (Keane 2006, pp. 290, 320). The use of health/safety language, however, means that the EU regulations conflict with the Agreement on the Application of Sanitary and Phytosanitary Measures (1994).

The problem is that "health and safety" measures fall under the purview of the Sanitary and Phytosanitary/World Trade Organization (SPS/WTO), and their judgment about what does or does not constitute "sound science." Hence, paradoxically, it is the consumers' right to know that should have been emphasized from the start by the EU, thus avoiding debates about health and safety altogether, and any discussion about the validity about the EU's expert's scientific standards. Morally, it seems clear that the protection of health and safety ought to be primarily in the dispute over GMOs. However, moving the argument to the procedural aspects of the question, that is, to the right to know, would bypass the difficulties involved in adjudicating between different scientific findings.

In that case, the previous statement that the litigation concerning GMOs might be the best way to focus on the environmental hazards or public health issues in the constructive manner may have been somewhat precipitous, from a practical point of view; the ongoing debate on the issue reinforces this conclusion (Applegate 2001; Macmillan & Blakeney 2001; Scott 2003; Keane 2006, pp. 315–317).

As shown previously, the WTO (1994) permits "adopting or enforcing measures necessary to protect human health," as long as the measures are not so applied as to "constitute a means of arbitrary or unjustifiable discrimination," hence as long as no taint of protectionism may be attached to the measures. The preamble of the SPS agreement, however, explicitly intends to harmonize its mandates with the Codex Alimentarius Commission (Codex) of 1963, which was originally created to support the joint Food and Agriculture Organization/World Health Organization (FAO/WHO) Food Standards Programme. In 2003, the Codex (Codex 2003) redefined part of the scientific basis of the SPS regulations but left the right of consumers to know aside.

> To justify a GM food regulation, the Codex standards call for an assessment of human health risks, while explicitly forbidding the inclusion of "environmental, ethical, moral and socio-economic aspects" in the assessment (Keane 2006, p. 326).

Further, even the precautionary principle, although officially adopted by the EU (2000) is not sufficient because the SPS requires a "science based risk assessment" to follow any appeal to the uncertainty of science on any issue.

This renders any progress toward labeling of GMOs extremely uncertain in today's climate of economic/trade supremacy in which multinational corporations (MNCs) such as Monsanto, for instance, routinely can and do tie up individuals who object to their products and their invasiveness and power in lengthy and costly litigations, such as the one involving farmer Percy Schmeiser in Canada (*Monsanto Canada Inc.* v. *Schmeiser* 2004) or the Oakhurst Dairy in Portland, Maine (Philipkoski 2003). In the latter case, Oakhurst's origin label read "Our Farmers Pledge: No artificial Growth Hormone," which Monsanto took to demean its product as it stood. Schmeiser ran afoul of Monsanto because (a) he refused to use their "terminator" seed or any other GMO product and (b) complained loudly when some of those seeds drifted over from neighboring farms, and Monsanto expected to get paid for their "use."

Essentially, Monsanto and other MNCs use their power and resources to practice their own brand of "protectionism" not for the public good as the EU does but for their hazardous products and the profits these generate. This ongoing battle is particularly galling because it has continued unabated for a long time, and it has little logic appeal, when for instance, organic food are so labeled, and one could claim that that label *implicitly* defends the superiority of those products against others that are not organic. Organic products also proclaim the importance of the ecological integrity of the systems where they grow, as well as the importance of the biological integrity and safety of those who purchase these products.

In the next section, the presence of hazardous lifestyle choices that also entail grave disregard for the rights of the hungry will be discussed.

8.4 Western Diets and Lifestyle Preferences: Vegan versus Carnivore

Within the agricultural sector, livestock create the most severe environmental impacts. The case to demote cattle on the development, environmental, health, ethical, and poverty alleviation agendas is strong and intensifying. Cattle have arguably caused or are related to the most environmental damage to the globe of any nonhuman species and suffer numerically the most of any other kinds of animals. Cattle numbers have increased 100% over the last 40 years. Livestock now outnumber humans 3 to 1 (Goodland 1998, p. 235).

In the previous section, it was noted that GMOs could be attacked on several grounds, whereas that it was the consumer's right to know, to choose, and to be safe, that provided the most important and strongest impetus against GMOs. In contrast, for the issue of diet choices and preferences, the consumer is no longer aligned with environmentalists on the side of integrity; on this issue, consumers, and, in general, people in Western affluent countries, have been manipulated by business interests and convinced they "need" meat protein far in excess of their real needs, their health, and environmental safety and integrity.

In the previous section, it was noted that the overwhelming majority of genetically modified grains are fed to animals, not people. According to Goodland (1998), and 1998 statistics, 68% of grain produced in the United States is fed to livestock (p. 237). On June 19, 2008, Clare Oxborrow, GM campaigner for Friends of the Earth, wrote in the *Independent*:

> Industry claims that GM crops are necessary to feed the world, are a cynical attempt to use the food crisis for financial gain—and governments should look at the industry's record before believing the hype. After a decade of commercialization, most GM crops are used for animal feed –not food, and they do not yield more than conventional crops (see Grice 2008).

In contrast, scientists have argued that "world population of 7 billion could be supported … on a vegetarian diet, assuming ideal distribution and no grain for livestock" (Goodland 1998, p. 236). The world can be divided between affluent countries and poor countries. The former consume about 800 kg of grain *indirectly* because it is converted into animal flesh and other products, without regard for energy efficiency or ecological safety; the latter consume about 200 kg of grain *directly* (Brown 1994).

When we consider the side effects of animal production, even aside from ethical considerations of the unacceptable conditions of all animals in industrial agriculture, there are many solid reasons to reopen the question of present diet preferences, especially when energy requirements and global warming are considered. Feeding "grain and vegetables to people rather than to biotech" (Goodland 1998, p. 237) is perfectly logical, and it even runs counter to the trade protectionism that is at the basis of WTO decisions and most trade agreements and the manipulated "freedom" of consumers to choose what is harmful to their health as well as the survival of impoverished people and of the planet as such.

The hazards of GMOs and of present diets are not generally publicized by the media. On May 26, 2008, even Canada voted "No" to GE food labeling.[1] The question remains, though: How are trends reversed that are strongly entrenched through ongoing marketing campaigns, that have convinced most of those who can afford it that eating meat is absolutely necessary, as well as demonstrating that one belongs to a more "advanced" or "better" society?

At this time, eating lower on the food chain (Goodland 1998, p. 242) is not the policy of any government, including, surprisingly, any Green platform. To attempt to turn back the tide—so to speak—will not be an easy task. The question of the injustice that is being practiced against the citizens of developing countries, although it should be primary, in fact it should represent a moral imperative, does not appear to make a dent, no matter how many starving African children are seen daily on television news. This is more than compassion fatigue: the connection between our consumerism, or choices and preferences, and their dreadful fate do not seem to connect in our minds. I propose two other avenues to reverse the trend: one is the appeal to our health (something that is often a good motive to initiate change), and the other is present spiraling energy costs that have a direct impact on most affluent people who own and often must drive a car.

8.5 Conclusion

We can finally turn to Comment No. 12[2] to consider what international law says about the "right to adequate food":

> The Right to Adequate Food (Article 11)
> 15. The right to adequate food, like any other human right, imposes three types or levels of obligations on State parties: the obligation to respect, to protect and to fulfill. In turn, the obligation to fulfill incorporates both an obligation to facilitate and an obligation to provide. The obligation to respect existing access to adequate food requires states parties not to take any measures that result in preventing such access. The obligation to protect requires measures by the state to ensure that enterprises or individuals do not deprive individuals of their access to adequate food. The obligation to fulfill (facilitate) means the State must proactively engage in activities intended to strengthen people's access to and utilization of resources and means to ensure their livelihood including food security. Finally, whenever an individual or group is unable for reasons beyond their control, to enjoy the right to adequate food by the means at their disposal, States have the obligation to fulfill (provide) that right directly. This obligation also applies for persons who are victims of natural or other disaster.

At the Vienna World Conference in 1993, the ESCR committee noted the "shocking reality" of state's tolerance for "massive and direct denials of economic, social and cultural rights"[3], and that document emphasized the fact that—had similar deprivations occurred in relation to civil and political rights—they would not have been tolerated.

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[1] Steinman, Jon. (2008), "Deconstructing Dinner" on Bill C-517's Defeat in the House of Commons, *The Tyee*, May 29, 2008; http://thetyee.ca/life/2008/05/26/Bill 517, saying inter alia "GM seeds/products have only one purpose, to increase the profits of Monsanto and a few other corporations. They have no other benefits. [They] do not increase production [or] cut back on chemicals."

[2] Comment No. 12, UN Doc.E/C.12/1999/5.

[3] U.N. Doc.E/1993,/22, Annex III, paras. 5 and 7.

The United Nations (UN) High Commissioner for Human Rights[4] remarks that the billions of people in developing countries in extreme poverty, include "approximately a fifth [who] do not have enough dietary energy and protein" as the Report adds:

> the victims of poverty are in fact denied almost all rights, not only adequate food, health care and housing.

The deprivation of food and of a safe environment, in fact, makes the presence of civil and political rights futile. Anyone who is starving or gravely ill not only cannot participate in the political process but also has no desire or motive to do so.

As the UN High Commissioner's Report cited notes, however, the presence of globalization adds to the marginalization of many impoverished/hungry people in developing countries, so that progressive implementation may be problematic because it runs counter to the primacy of trade that globalization enforces, as already noted.

Hence, true respect for life in all its manifestations should form the basis of a radically changed world order regarding food.

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9 Soil Ecosystem Services

Sustaining Returns on Investment into Natural Capital

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9.1 Introduction

Sustaining soil productivity in response to climate change is critical for two reasons: feeding the world under straitened circumstances and adapting to and mitigating climate change itself.

The supporting, provisioning, and regulating ecosystem services provided by soil are critical for food provision and for meeting the challenges of climate change. In many cases, however, the supporting services of soils are inadequate for sufficient provisioning of food, fiber, and fuel. Water and nutrients are often needed to ensure economic levels of plant productivity. Irrigation and fertilizers are frequently used to overcome inadequate natural stocks of water and nutrients in the soil. It is estimated that irrigated agriculture covers some 260 million hectares of the earth's surface, such that this 17% of the world's cultivated lands can thankfully provide 40% of the global production of food and fiber (Fereres & Evans 2006). Irrigated agriculture uses about three quarters of the world's fresh water that is abstracted for human use. There are pressures on the quantity of water available for feeding the world. Globally, some 175 million tons of nitrogen are taken up by crops, and synthetic fertilizers account for about 40% of this. Takahashi (2006) calculated that some 2 billion people—one third of the world's population—are dependent on synthetic nitrogenous fertilizers. These fertilizers, along with manures, through the leakage of nitrates from the rootzone, are diminishing the quality of our stocks of ground and surface waters. There are scientific matters, policy imperatives, and ethical issues that need to be addressed so that soils, which are a finite resource, can continue to produce food, fiber, and fuel in the face of climate change.

Soils play a key role in climate regulation, so there are direct feed-forward and feedback links between soil productivity and climate change. Soils through their regulating services in relation to the two greenhouse gases (GHGs) of carbon dioxide (CO_2) and nitrous oxide (N_2O) are critical for climate-change mitigation and adaptation. There are about 750 Gt of carbon (C) currently in the atmosphere, whereas there are about 1700 Gt-C in the soil and about 550 Gt-C stored in vegetation. Small changes in soil C, or land-use impacts on vegetation, can thus have a significant impact on the carbon dioxide in the atmosphere. Sarmiento and Gruber (2002) noted that since preindustrial times, soils and vegetation have provided a sink for 65 Gt-C, thereby buffering the rise in atmospheric CO_2 in response to anthropogenic emissions. Yet through land-cover change, the terrestrial stock of carbon has been reduced by 124 Gt-C (Sarmiento & Gruber 2002). The carbon and nitrogen cycles in soil are intimately linked. Soil productivity and fertilizer use is therefore an integral part of strategies for climate-change mitigation and adaptation. Nitrous oxide is a potent GHG and the fourth largest GHG emission

Sustaining Soil Productivity in Response to Global Climate Change: Science, Policy, and Ethics, First Edition.
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in terms of radiative forcing (Intergovernmental Panel on Climate Change [IPCC] 2007). Soil is the dominant source of atmospheric N_2O, contributing about 9 Tg y^{-1}, or about 60% of the total annual global emission (IPCC 1997).

It is therefore imperative that policies based on sound scientific understanding be developed to ensure that soil productivity can be sustained to feed the world and to mitigate and adapt to climate change. In this chapter, the political and ethical issues associated with balancing the need to produce food with GHG mitigation is described. Then how an ecosystem services approach that recognizes and values the soil's natural capital stocks of carbon, air, nutrients, and water and offers a means to ensure maximized use of natural capital and minimized use of added capital resources is outlined. Then three examples are provided:

- how land management practices in relation to soil C can be adopted to improve soil functioning and health,
- how natural capital can be valued and used to enhance soil and water productivity, and
- how resource management policy based on the natural capital value of the soil enables best use of the land and water resources within a catchment to realize a desired environmental outcome.

This chapter derives from a presentation made at the Organisation for Economic Development (OECD) workshop on "Sustaining Soil Productivity in Response to Global Climate Change—Science, Policy and Ethics" held in Madison, Wisconsin, in July 2009. Before proceeding to outline how returns on our investment into the natural capital of our soils can be sustained, it is pertinent to reflect on the seminal work on sustainability by Franklin Hiram King—a professor of agricultural physics at the University of Wisconsin, Madison, between 1888 and 1902 (Tanner & Simonson 1993).

9.2 F. H. King—"Farmers of Forty Centuries"

What is a temporal metric of sustainable soil productivity?

In 1909, F. H. King (Fig. 9.1) visited Japan, Korea, and China, which were countries where farmers had been farming productively on the same plot of land for 40 centuries (King 1911, p. 2). King set out to "consider the practices of some five hundred millions of people who have an unimpaired inheritance acquired through four thousand years" and sought "to learn how it is possible after even 40 centuries for their soils to be made to produce sufficiently for the maintenance of such dense populations." This challenge still remains a clarion call for today's researchers.

King found that "almost every foot of land is made to contribute material for food, fuel and fabric" (1911, p. 13) and noted that " which ever way we turned we were amazed at how these nations have been and are conserving and utilizing their natural resources and surprised at the magnitude of the returns they were getting from their fields. It is evident that these people, centuries ago, came to appreciate the value of [natural resources] in crop production" (King 1911, p. 2). What is amazing to us now is that a century ago King was using the language currently associated with contemporary ecological economics and natural capital valuation.

In delving deeper, King found that "judicious and rational methods of fertilization are everywhere practiced. Lumber and herbage for green manure and compost, and ash of the fuel and lumber used at home finds its way ultimately to the field as fertilizer. Manure of all kinds, human and animal, is religiously saved and applied to the fields in a manner which secures an efficiency far above our own practices" (pp. 8–9). Figure 113 from King (1911) is reproduced here as Figure 9.2, where King has added the legend that sustained soil productivity "is the product of brain, brawn and utilized waste."

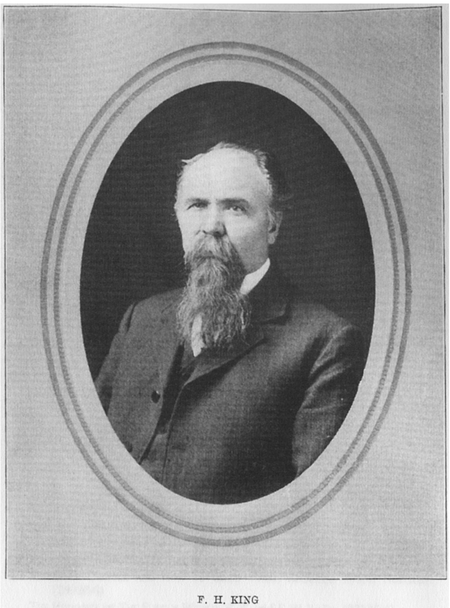


Figure 9.1 Franklin Hiram King (1848–1911), Professor of Agricultural Physics, University of Wisconsin, Madison between 1888 and 1901. King travelled to Asia in 1909 and wrote the book *Farmers of Forty Centuries*, which was published by his wife soon after his death in 1911.
Reproduced with the kind permission of Dover Publications.

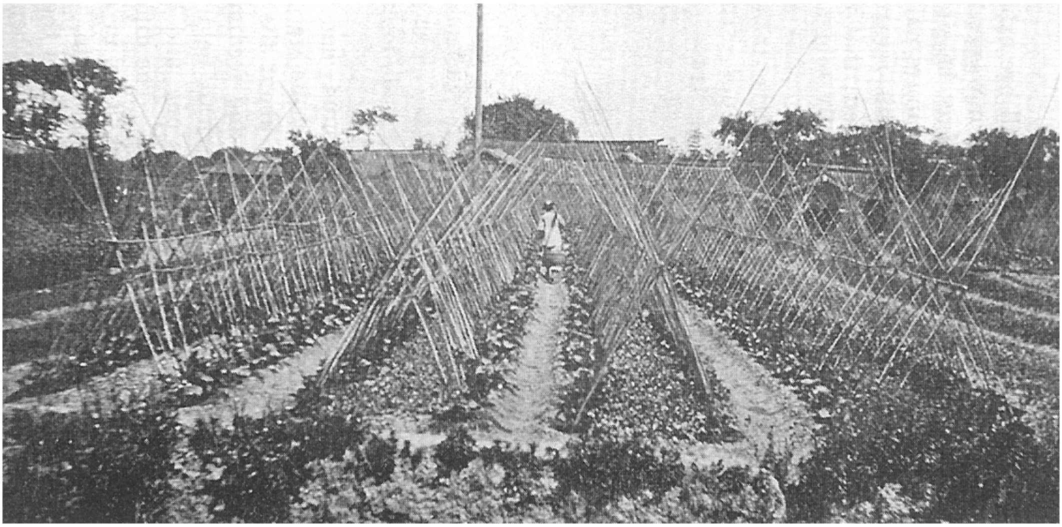


Figure 9.2 Where yield is the product of brain, brawn, and utilized waste. This is a reproduction of Figure 113 from F. H. King's book *Farmers of Forty Centuries*.
Reproduced with the kind permission of Dover Publications.

There is an interesting connection made by King in relation to his observation of the Asian farmers' utilization of organic wastes to sustain production through 40 centuries. He found that "the drinking of boiled water has been universally adopted as an individually available, thoroughly efficient safeguard against that class of deadly disease germs in the drinking water of a densely peopled country [where the wastes of the body, of fuel, and of fabric beyond use are taken back to the field" (King 1911, p. 323). King thus keenly concluded that "there is little reason to doubt that the tea industry had its foundation in the need of something to render boiled water palatable for drinking purposes."

Thus, one return on investment into the natural capital of recycled waste in soil has been the cultural service of tea drinking.

9.3 Soil: Valuable Natural Capital

The natural capital concept attempts to integrate thinking about economics and ecology by conceiving nature as capital (Fenech et al. 2003). Fenech et al. (1999) had noted that a skeletal conception of natural capital emerged around 1994; however, the notion can even be seen to be inherent in the earlier thinking of King and others. In observing the consequences of the losses of soil assets during the Dust Bowl era, Franklin D. Roosevelt, US President from 1933 to 1945, noted that "the nation that destroys its soil destroys itself" (*Letter to all State Governors on a Uniform Soil Conservation Law*, 1937). In the formation in New Zealand of a multi-institute research program called the Sustainable Land Use Research Initiative (SLURI), it was calculated that 17% of the nation's gross domestic product (GDP) was reliant on the top 150 mm of soil (Kirkham & Clothier 2007). Soil is indeed valuable natural capital.

Akin to the returns on financial capital, humans also benefit from returns on investment into natural capital through the ecosystem goods and services that flow from natural capital stocks. This recent notion of ecosystem services (Costanza & Daly 1992) can indeed be seen latent in the thinking of early ecologists. In 1949, Aldo Leopold wrote in his A *Sand County Almanac* that "land then, is not merely soil, it is a fountain of energy flowing through a circuit of soils, plants and animals" (p. 253).

Here soil is discussed as valuable natural capital, and in the next section, the ecosystem goods and services that flow from the soil's natural capital are discussed. Natural capital and ecosystem services are defined first. Following Dominati et al. (2010), natural capital assets are the stocks of natural materials and energy. Ecosystem services, which are discussed later, are the beneficial flows of goods between natural capital stocks or between stocks and humans.

Fenech et al. (1999) noted that "by bringing economic science and environmental science to an objective common ground, a natural capital model has the potential to provide a concrete means of comparing the economic and ecological costs and benefits of particular policies and programmes." They opined that "existing microeconomic theory may be 'ungreenable', if it is not reformulated" (p. 3). An inconvenient truth for economists.

Costanza (2009) has revisited this in light of the recent economic crisis, and he asserts that "the current financial meltdown is the result of under-regulated markets built on an ideology of free market capitalism and unlimited economic growth." The basis for this was that "the mainstream vision of the economy is based on a period when the world was still relatively empty of humans and their built infrastructure [and] in this 'empty world' context, built capital was the limiting factor, while natural capital and social capital were abundant. But the world has changed dramatically [as we recognize] that natural capital and social capital are not infinitely substitutable for built and human capital and that real biophysical limits exist to the expansion of the market economy." He calls for "a more sustainable and desirable future that focuses on quality of life rather than merely quantity of consumption" (p. 21).

Intensification of land use can, in the short term, meet human demands for increased quantities of food, fiber, and fuel and so achieve returns on investment into the soil's natural capital. However, through intensification we can, as Hawken et al. (1999) warn "temporarily exceed the carrying capacity of the earth, but put our natural capital into decline" and then wryly added "put another way, the ability to accelerate a car that is low on gasoline does not prove the tank is full" (p. 310).

The World Wide Fund for Nature (WWF) released its Living Planet Report in 2008. They commence by stating that "we only have one planet [and] when human demand on this capacity exceeds what is available we surpass ecological limits" (p. 2). Indeed they assert that humanity's ecological footprint exceeded the world's biocapacity of a single planet around 1986. They calculated that humans' ecological footprint now exceeds the planet's regenerative capacity by about 30%. To describe this better, they refer to the footprint exceedance in financial terms as being ecological debt, and they call for an ecosystems approach to enable a return to sustainability by reducing the ecological debt, and reestablishing a global biocapacity reserve.

A prime natural-capital stock is that of the waters in rivers, lakes, groundwaters, and soil storages. Soil provides the supporting and provisioning ecosystem services for growing plants and raising animals that enables the world to attempt to feed itself. There are, and increasingly there will be, critical challenges to ensure that we can produce enough food to feed ourselves. Sustaining soil productivity will be critical. Yet, as *The Economist* (September 18, 2008) reported, "the world is not facing so much a food crisis as a water crisis." *The Economist* then added that presently some 70% of the world's water consumption is used in farming and that there are pressing needs to make these natural capital stocks go further by developing knowledge and tools to increase water-use efficiency—that is, to reduce the water footprint of food, fiber, and fuel production. It concluded that indeed "farming tends to offer the best potential for thrift" (http://www.economist.com/node/12260907). This will nonetheless be a challenge. Robert Glennon in his book *Unquenchable: America's Water Crisis* (2009) notes that "California growers consume 80% of the state's water yet contribute only 2% to the gross state product [and] while cynics accuse farmers of milking the government, farmers are suffering from their own remarkable productivity … the United States has the cheapest food supply in the world. Better equipment, mechanization, hybrid seeds, fertilisers, pesticides and irrigation explain the so-called green revolution" (p. 276). Yet Glennon concluded optimistically for the case of agriculture, as "farmers are responding nimbly to these [thrifty] challenges by engaging in vanguard agriculture [through] identifying new ways of growing and marketing produce" (p. 278).

This thrifty imperative for vanguard agriculture will be ever more challenging and will require nimble responses to climate change.

The IPCC (2007) has released its fourth assessment report on the causes and impacts of climate change. Most IPCC climate-change scenarios point to a reduction in the natural capital stocks of water in the world's major food-producing regions. The IPCC Special Report on Emissions Scenarios (2000) considers four storylines. The one considered here, storyline A1, is for a market-oriented world, with strong economic growth and strong governance. The B scenario of this storyline is for a balance of energy production from both fossil and nonfossil sources, such that greenhouse gas emissions peak in 2050 and then decline. Scenario A1B is therefore a moderate scenario in terms of the global rise in temperature. Figure 9.3 shows the projections by the IPCC (2007) for the change in annual water runoff, which is a metric of the availability of water stocks, in terms of %ages for 2090–2099, relative to 1980–1999. The predicted diminutions in the natural capital stocks of available water are large in the food-producing areas of the western United States, Mexico, Chile, Argentina, South Africa, Australia, and especially the so-called

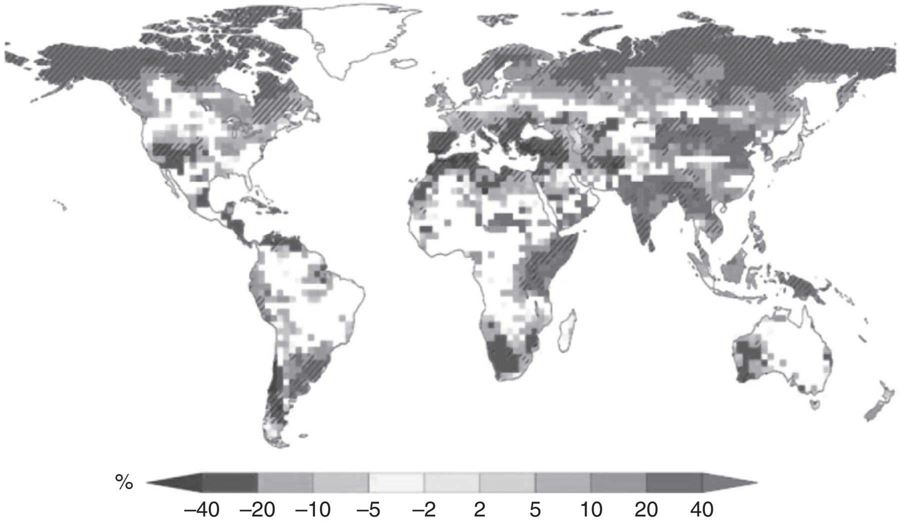


Figure 9.3 The projection by the Intergovernmental Panel on Climate Change using 12 models for the relative change, from the present, in the availability of stocks of water at the end of the twenty-first century under scenario A1B. The cross-hatching indicates where 90% of the models agree on the sign change.
Reproduced with permission from Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Figure 3.5 IPCC, Geneva, Switzerland.

MENA countries of the Middle East and North Africa. In contrast, the emerging economies of the BRIC countries of Brazil, Russia, India, and China will be blessed with largely unchanging or enhanced stocks of water availability to sustain soil productivity.

The global challenge for all countries, however, is to sustain productivity and returns on investment into their natural capital stocks of our soils and waters. Two international trends are working in diametrically opposing directions in relation to reducing the ecological footprint of humanity and sustaining global productivity. Water footprinting and ethical-eating initiatives are working toward reducing ecological debt. On the other hand, transnational land-for-food deals and food protectionism are threatening global ability to feed ourselves.

In the United Kingdom on August 20, 2008, the newspaper *The Guardian* cited the WWF report by Chapagain and Orr (2008) that "revealed the massive scale of UK's water consumption" (www.guardian.co.uk/environment/2008/aug/20/water.food1?INTCMP=SRCH). Whereas household water use in the United Kingdom is about 150 liters per person per day, Britons consume nearly 30 times as much in the "virtual water" that is used in the production of, or embedded in the imported food and textiles. Chapagain and Orr (2008) therefore estimated, in sum, that each Briton consumes 4,645 liters per day. Of that, only 38% of the water comes from Britain's own resources, and the rest depends on the water systems of other countries, many of whom are already, or are likely to be, adversely affected by climate change. For example, Spain exports some 1.4 million cubic meters of virtual water to the United Kingdom each year, and the top three "containers" of this virtual water are olives (344 mm^3/y), grapes (180), and oranges (91). Spain uses 70% of its available "blue" water from rivers, lakes, and groundwater for agriculture. Thus, there is an imperative to manage soils and irrigation to use this as efficiently as possible and to establish procedures to reduce the reliance of horticultural production on blue water and to develop strategies to maximize the natural capital stocks of the "green" water stored in the soil from rainfall. In *The Guardian* article, the technical director of the supermarket Marks & Spencer's, David Gregory, said "water was already a key part of the company's strategic decisions about where to source food for its stores … and where to grow crops in the future." There are moves to develop water footprinting labels on products, especially food, so that consumers can see how their purchasing choices affect the country-of-origin's natural capital stocks of water. The Food Ethics Council of the United Kingdom released its recommendations on water labels for food (Segal & MacMillan 2009). This initiative is aimed at consumers so that they can make ethical purchase choices that will act to reduce the consumption of virtual water associated with products and that will enable us to move toward meeting the WWF's challenge of 2008 "to reduce our footprint and get better at managing the ecosystems that provide services" (p. 1). Ethical eating might help us sustain soil productivity. There is, however, a contrary side to this story: a new form of food protectionism.

The Economist of May 21, 2009, reported on a powerful and contentious trend sweeping the poor world that might imperil the sustainability of global soil productivity: the outsourcing of food production by sovereign states to foreign lands. *The Economist* found many examples in which countries that export built and financial capital, but import food, are outsourcing farm production to countries that need financial capital but have the natural capital of land to spare. In their report, *The Economist* cites Peter Brabeck-Letmathe, the Chairman of Nestlé who asserts that "the purchases weren't about land, but water. For with the land comes the right to withdraw the water linked to it, in most countries essentially a freebie that increasingly could be the most valuable part of the deal—the great water-grab" (http://www.economist.com/node/13692889). *Fortune* magazine (June 16, 2009) even reported on "reaping reward from farmland," and they noted that "the biggest investors in farmland over the next decade will probably be sovereign wealth funds and governments of crop-starved countries eager to secure food supplies for their rapidly growing populations" (http://money.cnn.com/video/fortune/2009/06/10/fortune.investing.farmland.fortune/).

This aspect of food production raises another ethical issue. What value has the land ethic by companies or sovereign states that outsource food production to foreign lands? Leopold defined his land ethic as being simply an enlargement of "the boundaries of the community to include soils, waters, plants, and animals, or collectively: the land…. [A] land ethic changes the role of *Homo sapiens* from conqueror of the land-community to plain member and citizen of it" (Leopold 1949, p. 240). Will foreign-based companies or foreign states sustain a land ethic when they are neither a member of the community in which their food is grown nor a citizen of the country from which their food is sourced? It is doubtful and it is concerning because it seems to us that this variant form of neocolonialism is unfortunately returning *Homo sapiens* [again to a] conqueror of the land-community and worse, conqueror of someone else's land community!

The outsourcing of food production to foreign and often fragile soils will lead to further degradation of global natural capital stocks and more reductions in the number and vitality of global ecosystem services. What global value have such services?

9.4 Valuing Ecosystem Services

In a landmark paper, Costanza et al. (1997) quantified how valuable ecosystem services are. They determined how the flow of goods and services from natural capital stocks provide value over and above the simple rent, or producer surplus, that is received from them because there is also value in a consumer surplus that comes from nonmarketed benefits. Costanza et al. considered 17 ecosystem services across 16 biomes covering both marine and terrestrial systems. They based their valuation on estimates of "willingness-to-pay" and concluded that on average the global value of these services would be US$33 trillion, being some 1.8 times their estimate of global gross national product.

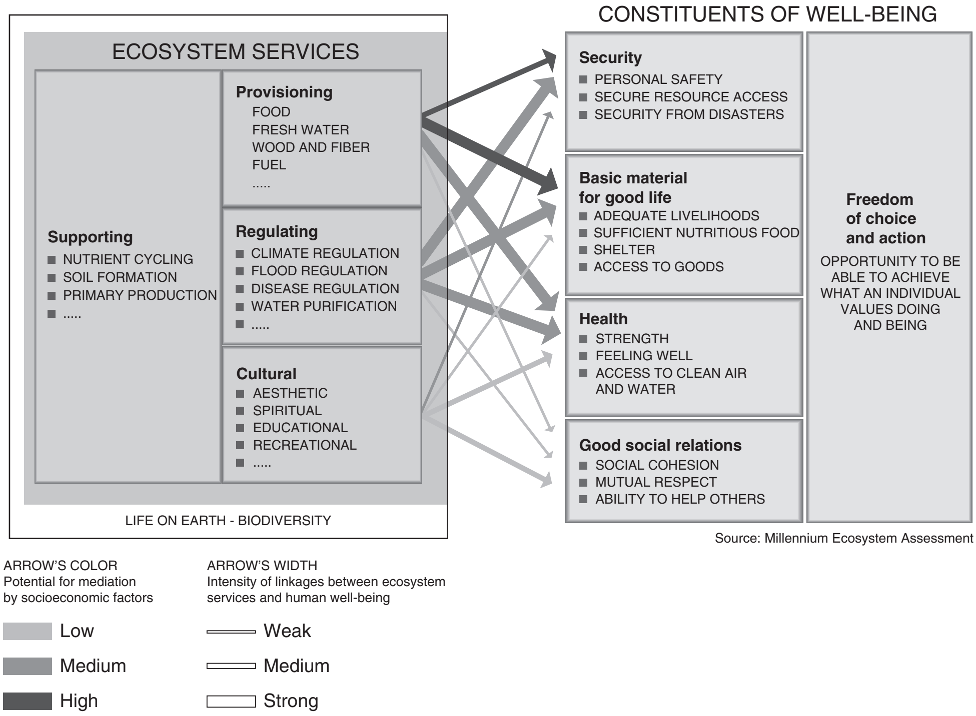
Despite the massive economic value of these natural capital stocks and these ecosystem services, it was detected early in the twenty-first century that human actions were still resulting in losses of the inventory value of natural capital assets and reductions in the number and vitality of ecosystem services. In 2001, the Millennium Ecosystem Assessment (MA) program was established by the United Nations to assess the consequences of ecosystem change for human well-being and to provide the scientific basis for the actions needed to enhance the conservation and sustainable use of those systems and their contribution to human well-being. This assessment involved the work of more than 1,360 experts worldwide. Their findings (MA, 2005) provided a state-of-the-art scientific appraisal of the condition and trends in the world's ecosystems and the services they provide and the options to restore, conserve, or enhance the sustainable use of ecosystems. The MA categorized ecosystem services into four broad, often overlapping groups:

- Provisioning services
- Regulating services
- Cultural services
- Supporting services.

As shown in Figure 9.4, the MA linked these four ecosystem services to five constituents of human well-being: security, basic materials, health, social relations, and freedom of choice. Their ecosystem-services approach is based on considering many interacting ecosystem services and not just looking at the benefits from a single service. This holistic approach allows integrated assessment of the overall benefits that an ecosystem provides and enables assessment of how these benefits can change when different pressure are exerted on the ecosystem.

In 2007, the World Resources Institute (Irwin & Ranganathan 2007) published a report on restoring nature's capital, which was an action agenda to sustain ecosystem services. They lamented that national accounting systems had failed to keep track of the inventory value of natural capital assets, and they called for a fundamentally new approach to managing the natural capital assets upon which all life depends. A year later they produced a guide for decision makers on ecosystem services (Ranganathan et al. 2008). They suggested how decision makers could put into operation the concept of ecosystem services by identifying how a decision depends on nature's flows, or ecosystem services, and how a decision will in turn affect these flows. This procedure would increase the ability to understand and make trade-offs across ecosystem services, in space and time, and "in doing so win more and lose less." The guidance scheme seeks to improve the overall outcome of these trade-offs by building on knowledge gained from multiple-use ecosystem management, and through identifying ecosystem services more explicitly.

Nonetheless, Daily and Matson (2008) note that "transformations will be required to move from conceptual frameworks and theory to practical integration of ecosystem services into decision-making, in a way that is credible, replicable, scalable, and sustainable" (p. 9456). In relation to soil ecosystem services, Daily (1997) argued that "research to better characterize [than the MA classification] the ecosystem services supplied by soils, was needed, along with a better understanding of the relationships between the services supplied by soils and other systems" (p. 117). Dominati et al. (2009) noted that in the MA scheme the processes of soil functioning, which is the means of production of goods and services, are mixed up with the benefits. They have provided a draft framework that makes explicit distinction between soil



Source: Millennium Ecosystem Assessment

Figure 9.4 The four-way classification of ecosystem services of the Millennium Ecosystem Assessment (2005) and the links between these services and the five constituents of human well-being.

processes and the benefits derived from soil. Their draft framework relates the inherent and manageable properties of the soil's natural capital to natural capital stocks and inventories, as well as the underlying supporting processes. Dominati et al. (2010) then link the soil's natural capital through provisioning processes, regulating processes, and sociocultural processes to the servicing of human needs and creating benefits.

Daily and Matson (2008) conclude that "there remain many highly nuanced scientific challenges for ecologists, economists, and other social scientists to understand how human actions affect ecosystems, the provision of ecosystem services, and the value of those services" (p. 9456). This is an exciting area of active research, which is not without challenges.

The three examples of securing sustainable returns on investment into the soil's natural capital are now presented: soil processes controlled by carbon to soil ecosystem services are linked; supporting and regulating soil services in the provision of terroir value for wine are valued; and a valuation of the soil's natural capital to allocate a nutrient-loss right for policy to limit nonpoint source pollution by nutrients from farms is used.

9.5 Valuing Carbon and Soil Ecosystem Services

Soil carbon is critical for the biophysical processes operating in the soil, and it determines the value of the ecosystem services provided by soil. Carbon breathes life into soil. Soil carbon confers fertility to the soil beyond that provided by the weathered parent material. Carbon acts to sustain the soil functioning, which enables soil to provide the ecosystem services that are essential for human well-being. Soil without organic carbon, is called "rock." The natural capital stock of soil carbon is, in response, strongly controlled by land management practices. There are good returns on investment from enhancing the natural capital stocks of carbon. Lal (2009) has outlined land management strategies for enhancing soil carbon stocks: growing more biomass, recycling biomass and biosolids, reducing soil erosion, decreasing leaching, and minimizing decomposition. Here the changing value of the soil's ecosystem services as a result of different land management practices, which have resulted in neighboring apple orchards ending up with different values of soil carbon, are discussed.

Deurer et al. (2008) studied an organic apple orchard and a neighboring integrated apple production system in the Hawke's Bay, New Zealand. Both orchards had the same general soil characteristics. The genoforms of the soils (Droogers & Bouma 1997) are Fluvisols and have a silt-loam texture. The organic orchard system had been under organic management since 1997. The apple trees in the orchard were 13 years old. The apple cultivar was "Braeburn," and the rootstock cultivar was MM.106. As a source of nutrients, green-waste compost was brought in and was applied to the topsoil of the tree rows once a year at a rate of 5 to 10 t/ha, and lime was added at a rate of 300 kg/ha every 4 years. The apple trees in the adjacent integrated orchard system were 12 years old. The apple cultivar was "Sciros"/Pacific Rose™, and the rootstock variety was MM.106. A 0.5-m wide strip under the trees was kept bare by regular herbicide applications. The apple trees were drip-irrigated during the vegetative period. The irrigation, nutrient, and pest management followed the guidelines of integrated fruit production.

Spatially averaged, the total carbon stock in the top 0.3 m of the integrated orchard is now 2.6 kg-C m^{-2}, whereas it is significantly ($P < 0.05$) higher at 3.8 kg-C m^{-2} in the organic orchard. No initial soil carbon measurements were available, so rates of change have not been commented on, but rather current soil functioning is discussed. Deurer et al. (2009) found by substrate-induced respiration that the microbial biomass carbon in top 100 mm of the soil of integrated orchard was 73 g-C m^{-2}, whereas it was two times higher at 143 in the organic orchard. They also found a near-twofold difference in anecic worm fresh weight in the soil between the integrated orchard (85 g m^{-2}) and the organic orchard soil (154 g m^{-2}). Thus, after 12 years, these two similar soils now have different phenoforms (Droogers & Bouma 1997) as a result of the different carbon strategies and orchard-management practices. Not surprisingly then, the structures of the soils are now also quite distinct, as the two x-ray images in Figure 9.5 reveal. Deurer et al. (2009) have used tomographic analysis of these images to determine the impact of the different carbon contents on the macroporous structure of these soils.

Here, by selecting tomographic analyses from two cores, one each from the different orchards, the magnitude of, and reasons for, the different macroporous structure is revealed. Using the methodology of Deurer et al. (2009), Figure 9.6 presents the detailed profile in macroporosity of two cores from that study. Here, a macropore is a pore whose diameter is greater than 0.3 mm.

For core 1 from the integrated orchard, the average volumetric macroporosity is 3.1 ± 1.4%, whereas it is 9.4 ± 1.7% for the organic orchard. Deurer et al. (2009) present the results from the additional two cores taken from each orchard. On average the macroporosity found for soil of the integrated orchard was 2.4 ± 0.5% and for the organic orchard soil it was 7.5 ± 2.1%. This difference was despite the mean macropore radii being similar between the integrated orchard (0.41 ± .02 mm) and the organic orchard (0.39 ± 0.01 mm). Different carbon management practices have, therefore, led to these soils now having different phenoforms, especially in relation to macroporosity.

These different soils, so-called phenoforms because they reflect the consequences of different soil management practices, will also have different functioning, and so the ecosystems services

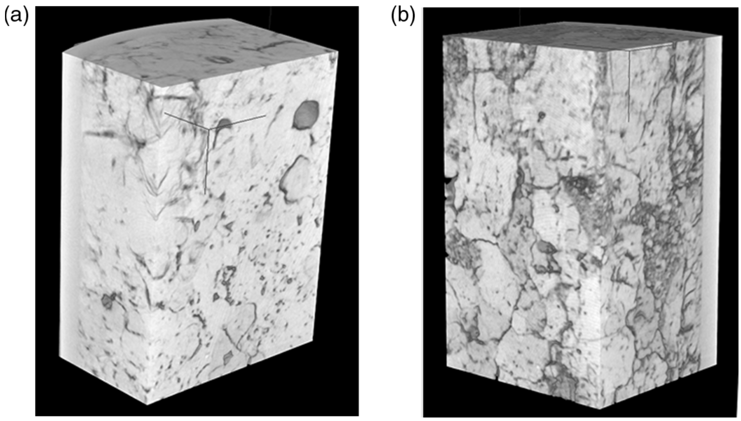


Figure 9.5 X-ray tomographic images of soil using a Metris X-tek Benchtop CT system at SIMBIOS Centre of the University of Abertay (Dundee, Scotland) with the 160 kV X-ray source and a 12-bit CCD camera. (a) *(Left)* An undisturbed soil core (70 mm diameter, 100 mm length) taken from row of the integrated apple orchard where the top of the column is the soil surface. (b) *(Right)* As for 9.5*A*, but for an undisturbed soil core from the row of the organic apple orchard.
Adapted from Deurer et al. 2009.

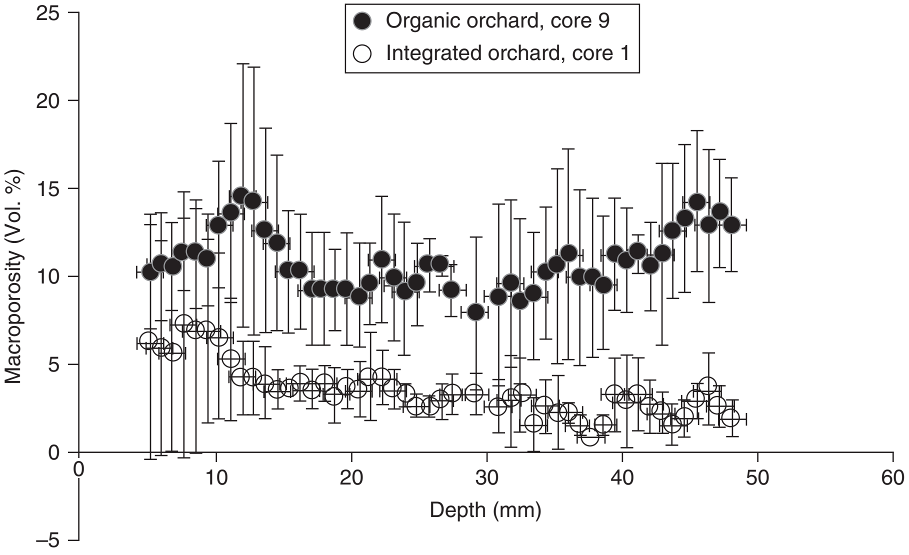


Figure 9.6 The macroporosity (pores >0.3 mm diameter) as a function of depth below the soil surface in the tree row of an organic (core 9) and integrated (core 1) apple-orchard system. On average the volumetric macroporosity of core 1 was 3.1% ± 1.4 and of core 9 it was 9.4% ± 1.7. For each depth, and core, the average and standard deviation of three subcolumns is shown, where the dimension of the subcolumns was 43 × 20 × 17 mm, such that the volume of the subcolumns was 14620 mm^3.

they provide will also be different. Clothier et al. (2008b) identified that 12 of the 17 terrestrial ecosystem services valued by Costanza et al. (1997) would be enhanced by soil macropores, and they estimated the global contribution of macropore functioning to be worth US$304 billion per year. Thus, the natural capital value of the soil in the organic orchard is now considered to be greater than that of the integrated orchard as a result of the different carbon management practices.

We detail the contrasting value of the soil ecosystem services differentially provided by these soils. The different value of different service types are considered: two are regulating services and one is a supporting service.

Deurer et al. (2009) simulated gaseous diffusion through the macropore systems of the two different soils (see Fig. 9.5). The relative diffusion coefficients, that is, relative to free-air diffusion, at the aggregate scale in the organic orchard soil was 0.024, whereas it was an order of magnitude less, at 0.0056 in the integrated orchard. This difference provides the regulating soil services of aeration, as well as drainage. Carbon management in the organic orchard has provided some mitigation of climate change by sequestering carbon in the soil. Then by maintaining a network of connected macropores, so carbon has sustained the regulating services of soil aeration and drainage that will assist with climate-change adaptation if we are to receive more intense rainfall events, for example.

Aslam et al. (2009) asked whether this increase in organic carbon would improve the filtering functioning of soil for organic pesticides—another regulating ecosystem service. Not only did they consider these two orchard soils, but they also considered phenoforms of a pastoral soil whose carbon contents now differ: the soil from a stock camp had a total carbon content of 8.5%, whereas the same soil type of the grazed pasture outside the stock camp was 4.8%. They found that for both land uses, the increase in soil carbon significantly increased the values of indicators of the pesticide filtering functioning for sorption and degradation of pesticides. This pesticide regulation is a valuable service, for Pretty et al. (2000) have assessed that the total external costs of pesticide use in agriculture in the United Kingdom is £33 ha^{-1} of farmland receiving pesticides, which on average amounted to 3.84 kg-active ingredient ha^{-1}. The total external cost to the United Kingdom of agricultural pesticide-use was found to equal £193 m. So, if by enhancing levels of soil carbon some of this could be filtered and rendered harmless in the soil, then the value of the external cost saving from that regulating service would be substantial.

However, in the pastoral system the higher level of soil carbon was found by Aslam et al. (2009) to increase the degree of soil hydrophobicity. This at first glance might suggest an ecosystem dis-service (Zhang et al. 2007), for hydrophobicity could probably lead to increased run-off of rainwater, which would be considered a regulating dis-service by wasting water and potentially leading to soil degradation through sheet erosion. However, as noted by Clothier et al. (2008b), if a hydrophobic soil also has an open-vented macroporous system, then any surface water-film created by water repellency would quickly be captured by the macropores and routed to the subsurface soil where water contents are likely to be higher, and the degree of hydrophobicity less severe to enable absorption there. Thus, macropores can provide a regulating service of water capture to overcome the dis-service created by the functioning of hydrophobicity.

The prime reason the organic growers use composts is to provide the supporting ecosystem service of nutrient cycling from the composted organic matter. Over and above the provision of nitrogen directly from the compost, the resulting change in the carbon content of the soil was found by Kim et al. (2009) to enhance the supporting soil service of nutrient creation through nitrogen (N) mineralization. They found using undisturbed soil cores that the average net N-mineralization, across three temperatures, in the integrated orchard was $0.41 \pm 0.25\,\mu g\text{-N g}^{-1}\,d^{-1}$, and some fivefold higher in the organic orchard soil at $2.28 \pm 0.50\,\mu g\text{-N g}^{-1}\,d^{-1}$. This difference they found to be correlated with relative sizes of the labile pool of soil carbon as measured using the hot-water extractable content of the soil's C (Sparling et al. 1998). The labile pool of soil carbon in the integrated orchard was found to be $0.06\,kg\text{-C m}^{-2}$ (cf. total C at 2.6), and for the organic orchard it was $0.11\,kg\text{-C m}^{-2}$ (cf. total C at 3.8). Thus, through different orchard practices in relation to organic matter, the soil of the organic orchard now has a significantly ($P<0.05$) higher level of total soil carbon and a significantly higher fraction of labile soil carbon than the integrated orchard. As a result of different soil functioning, the supporting ecosystem service of nutrient generation is greater in the soil phenoform with the higher soil carbon content.

The soil's supporting service of nutrient cycling can therefore be sustained if good carbon management practices are adopted. Furthermore, these same carbon management practices can actually assist with the mitigation of, and adaptation to, climate change. Sustaining soil productivity thus enables our landscapes to provide the valuable provisioning service of food production.

9.6 Valuing Terroir

The ecosystem services provided by soil, climate, and local landscape coupled with grape variety and the skills of the viticulturalists and oenologists confer on wine the valuable notion of terroir. Studies have shown that soil and weather ecosystem services explain most of the terroir effect (Conradie et al. 2002; Morlat 1998), with vine water supply, soil depth, and potential vine vigor being the major contributing factors (Morlat 2001; Bodin & Morlat 2006). Here the role of the supporting ecosystem services of soil water storage and nitrogen mineralization is quantified on the natural capital value of terroir. A natural capital valuation model for terroir was developed that contains four sub-models of a plant-growth meta-model based on weather and soil, soil and water management practices, environmental impacts, and economic valuations. This has been applied to examine two aspects of natural capital: the terroir return on investment into water for irrigation and the return on investment of changing the carbon content of the soil. Salient details are described as follows.

9.6.1 Plant Growth Model

A simplified meta-model of Soil Plant Atmosphere System Model (SPASMO; Green et al. 2008) is used to grow the vine through capturing carbon and allocating it to the plant parts of shoot, root, leaf, and berry in relation to the prevailing weather conditions and the status of soil-water and nitrogen in the rootzone. For simplicity the soil is considered as a single layer, and for each run we output the results for soil depths from 200 mm through to 1800 mm in steps of 200 mm. The model runs on a weekly time step and used a 30-year weather record for the viticultural region of Marlborough, New Zealand.

9.6.2 Soil and Water Management Practices

Irrigation is applied whenever the soil water content in the rootzone drops to a trigger value whereupon the deficit is replaced. Should the water content of the root zone exceed field capacity then drainage and leaching occurs. Two dressings of nitrogen (N) in 10 kg-N ha^{-1} applications on 1 November and 1 January are applied. Meanwhile nitrogen is mineralized by the soil in relation to the labile carbon fraction of the soil's humus pool and in response to soil temperature. Nitrogen is also mineralized from the litter pool of prunings, and there is transfer of carbon between the litter and humus pools. Nitrogen is leached depending on the concentration of nitrate in the soil solution, and nitrous oxide is generated according to IPCC rules in relation

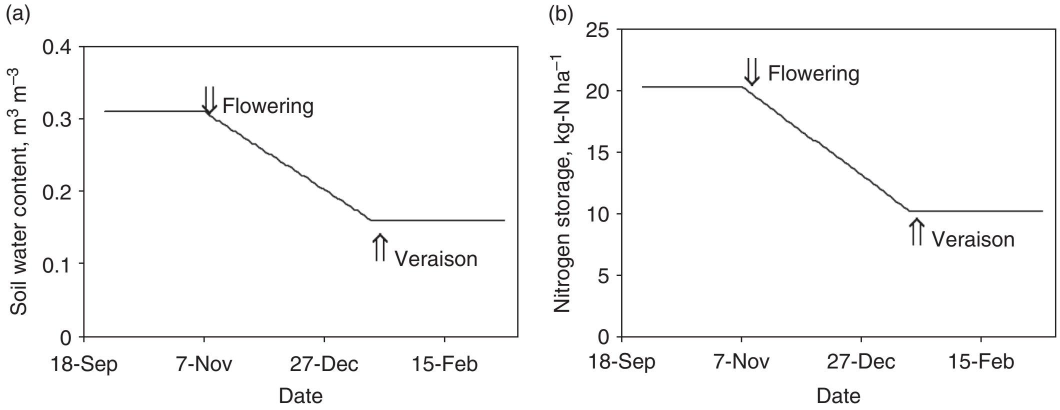


Figure 9.7 (a) The time course of water content in a viticultural soil in Marlborough, New Zealand, that would provide for optimum conditions for vine and berry growth and maximize the quality of the grapes to confer maximum terroir value. (b) The time course of soil nitrogen storage in a viticultural soil in Marlborough, New Zealand, that would provide for optimum conditions for vine and berry growth and maximize the quality of the grapes to confer maximum terroir value.

to nitrogen fertilizers and prunings. Vine growth is enhanced according to the water and nitrogen status of the root zone. The vines are pruned every time the canopy biomass reaches a trigger value, and the prunings left on the soil surface as decomposing litter.

9.6.3 *Environmental Impacts*

At present for environmental costs only nitrate leaching and nitrous oxide emissions have been considered by assigning an environmental cost to nitrate leaching of NZ\$10 per kg-N ha^{-1} (after Pretty et al. 2000) and a cost due to nitrous oxide emissions estimated using IPCC rules with the price of carbon set at NZ\$50 t^{-1}. It would be possible to add in easily the costs of other externalities, such as pesticides, by using such information as presented by Pretty et al.

9.6.4 *Economic Costs and Valuation*

A temporal trend from bud break to harvest in both the soil water content of the rootzone (Fig. 9.7a) and soil nitrogen storage (Fig. 9.7b) is defined and one that would confer the maximum value to terroir. Freely available water is considered best right up until flowering to ensure maximum fruit set and optimum nitrogen storage in the roots, vine, shoots, and leaves. After flowering through until veraison—that is the onset of berry ripening—it is best if there is a reduction in soil water and nitrogen, so as to limit vegetative vigour (Green et al. 2008). Following veraison, lower levels of water and nitrogen are considered ideal to limit vegetative vigor, enhance light penetration to the bunches, and encourage a rise in sugar (Brix) levels in the berries. The economic modeling penalizes any deviation from these ideal time courses.

The cost of any daily deviation from these ideal paths is subtracted, in weekly blocks from the maximum terroir value. A bottle of Sauvignon blanc from Marlborough can fetch over £20 (NZ\$50) in London, and so we take here the maximum terroir value to be NZ\$25,000 ha^{-1}.

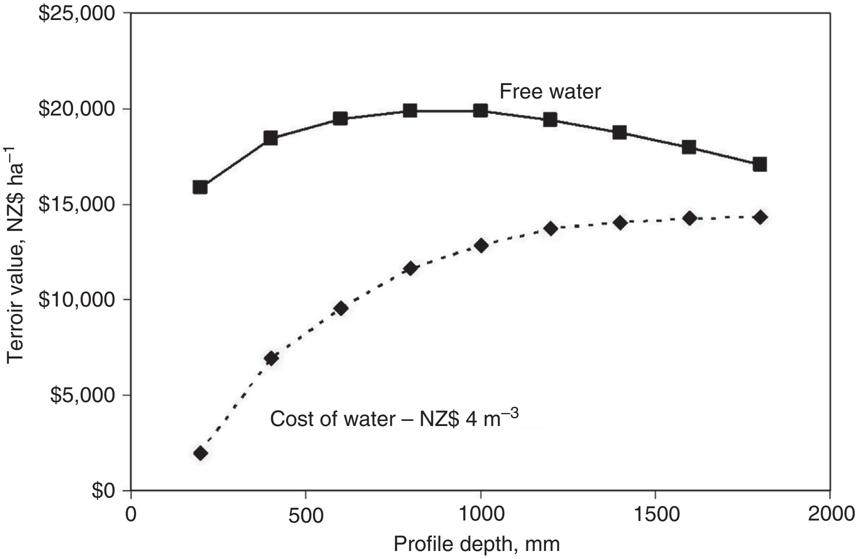


Figure 9.8 The pattern of terroir value as a function of soil depth calculated for a viticultural soil in Marlborough, New Zealand. The maximum terroir value was set at NZ$25,000 ha^{-1} and penalties were accrued throughout the season as rootzone conditions deviated from the ideal time courses for water and nitrogen stocks outlined in Figure 9.7. For the upper curve (*solid line*) there was no cost for the water, whereas for the lower curve (*dotted line*) water was priced at NZ$4 m^{-3}.

The daily deviation cost for when the soil water lies to either side of the optimum is taken to be NZ$20,000 per (m^3 m^{-3}) of water content. For nitrogen, because of its greater impact on vine vigor, any deviation from the optimum is penalized by the square of the distance from the ideal value, and a positive deviation is penalized more than a deficit. The daily penalty cost for N excess is taken to be NZ$0.40 per (kg-N ha^{-1})^2 and NZ$0.20 per (kg-N ha^{-1})^2 for an N deficit. The weekly penalty costs for deviating from the ideal water and nitrogen trajectories are summed, and then subtracted from the maximum terroir value, as are the environmental costs associated with nitrate leaching and nitrous oxide emissions.

The first application of the terroir calculator we consider here is for the case where the natural capital stock of blue water available for irrigation (Rockström et al. 1999) is considered to be free. The model irrigates “perfectly” by meeting green-water demands as required, and the only cost associated with irrigation is thus operational, say because of pumping costs, which we set at NZ$20 ha^{-1}. The value of terroir in this case is shown in Figure 9.8 as a function of soil depth. For shallow soils, there is a need to irrigate more frequently, and the operational cost of doing so reduces net terroir value. For deeper soils, the larger water holding capacity and greater provision of nitrogen through mineralization result in greater deviations away from the sought-after decline in water and nitrogen stocks. There are additional costs associated with leaf plucking and pruning. Morlat and Bodin (2006) found that Chenin vines growing on deeper soils had larger berries that were lower in sugars and anthocyanins, higher acidity, and with a lower phenolic index than those growing on shallower soils. In our case, a soil depth of 800 mm would maximize terroir value in relation to water and nitrogen regimes.

If water were not taken to be free because a value had been assigned to the natural capital stocks of blue water used for irrigation, then we can assess what impact this might have on terroir value. If the meta-model is rerun with the price for water at NZ$4 m^{-3}, being the cost of domestic

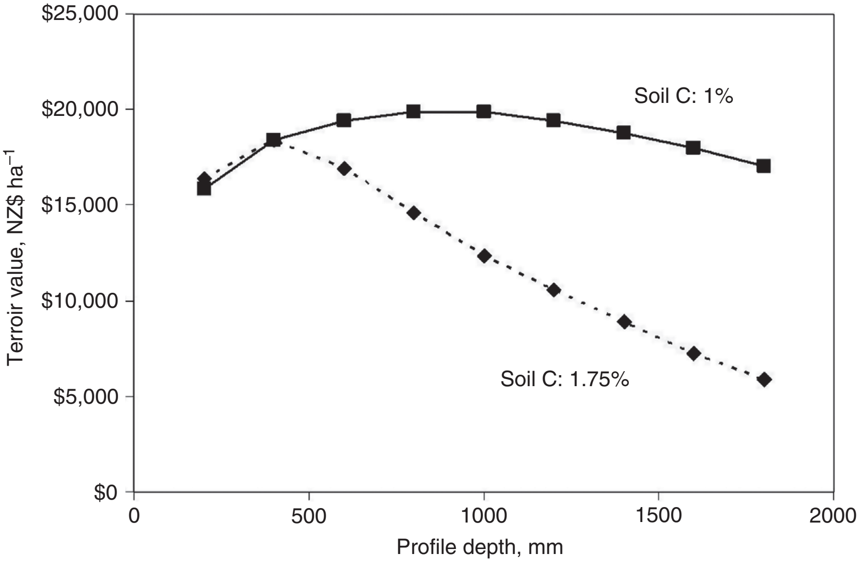


Figure 9.9 The pattern of terroir value as a function of soil depth calculated for a viticultural soil in Marlborough, New Zealand. For the upper curve the soil had a soil carbon content of 1%, whereas for the lower curve (*dotted line*) the carbon content of soil was increased to 1.75%, and there was enhanced soil water storage and nitrogen mineralization.

water in some American and European cities, a different pattern for terroir value is obtained. The return on investment into the soil's natural capital changes (see Fig. 9.8). It is now less because of the additional costs associated with using irrigation to meet water demands over and above those that cannot be supplied as green water from the supporting services from the soil and climate. For the shallowest soil of 200 mm, the inability to store sufficient water and the additional costs of supplying the vine's needs mean that terroir is almost valueless. In this case where water is a valuable commodity, deeper soils will have a much higher natural capital value.

Soil carbon is an inherent property of the natural capital value of soil through its role in controlling soil functioning. This inherent property would relate to the genoform of the soil (Droogers & Bouma 1997). But in addition, soil carbon can be changed through land management practices (see Fig. 9.5), and so it is also a manageable property of the soil's natural capital value (Dominati et al. 2010). Thus, land management by changing the soil's carbon content can affect its regulating and provisioning ecosystem services and therefore alter its natural capital value. The soil with a changed soil-carbon content due to land management practices is referred to as a phenoform (Droogers & Bouma 1997). Figure 9.9 compares the terroir value of the genoform with its soil carbon content of 1% with that of the phenoform having a soil carbon content of 1.75%. The water and nitrogen provisioning services of the soil were altered in relation to C using the soil water content changes suggested by Rawls et al. (2003), and for nitrogen mineralization by Kim et al. (2009). The 0.75-percent rise in soil carbon would, for such a sandy soil, result in a 3.75-percent increase in the field capacity value of the soil according to Rawls et al. (2003). The rise in soil carbon would, according to Kim et al. (2009) change the maximum mineralization rate from 0.2 mg-N l^{-1} d^{-1} to 0.39 mg-N l^{-1} d^{-1}. The increase in the water and nutrient supporting services provides a marginal increase in terroir value for shallow soils, but once the soil depth increases beyond about 500 mm, the additional water and nitrogen results in vegetative vigor as a result of not being able to track down the sought-after declining pattern of soil water content and nitrogen storage. The prescribed penalty of deviating from the nitrogen line of NZ\$0.40 per (kg-N ha^{-1})^2 means that 'pruning' costs go from NZ\$294 ha^{-1} for a 200-mm deep soil to NZ\$12,795 ha^{-1} for an 1800-mm deep soil.

Yet the comparative pattern of the two curves in Figure 9.9 does suggest how carbon management can be used in viticulture to enhance soil health and the maintenance of supporting, regulating, and provisioning services. Mulches of composted prunings and marc (the crushed grape skins) can be used to raise the carbon content of just the surface soil. Such a shallow depth of higher carbon contents does not provide excessive vigor through either enhanced water holding capacity, or nitrogen mineralization (see Fig. 9.9). Indeed, there are many other associated soil- and vineyard-health benefits from using mulches in vineyards, as detailed by Agnew et al. (2002). These include soil microbial diversity, weed suppression, and reduced herbicide use, plus increases in the yeast available nitrogen in the grape juice.

Thus, if nimble land management practices are used to manage better carbon in vineyards, the grower will be able to secure good returns on investment into the natural capital of the soil through enhanced supporting, regulating and provisioning services.

9.7 Land-Use Policy, Nutrient Management, and Natural Capital

To maintain food supplies and enhance the productive capacity of the landscape, there has been land-use intensification through the increasing use of fertilizers and irrigation to overcome shortfalls in the soil's natural capital (Mackay 2008). Soils have pores and are leaky. So there is a hydrologic connection between the soil of the rootzone and both surface and underlying groundwaters. The intensification of land use through fertilizer use and irrigation to realize levels of supporting services well beyond that supported by the natural capital value of the soil is putting at risk both our terrestrial and marine water resources. The *Guardian Weekly* noted in 2002 that "water is now known as 'blue gold' … and 'blue gold' is this century's most urgent environmental issue" (Vidal 2002, http://www.guardian.co.uk/environment/2002/aug/22/worldsummit2002.earth2?INTCMP=SRCH). Land management determines water quality. There is increasing urgency to manage our lands sustainably so that the "gold mine" of our waters is protected and enhanced. It is imperative for our productive and ecological futures that a policy for sustainable management of land is developed to protect the natural capital of our ground and surface waters.

Nutrient management policies have been developed over the last 20 to 30 years to limit nonpoint source pollution by fertilizers. In 1980, the European Union (EU) issued a directive on "The Quality of Water Intended for Human Consumption." In 1991 they issued a Nitrates Directives. Agriculture was increasingly becoming regulated by environmental policies. The Dutch introduced a nutrient accounting system called MINAS in an attempt to improve water quality: levies would be charged if farms exceeded certain nutrient loadings on the environment. However, this had limited success because the levies were not sufficiently prohibitive relative to the productive value of fertilizer. The Dutch have now simply resorted to focusing their controls by limiting applications of nutrients. In New Zealand, some regional councils have developed policy for nutrient caps based on a benchmarking of current fertilizer and farm practices, so called "grand-parenting." Trading and demanding changed farm practices is then intended to be used to bring down the loadings on water bodies from farms. This is the so-called "cap and trade" process. Such policy is a blunt instrument focused on inputs, and there are equity issues involved that inadvertently favor "today's polluter." In Australia, environmental auctions are being used to procure changes that will improve ecosystem services, and through bundling these it is hoped to realize water quality improvement, greenhouse gas reduction, and habitat provision. However, because of the small financial incentive in the value of the auction, relative to the required magnitude of the changes required to address widespread nonpoint source pollution by nutrients, these auctions are unlikely to be successful.

Reconsidering how nature's bounty is viewed by acknowledging natural capital stocks would provide a better foundation on which to base nutrient management policy. As we pointed out previously, Costanza (2009) concluded that if we are to move toward a new sustainable economy that we need to recognize "that natural capital [is] not infinitely substitutable for built capital, and that real biophysical limits exist" (p. 20). Hawken et al. (1999) questions "how is it that we have created an economic system that tells us it is cheaper to destroy the earth and exhaust its people than to nurture them?" (p. 321). They answer that this will be "when natural capital is no longer treated as free, unlimited and inconsequential, but as an integral and indispensable part of production [and] our system of accounting will change" (p. 61). One natural capital asset they highlighted was soil, noting that "we can no more manufacture a soil with a tank of chemicals than we can invent a rainforest" (p. 204), and they concluded that "understanding soil, the ultimate natural capital is the key to changing agriculture from part of the climate problem into part of the solution" (p. 204).

We now outline how we have been involved with policy analysts in developing a nutrient management policy for Horizons Regional Council in New Zealand that is based on the concept of natural capital. Horizons' new omnibus resource management policy (http://www.horizons.govt.nz/default.aspx?pageid=307), the One Plan, has in Rule 13-1, classified dairy farming and other intensive land uses as a controlled activity, rather than a permitted activity as it is now. Farming as a controlled activity will, if the policy becomes law, require a resource consent with nitrogen leaching and run-off values calculated in accordance with a Farmer Applied Resource Management (FARM) Strategy. The hearings for the One Plan took place in late 2009, with policy intended to be passed into law in 2010. Currently, however, appeals against the Commissioners' findings are being heard. Here, we outline how the FARM strategy, which is based on natural capital, was developed in the original plan.

Current nitrogen loadings in the Upper Manawatu River are more than twice (744,000 kg-N y^{-1}) the N limits (341,000 kg-N y^{-1}) based on recommended standards in the One Plan. Horizons Regional Council has good data sets on the contribution of the major point-source N loadings to the river. Remedial actions have been successful. We sought to determine the contributions of nonpoint source N loadings from dairy and sheep-beef farms in the Upper Manawatu catchment. By looking into the N loadings in the river from two linked catchments with different land-use patterns, it was inversely inferred that the N lost to the river from the average dairy farm would amount to 15.4 kg-N ha^{-1} y^{-1} and for sheep-beef farm the N loss would on average be 3.9 kg-N ha^{-1} y^{-1} (Clothier et al. 2007). Over 90% of the total N in the river was found to be from these two nonpoint sources, with dairy contributing about half the N loading in the river, despite only representing 16% of the land use in the catchment (Clothier et al. 2008a)

The N loss from the rootzone within the average dairy farm was calculated using the OVERSEER® farm nutrient-model and found to be 31 kg-N ha^{-1} y^{-1} and for the average sheep and beef farm, 7 kg-N ha^{-1} y^{-1}. Obviously then not all the N lost from farms makes it into the river because en route there are losses and attenuations. But a link between farm practice and river water quality had been established, with the N transmission coefficient being 0.5 for both dairying and sheep and beef operations (Clothier et al. 2008c). From this transfer function linking of land-management decisions, to farm N losses and the nutrient loadings in the river we could explore resource management policy options that would protect river water quality.

Mackay et al. (2008) noted that there are a number of policy approaches that could be used to manage nutrients on farms to protect receiving waters. These include:

- **Capping** current production systems and allocate nutrient losses on the basis of present performance by a process that has been called grand-parenting. Then there would be a managing downwards of these caps by ensuring improved farm management, and possibly by trading under what is termed a "cap & trade" market
- **Limiting** the losses of nutrients from intensive land uses This focused approach on the N loss "hot spots" would place restrictions on any further intensification and would require mitigation practices for any further land development, even including practices for the currently less intensively farmed lands
- **Equalising** nutrient loss limit across the catchment. This democratic approach would achieve water quality standards by sharing the loss between all land owners. For the Upper Manawatu catchment this would be a river-sensed loss of 6.5 kg-N ha^{-1} for each farm, or a reduction of 60% from current values
- **Allocating** N-loss rights based on the biophysical potential of the inherent natural capital value of the soils across the farm. If all land in the catchment had the same inherent natural capital, then equalizing the nutrient-loss limit across whole catchment would be simple. The reality is, however, that inherent natural capital varies enormously across the catchment from elite and versatile soils, through to soil with substantial limitations for production agriculture.

Horizons Regional Council opted for the last of these in their One Plan.

How then can the value of the soil's natural capital be quantified for use in determining an N-leaching loss right? Presently direct methods for calculating a soil's natural capital value are still in development. Dominati et al. (2010) have proposed a draft framework for classifying and measuring the value of the natural capital and ecosystem services of soil. This is based on our understanding of soil-forming processes, soil taxonomy, and classification, plus soil processes and the links to land use.

In the absence of a method for calculation of a soil's natural capital, a proxy that serves as a useful alternative is the ability of the soil to sustain a legume-based pasture that is fixing N biologically and is under optimum management, and this is before the introduction of additional technologies. A legume-based pasture is a self-regulating biological system with an upper limit on the amount of N that can be fixed, retained, cycled, and made available for plant growth. It reflects the underlying capacity of soil to retain and supply nutrients and water, as well as the capacity of the soil to provide an environment to sustain legume and grass growth under the pressure of the grazing animal. Potential production therefore reflects the underlying biophysical capacity of the soil's natural capital value and the ecosystem services of the climate to allow production with resilience and durability. To calculate the N-loss limit for a given landscape unit, the potential animal stocking rate that can be sustained by this legume-based pasture fixing N biological, under optimum management, before the introduction of additional technologies, is listed in the extended legend of the Land Use Capability (LUC) worksheets "Attainable potential livestock carrying capacity."

The LUC system (Lynn et al. 2009) has two components. First, the land resource inventory is compiled, which is an assessment of physical factors critical for long-term land use and management. Secondly, the inventory is then used for LUC classification, whereby land is categorized into eight classes according to its long-term ability to sustain one or more productive uses. The LUC classification ranges from Class I through to Class VIII, and this is in essence a classification of natural capital value, from high value land (Class I) to land whose value is less because of various limitations as a result of erosion, wetness, soil or climate (Class VIII). The language of the LUC system is that of natural capital and ecosystem services.

Table 9.1 The maximum nitrogen loss values for each Land Use Capability (LUC) class adopted as Table 13-2 by Horizons Regional Council in their notified One Plan. LUC is a proxy for natural capital value, and for LUC classes I through V, the One Plan seeks reductions in losses so that receiving-water quality is improved.

	LUC I	LUC II	LUC III	LUC IV	LUC V	LUC VI	LUC VII	LUC VIII
Year 1 (when rule comes into force kg of N/ha/year)	32	29	22	16	13	10	6	2
Year 5 (kg of N/ha/year)	27	25	21	16	13	10	6	2
Year 10 (kg of N/ha/year)	26	22	19	14	13	10	6	2
Year 20 (kg of N/ha/year)	25	21	18	13	12	10	6	2

From the attainable potential livestock-carrying capacity in the LUC, namely a measure of the supporting ecosystem services of that LUC class, a value for pasture production can be determined. This can then used in OVERSEER® to calculate the N leaching loss under that grazed pastoral use. The N-loss values that Mackay et al. (2008) calculated for each of the LUC classes were then used by Horizons Regional Council to establish Table 13-2 of their One Plan (Table 9.1), and this forms the basis of the FARM strategy that was incorporated into the One Plan.

It can be seen that soils of higher natural capital value are provided with a higher N-leaching loss right in terms of kg-N ha^{-1} y^{-1}. This approach recognizes the value in the natural capital of the most productive soils, and this acknowledges the reduced need to substitute for natural capital "failings" by using fertilizer as added capital. The unit of calculation for the FARM strategy is the farm. The loss right for each of the LUC units within the enterprise is really summed to provide a loss right for the farm in kg-N/y. This provides the farmer with flexibility to manage the enterprise as a unit to develop the most productive configuration of the farm, albeit within the constraint of the farm's total loss right. This approach enables change away from N-leaching losses based on resource-use efficiency to one that recognizes the flexibility of landscapes in relation to their natural capital values and their versatility for productive land uses and their mitigation options.

As time progresses under the One Plan, through its policy imperatives, improved farm practices are sought so that there is a continuous reduction in N losses from the landscape. The reduction in N loss is focused on the soils of higher natural capital value, LUC I–IV, for these more versatile soils are better able to be managed to mitigate N losses. Over time, water quality will improve, and the improvement in river water quality is predicted by the transfer function that we established (Clothier et al. 2008c). This policy approach recognizes the underlying natural biophysical resources of the landscape, irrespective of current land use, or even of future patterns of land use. It provides all land users in the catchment with certainty by defining a nutrient loss limit based on the biophysical assets of the suite of soils across their farms. The policy does not focus on capping inputs, but rather it seeks to engage with land users to maximize their return on investment into their natural capital assets and to encourage sustainable management of the landscape's biophysical resources without compromising the ecosystem services of receiving environments.

9.8 Conclusion

Sustaining soil productivity in response to climate change is imperative. The supporting, provisioning and regulating ecosystem services provided by soil are critical for food provision and for meeting the challenges of climate change (Dominati et al. 2010). In many cases, however, the supporting services of soils are inadequate for sufficient provisioning of food, fiber, and fuel. Water and nutrients are often needed to ensure economic levels of plant and animal productivity. Thus, irrigation and fertilizers are frequently used to overcome inadequate natural stocks of water and nutrients in the soil. Intensification of land use by this substitution of built capital for shortfalls in natural capital can, however, degrade the soil's regulating ecosystem services, and imperil the asset values of the natural capital stocks of our soils and receiving waters. In developing sustainable farm-management practices and for drafting good resource management policy, if we adopt an ecosystems services approach this will enable us win more and lose less by providing us with an assessment of the ecosystem impacts of our decisions, so that we might continue to be better able to feed the world and mitigate climate change.

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10 Climate and Land Degradation

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10.1 Introduction

The land area of the Earth covers a total of more than 140 million km^2—somewhat less than one third of the Earth's surface. Land resources are finite, fragile in some regions, and nonrenewable. Land degradation leads to a significant reduction of the productive capacity of land. In the United Nations Convention to Combat Desertification (UNCCD 1999, p. 7), land degradation is defined as a "reduction or loss, in arid, semiarid, and dry subhumid areas, of the biological or economic productivity and complexity of rain-fed cropland, irrigated cropland, or range, pasture, forest, and woodlands resulting from land uses or from a process or combination of processes, including processes arising from human activities and habitation patterns, such as: (i) soil erosion caused by wind and/or water; (ii) deterioration of the physical, chemical, and biological or economic properties of soil; and (iii) long-term loss of natural vegetation." In the conceptual framework of the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment 2005), Safriel and Adeel (2005) gave a much simpler definition of land degradation as "reduction or loss of ecosystem services, notably the primary production service" (p. 636).

Land degradation will remain an important global issue for the twenty-first century because of its adverse impact on agronomic productivity, the environment, and its effect on food security and the quality of life (Eswaran et al. 2001). According to UNCCD, over 250 million people are directly affected by land degradation. In addition, some 1 billion people in over 100 countries, whose nutritional needs depend strongly on productivity of lands that they cultivate, are at risk. These people include many of the world's poorest, most marginalized, and politically weak citizens. Land degradation also affects the majority of countries in Europe, Africa, Australia, and North and South America.

Land degradation threatens fuel wood, forage, freshwater, and other services important for global food supply, particularly for impoverished pastoral and agricultural populations worldwide (Scholes & Archer 1997). The economic costs of land degradation are enormous. According to the United Nations Environment Programme (UNEP), the global economy is losing US$42 billion each year as a result of the process of land degradation.

In assessing the extent, cost and impact of land degradation at the national level in seven countries, Berry et al. (2003) showed that all countries had problems of sustainable land management impacting the economy at a rate of 3 to 7% of agricultural gross domestic product (GDP). These case studies demonstrated a close link between poverty and land degradation. For example, the direct costs of land degradation in China in 1999 were estimated at $7.7 billion or about 4% of the GDP, whereas indirect costs were estimated at $31 billion.

Sustainable land management practices are needed to avoid land degradation. To accurately assess sustainable land management practices, the risks of climate change and climate variability

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and of climate-related or induced natural disasters in a region must be known. Only when climate resources are paired with potential management or development practices can the land degradation potential be assessed and appropriate mitigation technology considered. The use of climate information must be applied in developing sustainable practices because climatic variation is one of the major contributing factors to land degradation, and there is a clear need to consider carefully how climate induces and influences land degradation.

10.2 Influence of Land Surface Changes on Climate

Land surface is an important part of the climate system. It controls the partitioning of available energy at the surface between sensible and latent heat and controls the partitioning of available water between evaporation and runoff. Land-atmosphere interaction is essentially the exchanges of water and energy between the land surface and the atmosphere. The interaction between the land surface and the atmosphere involves multiple processes and feedbacks, all of which may vary simultaneously.

Land surface characteristics can affect temperature and humidity levels in the lower atmosphere. Durre et al. (2000) conducted a study on the summertime extreme daily maximum temperatures and antecedent soil moisture. They found that, in the central United States, drier soil is associated with higher air temperatures.

It is frequently stressed (Henderson-Sellers et al. 1993; McGuffie et al. 1995; Sud et al. 1996) that the changes of vegetation type can modify the characteristics of the regional atmospheric circulation and the large-scale external moisture fluxes. Changes in the nature of vegetation cover, particularly from forest to nonforest, can significantly alter the surface moisture budget and exert further effects on the surface energy budget. Forest loss reduces evaporation, causing a greater proportion of the available energy at the land surface to flow to the atmosphere in the form of sensible heat rather than latent heat; this exerts a warming influence on the near-surface air temperature. Reduced evaporation also reduces the flux of moisture to the atmosphere, potentially decreasing the quantity of moisture available for precipitation.

Many modeling studies have been done on the climate changes caused by land cover changes in the African Sahel (e.g., Xue & Shukla 1993; Taylor et al. 2002), the Amazon (Dickinson & Kennedy 1992), and some other regions (Fu 2003). Almost all the studies have demonstrated that large-scale deforestation may lead to decreased precipitation and increased temperature.

From their analysis of satellite-derived monthly and annual time series of rainfall, fires, and deforestation in the Brazilian Amazonia, Aragao et al. (2008) demonstrated that anthropogenic forcing, such as land-use change, is decisive in determining the seasonality and annual patterns of fire occurrence. They showed that droughts can significantly increase the number of fires in the region even with decreased deforestation rates. It is expected that the ongoing deforestation, currently based on slash and burn procedures, and the use of fires for land management in Amazonia will intensify the impact of droughts associated with natural climate variability or human-induced climate change and, therefore, a large area of forest edge will be under increased risk of fires.

10.3 Climate Change and Land Degradation

The climate system is a complex, interactive system consisting of the atmosphere, land surface, snow and ice, oceans and other bodies of water, and living things. The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the World Meteorological Organization

(WMO) and UNEP to assess scientific information on climate change, as well as its environmental and socioeconomic impacts, and to formulate response strategies. Climate change is defined by the IPCC as any change in climate over time, whether due to natural variability or as a result of human activity (IPCC 2007a). Evidence from observations of the climate system has led to the conclusion that human activities are contributing to a warming of the earth's atmosphere. Human activities—primarily burning of fossil fuels and changes in land cover—are modifying the concentration of atmospheric constituents or properties of the Earth's surface that absorb or scatter radiant energy. In particular, increases in the concentrations of greenhouse gases (GHGs) and aerosols are strongly implicated as contributors to climatic changes observed during the twentieth century and are expected to contribute to further changes in climate in the twenty-first century and beyond. In the 1950s, the GHGs of concern remained carbon dioxide (CO_2) and water vapor (H_2O), the same two identified by Tyndall (1861) a century earlier. It was not until the 1970s that other GHGs—methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs)—were widely recognized as important anthropogenic GHGs (Ramanathan 1975; Wang et al. 1976; IPCC 2007a). By the 1970s, the importance of aerosol-cloud effects in reflecting sunlight was known (Twomey 1977), and atmospheric aerosols (suspended small particles) were being proposed as climate-forcing constituents. The amount of CO_2 in the atmosphere has increased by about 35% in the industrial era, and this increase is known to be due to human activities, primarily the combustion of fossil fuels and removal of forests. These changes in atmospheric composition are likely to alter temperatures, precipitation patterns, sea level, extreme events, and other aspects of climate on which the natural environment and human systems depend.

10.3.1 Observed Climate Change

As climate science and the Earth's climate have continued to evolve over recent decades, increasing evidence of anthropogenic influences on climate change has been found. Correspondingly, the IPCC has made increasingly more definitive statements about human impacts on climate. IPCC released its Fourth Assessment Report (FAR) in 2007 that focused on observed climate change and the potential impacts of future climate change. Evidence from observations of the climate system show an increase of 0.74 ± 0.18°C in global average surface temperature during the hundred year period from 1906 to 2005 and an even greater warming trend over the 50-year period from 1956 to 2005 than over the entire 100-year period (i.e., 0.13°C ± 0.03°C versus 0.07°C ± 0.02°C per decade [IPCC 2007a]). Eleven of the 12 years in the period between 1995 to 2006 are among the 12 warmest years since the instrumental record of global surface temperature was started in 1850 (IPCC 2007a). According to Arndt et al. (2010), global average surface and lower-troposphere temperatures during the last three decades have been progressively warmer than all earlier decades, making 2000 to 2009 (the 2000s) the warmest decade in the instrumental record. This warming has been particularly apparent in the mid- and high-latitude regions of the Northern Hemisphere and includes decadal records in New Zealand, Australia, Canada, Europe, and the Arctic.

Land regions have warmed at a faster rate than the oceans. Warming has occurred in both land and ocean domains and in both sea surface temperature (SST) and nighttime marine air temperature over the oceans. However, for the globe as a whole, surface air temperatures over land have risen at about double the ocean rate after 1979 (more than 0.27°C per decade versus 0.13°C per decade).

Another manifestation of changes in the climate system is a warming in the world's oceans. Global integrals of upper-ocean heat content for the last several years have reached values consistently higher than for all prior times in the record, demonstrating the dominant role of the oceans in the planet's energy budget (Arndt et al. 2010). The global ocean temperature rose by 0.10°C from the surface to 700 m depth from 1961 to 2003 (IPCC 2007a). Warming causes seawater to expand and thus contributes to sea level rise. This factor, referred to as thermal expansion, has contributed 1.6 ± 0.5 mm per year to global average sea level from 1993 to 2003. Other factors contributing to sea level rise over the last decade include a decline in mountain glaciers and ice caps (0.77 ± 0.22 mm per year) (IPCC 2007a).

10.3.2 Future Climate Change

Looking ahead, IPCC (2007a) projects increases in global mean surface air temperature (SAT) continuing over the twenty-first century, driven mainly by increases in anthropogenic GHG concentrations, with the warming proportional to the associated radiative forcing. An expert assessment based on the combination of available constraints from observations and the strength of known feedbacks simulated in the models used to produce the climate change projections indicates that the equilibrium global mean SAT warming for a doubling of atmospheric CO_2, or "equilibrium climate sensitivity," is *likely* to lie in the range 2°C to 4.5°C, with a most likely value of about 3°C (IPCC 2007a). Warming in the twenty-first century is expected to be greatest over land and at the highest northern latitudes. It is *very likely* that heat waves will be more intense, more frequent and longer lasting in a future warmer climate. Increasingly reliable regional climate change projections are now available due to advances in modeling and understanding of the physical processes of the climate system. IPCC (2007a) projections show that drier subtropical regions are warming more than the moister tropics.

10.3.3 Linkages between Climate Change and Land Degradation

According to IPCC (2007b), ecosystems are subject to many pressures (e.g. land-use change, resource demands, population changes); their extent and pattern of distribution is changing, and landscapes are becoming more fragmented. Climate change constitutes an additional pressure that could change or endanger ecosystems and the many goods and services they provide. Soil properties and processes—including organic matter decomposition, leaching, and soil water regimes—will be influenced by temperature increase. Soil erosion and degradation are likely to aggravate the detrimental effects of a rise in air temperature on crop yields. Climate change may increase erosion in some regions, through heavy rainfall and through increased wind speed.

Land-use and land-cover change and global environmental change form a complex and interactive system linking human induced use/cover change to environmental feedbacks to their impacts and human responses. Land-use and land cover changes influence carbon fluxes and GHG emissions (Houghton 1995; Braswell et al. 1997), which directly alter atmospheric composition and radiative forcing properties. They also change land-surface characteristics and, indirectly, climatic processes. Deforestation and other land-use changes have contributed on average 28% of the total global CO_2 emissions for the period between 1980 and 1998 (Watson et al. 2000). Forest ecosystems cover more than 4.1×10^9 hectares of the Earth's land area (Dixon et al. 1994) and contain about 1146 Pg C, with approximately 378 Pg in vegetation and the remaining 768 Pg in soils. Assessments of CO_2 emissions from deforestation practices have been conducted at global and regional scales (Houghton 1995), at national scales (Masera et al. 1995), and at local levels (Cairns et al. 2000). Masera et al. (1995) suggested that conversion of forest lands to other uses can be contributing as much as 41% of the CO_2 for Mexico and for the globe it is approximately 25% (Houghton 1995).

Established evidence links land degradation to the loss of biodiversity and climate change, both as cause and effect (Gisladottir & Stocking 2005). CO_2-induced climate change and land degradation remain inextricably linked because of feedbacks between land degradation and precipitation. Climate change might exacerbate land degradation through alteration of spatial and temporal patterns in temperature, rainfall, solar radiation, and winds. Several climate models suggest that future global warming may reduce soil moisture over large areas of semiarid grassland in North America and Asia (Manabe & Wetherald 1986). This climate change is likely to exacerbate the degradation of semiarid lands that will be caused by rapidly expanding human populations during the next decade. Emmanuel (1987) predicted that there will be a 17% increase in the world area of desert land due to the climate change expected with a doubling of atmospheric CO_2 content.

10.4 Climate Variability and Impacts on Land Degradation

Precipitation and temperature determine the potential distribution of terrestrial vegetation and constitute principal factors in the genesis and evolution of soil. Precipitation also influences vegetation production, which in turn controls the spatial and temporal availability of forage. Vegetation cover becomes progressively thinner and less continuous with decreasing annual rainfall. Plants and animals display a variety of physiological, anatomical and behavioral adaptations to moisture and temperature stresses brought about by large diurnal and seasonal variations in temperature, rainfall and soil moisture.

Structural crusts/seals are formed by raindrop impact, which could decrease infiltration, increase runoff and generate overland flow and erosion. The severity, frequency, and extent of erosion are likely to be altered by changes in rainfall amount and intensity and changes in wind.

From the assessment of the land resource stresses and land degradation in Africa, which was carried out by the Natural Resources Conservation Service of the US Department of Agriculture utilizing information from the soil and climate resources of Africa, Reich et al. (2001) concluded that climatic stresses account for 62.5% of all the stresses on land degradation in Africa (Table 10.1). These climatic stresses include high soil temperature, seasonal excess water; short duration low temperatures, seasonal moisture stress, and extended moisture stress and affect 18.5 million km^2 of the land in Africa. This study clearly exemplifies the importance of the need to give a more careful consideration of climate effects on land degradation.

10.4.1 Rainfall

Rainfall is the most important climatic factor in determining areas at risk of land degradation and potential desertification. In most of the arid and semiarid regions, rainfall is highly variable, with sporadic daily pulses, marked seasonality, and interannual to multidecadal fluctuations (Chesson et al. 2004). High temperatures during the rainy season cause much of the rainfall to be lost in evaporation, and the intensity of tropical storms ensures that a significant amount runs off in floods. Studies by Bai and Dent (2008) in South Africa showed that biomass productivity (represented by sum Normalized Difference Vegetation Index [NDVI]) essentially follows annual rainfall amount, which is variable both spatially and cyclically. Statistics showed a high

Table 10.1 Major land resources stresses and land quality assessment of Africa.

Land stresses			Inherent land quality		
Stress class	Kinds of stress	Area (1,000 km^2)	Class	Area (1,000 km^2)	Area (%)
1	Few constraints	118.1	I	118.1	0.4
2	High shrink/swell	107.6	II		
3	Low organic matter	310.9	II		
4	High soil temperatures	901.0	II	1,319.6	4.5
5	Seasonal excess water	198.9	III		
6	Minor root restrictions	566.5	III		
7	Short duration low temperatures	.014	III	765.4	2.6
8	Low structural stability	333.7	IV		
9	High anion exchange capacity	43.8	IV		
10	Impeded drainage	520.5	IV	898.0	3.1
11	Seasonal moisture stress	3,814.9	V		
12	High aluminum	1,573.2	V		
13	Calcareous, gypseous	434.2	V		
14	Nutrient leaching	109.9	V	5,932.3	20.2
15	Low nutrient holding capacity	2,141.0	VI		
16	High P, N retention	932.2	VI		
17	Acid sulfate	16.6	VI		
18	Low moisture and nutrient status	0	VI		
19	Low water holding capacity	2,219.5	VI	5,309.3	18.1
20	High organic matter	17.0	VII		
21	Salinity/alkalinity	360.7	VII		
22	Shallow soils	1,016.9	VII	1,394.7	4.8
23	Steep lands	20.3	VIII		
24	Extended low temperatures	0	VIII	20.3	0.1
25	Extended moisture stress	13,551.4	IX	13,551.4	46.2
Land Area		29,309.1			
Water bodies		216.7			
TOTAL AREA		29,525.8			

Source: Reich et al. 2001.

correlation between NDVI and annual rainfall at the pixel level and 72% of the variation in biomass productivity is explained by variation in annual rainfall.

Soil scientists consider rainfall intensity as one of the most important among the many factors that cause soil erosion (Zachar 1982). The velocity of rain hitting the soil surface produces a large amount of kinetic energy that can dislodge soil particles. Once the soil particles have dislodged they become susceptible to transport in runoff. In general, the higher the intensity of the rainfall, the greater is the quantity of sediment in runoff water. Also, the greater the intensity of rainfall and subsequent surface runoff, the larger are the soil particles that can be carried away.

The extremes of either too much or too little rainfall can produce soil erosion that can lead to land degradation. The frequency of extreme events may be affected by seasonal to interannual fluctuations of large scale climate variations such as El Niño/Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) (Schweirz et al. 2006). Romero et al. (2007) showed that in the La Encañada watershed in north Peru, mean annual rainfall in neutral years was less than 600 mm, whereas during El Niño and La Niña years, the annual total increased, the maximum being 1200 mm. In general, rainfall intensities were very low, with 96% of events less than 7.5 mm h^{-1}. But during the El Niño year, the number of high intensity events increased in the lower part of the watershed

(18%) where normally only 4% of events were high intensity. The La Niña year was characterized by a large rainfall total, but lower intensities. Erosivity analysis showed that in the lower part of the watershed, rain events are more erosive, especially during abnormal years such as El Niño.

In sub-Saharan Africa the dynamics of rainfall are related to the combined effect of the NAO and ENSO (Oba et al. 2001). The authors were able to attribute 75% of interannual rainfall variation to these effects. Trigo et al. (2005) analyzed the inventory of 19 landslides in the Lisbon area of Portugal, occurring between 1958 and 2001, in terms of both antecedent rainfall and the status of the NAO. All of the landslide events were associated with negative values of the NAO index. Episodes of gully incision and channel erosion during flood events have been related to increases in winter precipitation during El Niño–related circulation patterns (Waters & Haynes 2001).

10.4.2 Droughts

Droughts are the consequence of a reduction in the amount of precipitation over an extended period of time, usually a season or more in length, often associated with other climatic factors—such as high temperatures, high winds, and low relative humidity—that can aggravate the severity of the event. With normal climatic variability, in some years the water deficits can be larger than others but sometimes there can be a several year period of water deficit or long-term drought. During such periods, one can see examples of land degradation such as during the Dust Bowl years of the 1930s in the Great Plains or the nearly two decade long drought in the Sahel in the 1970s and 1980s. It was this severe drought in the Sahel that heightened the current concern over desertification.

The 2002–2003 El Niño related Australian drought (Coughlan et al. 2003), which lasted from March 2002 to January 2003, was arguably one of, if not the, worst short-term drought in Australia's recorded meteorological history (Nicholls 2004). Analysis of rainfall records for this 11-month period showed that 90% of the country received rainfall below that of the long-term median, with 56% of the country receiving rainfall in the lowest 10% (i.e. decile-1) of recorded totals (Australia-wide rainfall records commenced in 1900). During the 2002–2003 drought Australia experienced widespread bushfires, severe dust storms, and agricultural impacts that resulted in a drop in Australia's gross domestic product of over 1% (Watkins 2005). The first 5 months of 2005 were exceptionally dry for much of Australia (Fig. 10.1), leading many to label this period a truly exceptional drought.

Persisting over months or years, droughts can affect large areas and may have serious environmental, social, and economic impacts. Mean and long-term effects, such as land degradation and desertification are, however, most severe consequences of repeated drought events.

The interlinkages between normal dry periods, drought and land degradation are manifold and two-directional. Semiarid ecosystems are considered to be "drought-adapted" (i.e. dry periods) and more severe droughts naturally occur and the ecosystem is adapted to its occurrence. The interlinkages are exacerbated, however, by the increasing population pressure, increased consumption expectations, as well as an overall increase of rural poor (Zeidler & Chunga 2007).

Extended droughts in certain arid lands have initiated or exacerbated land degradation. Records show that extensive droughts have afflicted Africa, with serious episodes in 1965–1966, 1972–1974, 1981–1984, 1986–1987, 1991–1992, and 1994–1995.

Sea surface temperature anomalies, often related to the ENSO or NAO, contribute to rainfall variability in the Sahel. Droughts in West Africa correlate with warm SST in the tropical south Atlantic. Examination of the oceanographic and meteorological data from the period 1901–1985

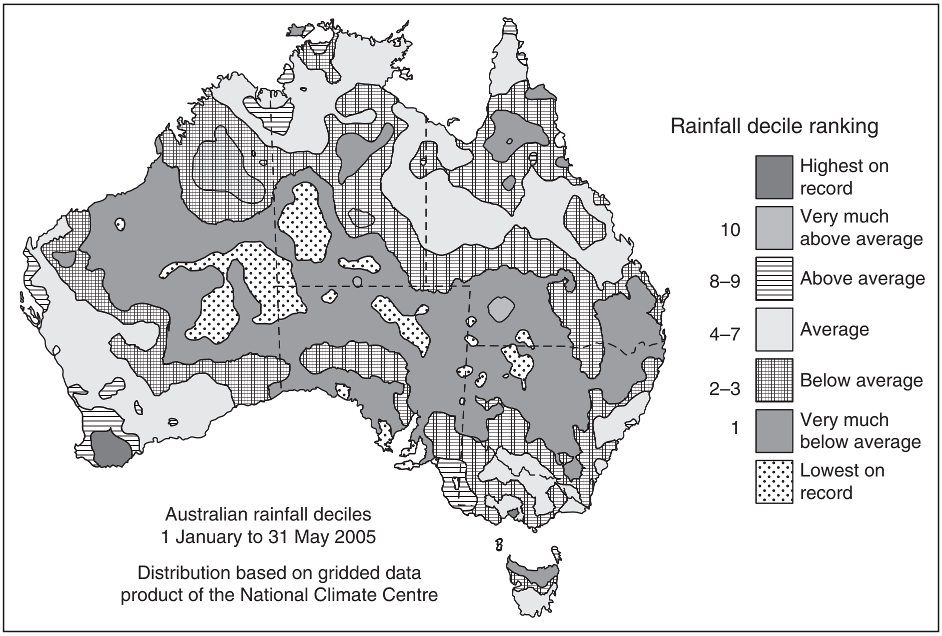

Figure 10.1 Rainfall deciles for January to May 2005 in Australia.
Watkins 2005.

showed that persistent wet and dry periods in the Sahel were related to contrasting patterns of SST anomalies on a near-global scale (Giannini et al. 2003). From 1982 to 1990, ENSO-cycle SST anomalies and vegetative production in Africa were found to be correlated. Warmer eastern equatorial Pacific waters during ENSO episodes correlated with rainfall of less than 1,000 mm yr^{-1} over certain African regions.

10.4.3 Temperature and Evaporation

Along with rainfall, temperature is the main factor determining climate and therefore the distribution of vegetation and affecting soil processes. Soil formation is the product of many factors that include: the parent material (rock), topography, climate, biological activity, and time. Temperature and rainfall cause different patterns of weathering and leaching in soils. Seasonal and daily changes in temperature can affect soil moisture, biological activity, rates of chemical reactions, and the types of vegetation. Important chemical reactions in the soil include the nitrogen and carbon cycles, with critical impacts on plant growth.

In the tropics, surface soil temperatures can exceed 55°C and this intense heat contributes to the cracking of high clay soils that expose not only the soil surface but the soil subsurface to water or wind erosion. Of course, these high temperatures will also increase soil water evaporation and further reduce available soil moisture for plant growth.

In temperate dry lands, the freeze-thaw cycle can have a direct effect on the composition of the soil by the movement of rocks and stones from various depths to the surface. In high elevations, freeze-thaw is one factor degrading rock structure, causing cracks and fissures that could lead to landslides and rock avalanches.

Evaporation is the conversion of water from the liquid or solid state into vapor and its diffusion into the atmosphere. A vapor pressure gradient between the evaporating surface and the atmosphere and a source of energy are necessary for evaporation. Solar radiation is the dominant source of energy and sets the broad limits of evaporation. Solar radiation values in the tropics are high and are modified by cloud cover, which leads to a high evaporative demand of the atmosphere. In the arid and semiarid regions, considerable energy may be advected from the surrounding dry areas over irrigated zones. Rosenberg et al. (1983) lists several studies that have demonstrated the "oasis effect" which is the transfer of energy across an evaporating surface and can cause large evaporative losses in a short period of time.

Climatic factors induce an evaporative demand of the atmosphere, but the actual evaporation resulting will be influenced by the nature of the evaporating surfaces as well as the availability of water. On a degraded land, the land surface itself influences the evaporative demand by the albedo and surface roughness, the latter affecting turbulence. In the arid and semiarid regions, high evaporation that greatly exceeds precipitation leads to accumulation of salts on soil surface. Soils with high salinity are easily dispersed, resulting in increased runoff and the low moisture levels lead to limited biological activity.

10.4.4 Wind

It has been estimated that in the arid and semiarid zones of the world, 24% of the cultivated land and 41% of the pasture land are affected by moderate to severe land degradation from wind erosion (Rozanov 1990). The occurrence of sand/dust storms induced by wind erosion is a process that accelerates land degradation and can also be considered as an indicator of desertification. There is growing evidence that the frequency of sand storms/dust storms is increasing. For example, the dust and sand storms that have plagued Asia for millennia are becoming more frequent and intense, with some areas experiencing a fivefold increase in the last 50 years.

The worldwide total annual production of dust by deflation of soils and sediments was estimated to be 61 to 366 million tons (Middleton 1986). For Africa, it is estimated that more than 100 million tons of dust per annum is blown westward over the Atlantic. The amount of dust arising from the Sahel zone has been reported to be approximately 270 million tons per year, which corresponds to a loss of a layer of 20 mm over the entire area (Stahr et al. 1996).

Xu et al. (2006) showed that since 1995 surface vegetation cover in large areas of Northern China has significantly deteriorated. Moreover, a high correlation is shown to exist among the annual occurrence of sand–dust storms, surface vegetation cover and snowfall. This suggests that the deterioration of surface vegetation cover may strongly influence the occurrence of sand/dust storms in China.

Dust storms have a number of impacts on the environment including radiative forcing and biogeochemical cycling (Goudie 2009). Sand and dust storms are hazardous weather events and cause major agricultural and environmental problems in many parts of the world. There is a high on-site as well as off-site cost due to the sand and dust storms. They can move forward like an overwhelming tide and strong winds take along drifting sands with numerous impacts including burial of farmlands, blowing top soil, injuring animals, damaging human settlements, covering railroads and roads, and affecting the quality of water in rivers and streams. Dust storms accelerate the process of land degradation, cause serious environmental pollution and impact the terrestrial ecology and living environments (Wang Shigong et al. 2001). Atmospheric loading of dust caused by wind erosion also affects human health and environmental air quality.

Figure 10.2 Sand and dust storms move forward like an overwhelming tide and strong winds take along drifting sands to bury crops.

Wind erosion-induced damage includes direct damage to crops through the loss of plant tissue and reduced photosynthetic activity as a result of sandblasting, burial of seedlings under sand deposits, and loss of topsoil (Fryrear 1971; Amburst 1984; Fryrear 1990). The last process is particularly worrying because it potentially affects the soil resource base and hence crop productivity on a long-term basis, by removing the layer of soil that is inherently rich in nutrients and organic matter. Wind erosion on light sandy soils can provoke severe land degradation and sand deposits on young seedlings can affect crop establishment (Fig. 10.2).

10.4.5 Wild Fires

Uncontrolled wildfires occur in all vegetation zones of the world. It is estimated that fires annually affect 10–15 million ha of boreal and temperate forest and other lands, 20–40 m ha of tropical rain forests due to forest conversion activities and escaped agricultural fires, and up to 500 m ha of tropical and subtropical savannas, woodlands, and open forests (WCMC 2000).

Globally, biomass burning, which includes wild fires, is estimated to produce 40% of the CO_2, 32% of the carbon monoxide, 20% of the particulates, and 50% of the highly carcinogenic polyaromatic hydrocarbons produced by all sources (Levine 1990). Emissions from fires are considerable and contribute significantly to gross global emissions of trace gases and particulates from all sources to the atmosphere.

The influence of fire on soil characteristics (soil-water content, soil compaction, soil temperature, infiltration ability, soil properties especially organic matter, pH, exchangeable Ca, Mg, K, Na, and extractable P) of a semiarid southern African rangeland was quantified over two growing seasons (2000/01–2001/02) following an accidental fire (Snyman 2003). The decrease in basal cover due to fire (head fires) exposed the soil more to the natural elements and therefore to higher soil temperatures and soil compaction in turn leading to lower soil-water content and a decline in soil infiltrability.

10.5 Technologies, Policies, and Measures to Address the Linkages between Climate and Land Degradation

The current rate of land degradation is unprecedented, and it is certainly undermining the foundation of long-term sustainable agricultural development. The challenge to double food production in the next 25 years to feed the growing human population puts additional pressure on land and hence the issue of controlling land degradation merits a serious consideration. Dealing with this problem is of course difficult because of cyclical swings in rainfall, land tenure that is no longer well adjusted to the environment, and because local management is driven by regional and global forces. These forces have to be addressed by national, regional, and global policies. Local responses need to be guided by consistent measurement of indicators of long-term ecosystem changes (UNEP 2007).

In broad terms, the availability of natural goods and services is controlled by the hydrologic cycle, biogeochemical cycles, the climate system, and the maintenance of biological diversity and functioning ecosystems (Watson et al. 1998). The damage due to land degradation can be arrested, even reversed, but this requires concerted, long-term investment across sectors, by all levels of government and by individual land users, research to provide reliable data, and adaptation of technologies appropriate to local circumstances. Such a package of measures has rarely been attempted (UNEP 2007).

In this chapter, the issue of climate change and the impact of the variability in the various climatic elements on land degradation had been highlighted and this needs to be examined more thoroughly in the future and technologies, policies, and measures need to be put in place to control land degradation. Integrating perspectives on climatic risks in the current policies and programs in different sectors such as water resources management, land use, and agricultural development will lead to increased adaptive capacity to current as well as future climate variability. For example, early warning systems can reduce the impacts of drought by providing timely information about the onset of drought (Wilhite et al. 2000). Tracking certain indicators such as stream flow or soil moisture can help in formulating drought index values—typically single numbers, far more useful than raw data for decision making. A dense network of weather stations for standardized, real-time monitoring of rainfall and temperatures needs to be established, especially in the arid and semiarid regions.

Developing effective and sustainable uses of land and natural resources that do not endanger their future productivity is crucial. From their studies on runoff and sediment losses from 27 upland catchments in Southeast Asia, Valentin et al. (2008) concluded that failure to adopt appropriate land-use management strategies will result in further rapid resource degradation with negative impacts to downstream communities. Necessary provisions need to be included in the development plans to address the issues of attaining twin objectives coping with climate change and improving resource use productivity. For example, policies and incentives for appropriate organic matter management in rural areas would encourage farmers to sequester carbon in the soil and improve soil health and use water and energy more efficiently.

10.6 Future Perspectives

Producing enough food for the growing population in the world in a background of reducing resources in a changing climate scenario, while minimizing land degradation, is a considerable challenge. The definition of land degradation adopted by UNCCD assigns a major importance to climatic factors contributing to land degradation, but there is no concerted effort at the global level to systematically monitor the impacts of different climatic factors on land degradation in different regions and for different classes of land degradation. Hence, there is an urgent need to monitor the interactions between climate and land degradation. To better understand these interactions, it is also important to identify the sources and sinks of carbon, aerosols and trace gases.

There are serious gaps in the basic meteorological network and observational facilities in many areas, some of them in regions with severe land degradation problems. The most serious single and geographically widespread shortcoming is the lack of information on rainfall intensity.

There is an urgent need to implement strategies for efficient management of land and water and development of decision support tools for translating weather information into operational management practices could aid this process. Comprehensive planning for conservation of water resources and using them for alleviating droughts during periods of water stress could help reduce land degradation during extended drought periods.

Research needs to be strengthened to enhance the capacity to adapt to climate change and reduce land degradation. Modifying the input management can assist in the management of small changes in climatic parameters, but larger changes in the climatic parameters may require the consideration of alternate land-use systems. A thorough quantitative assessment of the potentials and constraints of land is needed, in which scientific knowledge, socioeconomic conditions and the conflicting interests of various stakeholders can be harmonized and most efficient and sustainable land-use systems can be identified. Current availability of simulation models and other systems research tools provides an opportunity for an interdisciplinary approach for this (Roetter et al. 2007). Sequestering soil carbon is an effective strategy to mitigate GHG and practices such as increased use of organic manures, minimal tillage, residue management, use of improved water, and nutrient management approaches needs to be more actively promoted.

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11 The Role of Soils and Biogeochemistry in the Climate and Earth System

Elisabeth A. Holland

11.1 Introduction

Soils play a crucial role in the biogeochemical cycles, in climate change, and in sustaining life on earth. Soils constitute one of the largest single reservoirs of carbon and nitrogen on earth (Figs. 11.1a and b). A "safe operating space for humanity" depends on 10 planetary operating systems according to Rockström et al. (2009) and soils play a role in each of those systems. The Earth system processes include: (1) *climate change*, where soils provide a large carbon reservoir, (2) *rate of biodiversity loss*, where soils provide a medium for biological growth, (3) *nitrogen cycles*, (4) *phosphorus cycles*, where soils play a central role, (5) *stratospheric ozone depletion*, where soils provide key sources of nitrous oxide (NO) and methyl bromide, (6) *ocean acidification*, where soil inputs to the ocean provide additional buffering capacity through dust deposition, (7) *global freshwater use,* soils provide water filtration, (8) *chemical pollution*, where soils provide water filtration, (9) *atmospheric aerosol loading*, where soils play an important role as a source of aerosol precursors including NO_x, ammonia, and dust, and 10) *change in land use*, where soils are altered by human activity. How humans view, value, and represent soils and agriculture in the Earth system model must be part of ethical discussions as humans approach the planetary and societal transformations that climate change brings.

This chapter provides background on climate change and the role of soils in the Earth system, specifically focusing on the carbon and nitrogen cycles and the need for better representation of soils in Earth system models.

11.2 Lessons Learned from the Intergovernmental Panel on Climate Change

A discussion of the role of soil productivity in response to climate change requires an understanding of what is meant by climate change, particularly global climate change. The international body tasked with assembling and synthesizing the relevant climate data and future projections of climate change is the Intergovernmental Panel on Climate Change (IPCC) under the auspices of the United Nations Environmental Program (UNEP) and the World Meteorological Organization (WMO; Bolin 2007). The IPCC was founded in 1988 under the leadership of Bert Bolin who served as the chairman of the IPCC from 1988 through 1997. The IPCC was formed in recognition that governments require information on climate change for their negotiations.

The resounding message of the Fourth Assessment Report (AR4) is: "***warming is unequivocal***" (IPCC 2007a, 2007b). The words were carefully chosen by Susan Solomon and Dahe Qin, cochairs of Working Group 1 (WG 1), and the writing team for the Summary for Policy Makers, and then approved by the author team of WG 1 of IPCC. Rarely in the scientific community can one find a circumstance in which the 152 lead authors and leading scientists, of WG 1 can support

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Sustaining Soil Productivity in Response to Global Climate Change: Science, Policy, and Ethics, First Edition.
Edited by Thomas J. Sauer, John M. Norman and Mannava V. K. Sivakumar.

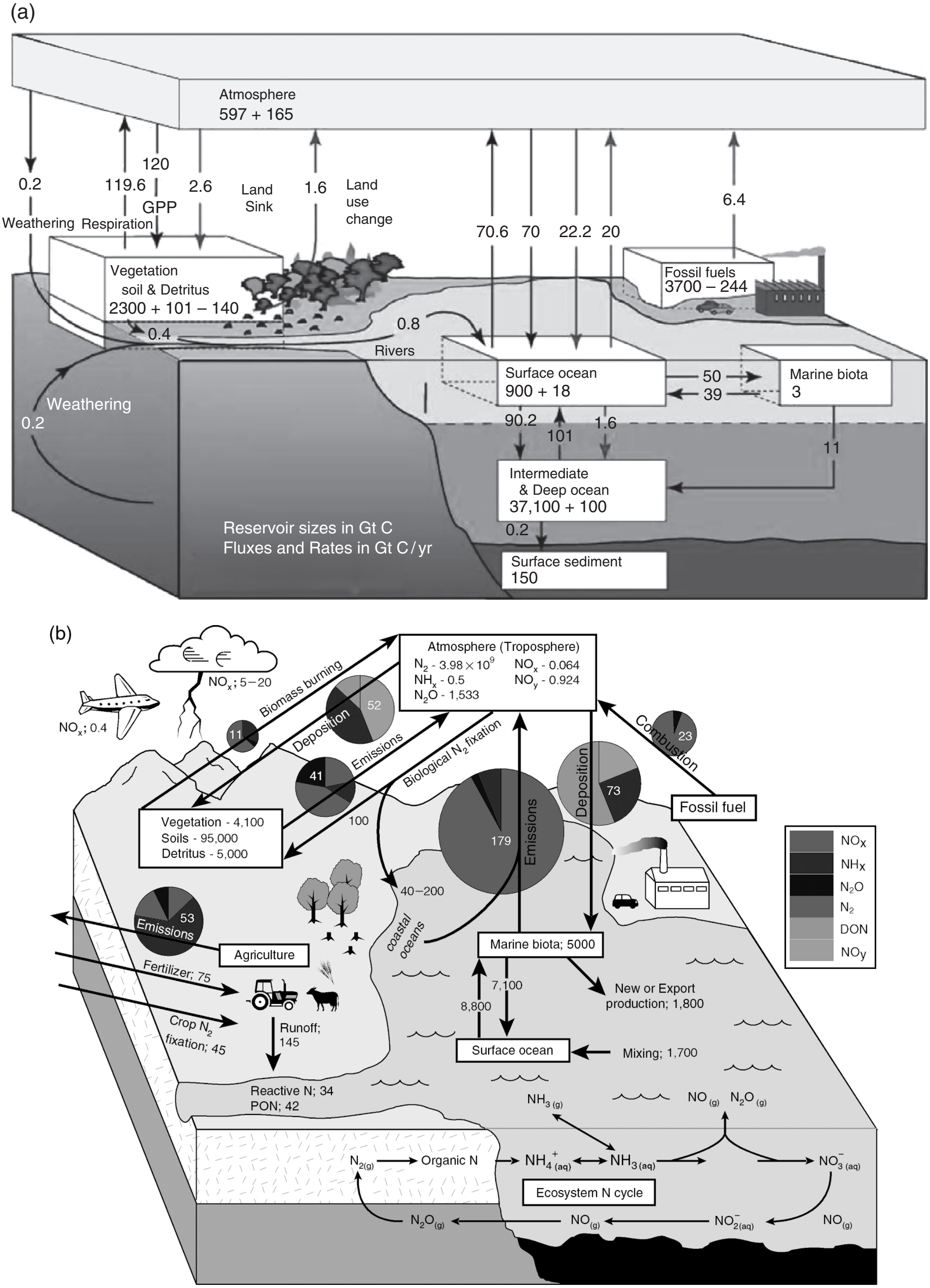


Figure 11.1 The global carbon (a) and nitrogen (b) cycles. The carbon cycle is reproduced from the IPCC AR4 report, (Figure 7.3) showing the 1990s pools and fluxes in GtCy^{-1}, anthropogenic fluxes are land use change and fossil fuel emissions at 1.6 and 6.4 GtCy-1 respectively. The pre-industrial "natural" fluxes are the remaining fluxes. The details of the carbon calculations and sources can be found in Denman et al. (2007). The nitrogen cycle is presented in Tg N y^{-1} and is assembled from a variety of sources including those cited in Galloway et al. (2004) and Denman et al. (2007). The total nitrogen fluxes are shown as the number in each pie chart. The pie charts are divided by chemical species as shown in the legend. NOx emissions are driven by fossil fuel combustion and NHx emissions are driven by agriculture.

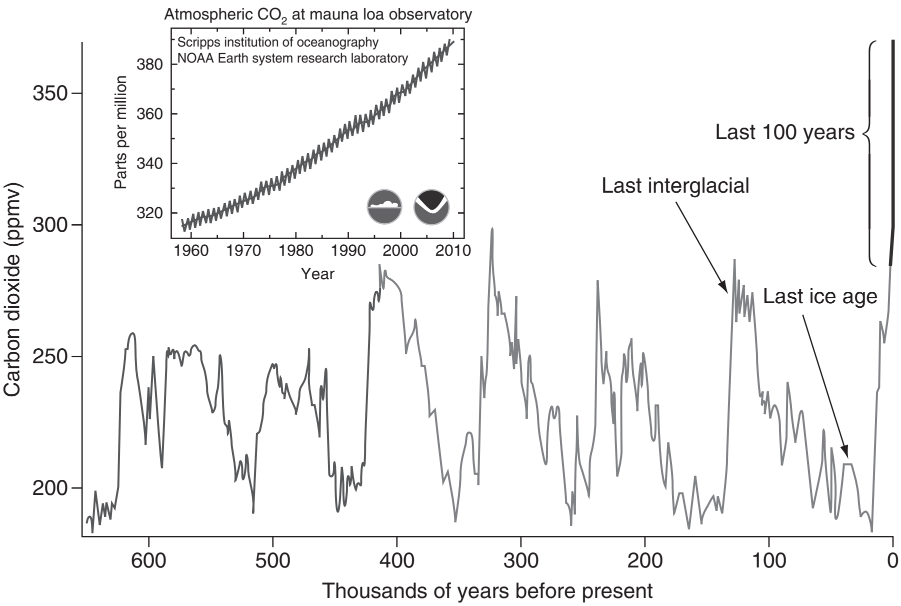


Figure 11.2 The atmospheric CO$_2$ record for the last 650,000 years adapted from Figures 6.3 and 6.4 of (IPCC 2007a). The inset is the most recent monthly mean atmospheric carbon dioxide at Mauna Loa Observatory, Hawaii. "The carbon dioxide data, measured as the mole fraction in dry air, on Mauna Loa constitute the longest record of direct measurements of CO$_2$ in the atmosphere. They were started by C. David Keeling of the Scripps Institution of Oceanography in March of 1958 at a facility of the National Oceanic and Atmospheric Administration (Keeling et al. 1976). NOAA started its own CO$_2$ measurements in May of 1974, and they have run in parallel with those made by Scripps since then (Thoning et al. 1989). The black curve represents the seasonally corrected data. Data are reported as a dry mole fraction defined as the number of molecules of carbon dioxide divided by the number of molecules of dry air multiplied by one million (ppm)", Dr. Pieter Tans, NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/).

wording as strong as, "warming is unequivocal." The chairs of WG 1 were repeatedly challenged about the word choice; "*unequivocal*" is not official IPCC terminology to describe uncertainty. The IPCC did not anticipate having the overwhelming body of evidence with rising atmospheric temperature, increasing water vapor content of the atmosphere, continuing reductions in Northern Hemispheric snow cover, glacial retreat, decreases in arctic sea ice extent, increases in extreme temperatures, and more when they decided on the uncertainty terms and their use.

Climate system models, which are a cornerstone of the IPCC forecasts, have gotten increasingly sophisticated since the first IPCC report in 1990. Early climate models that included representations of radiation balance, clouds, and a "swamp" ocean evolved to include sophisticated representations of atmospheric chemistry, sea ice, interactive vegetation, and the carbon cycle within the climate system used in the AR4 (Le Treut et al. 2007). One of the most powerful advances across the history of the IPCC reports has been in the ability to both detect climate change based on many different lines of evidence and to attribute climate change using both observations and models. In 1995, the Second Assessment Report (SAR) found, "Balance of evidence suggests discernible human influence" (IPCC 1996). In 2001, the Third Assessment Report stated, "Most of global warming of past 50 years likely (odds 2 out of 3) due to human activities" (IPCC 2001). In 2007, IPCC concluded "Most of global warming of past 50 years very likely (odds 9 out of 10) due to human increases in greenhouse gases" (IPCC 2007a and b). Conferences like this can now turn to understanding as to how soil productivity can be sustained in response to global climate change knowing that human management of soils is integral to climate change.

Some key findings of the AR4 pertain specifically to how the current changes in biogeochemistry fit into the historical record (Fig. 11.2; Denman et al. 2007, p. 512). "The

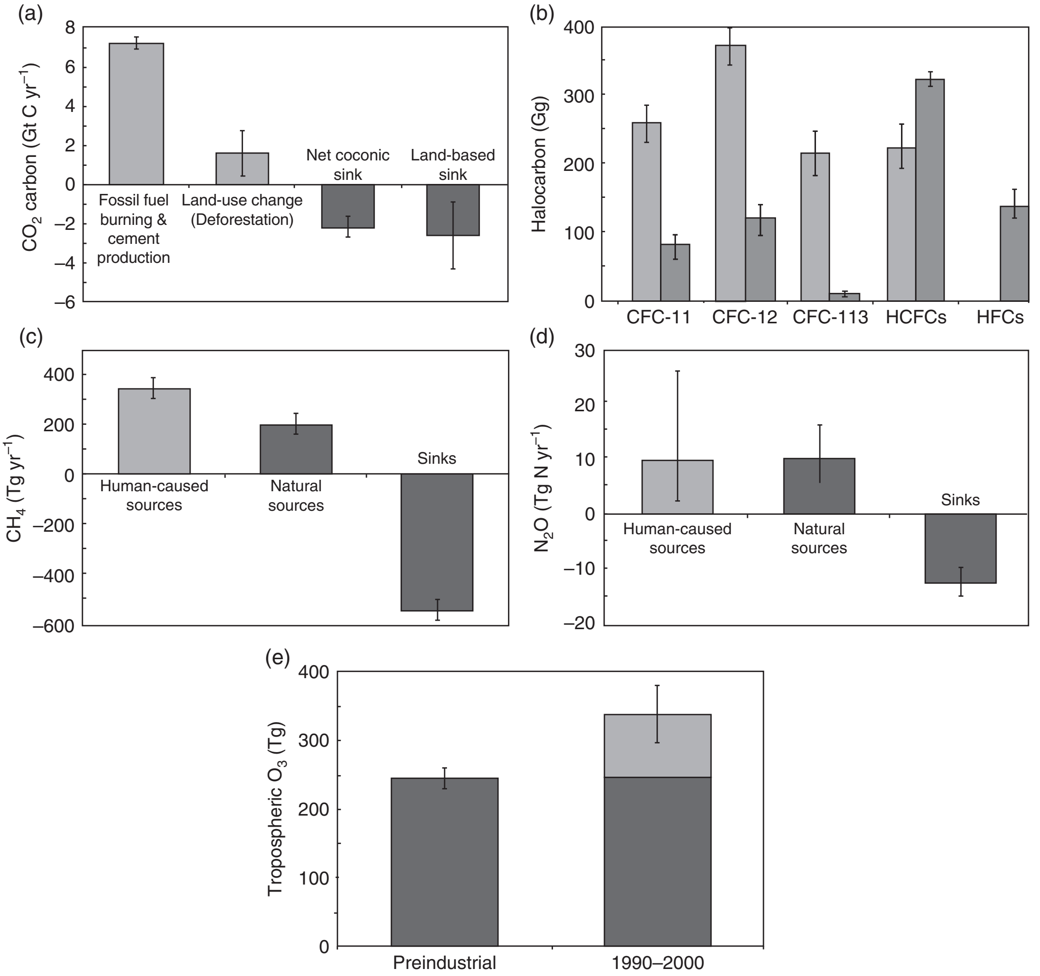
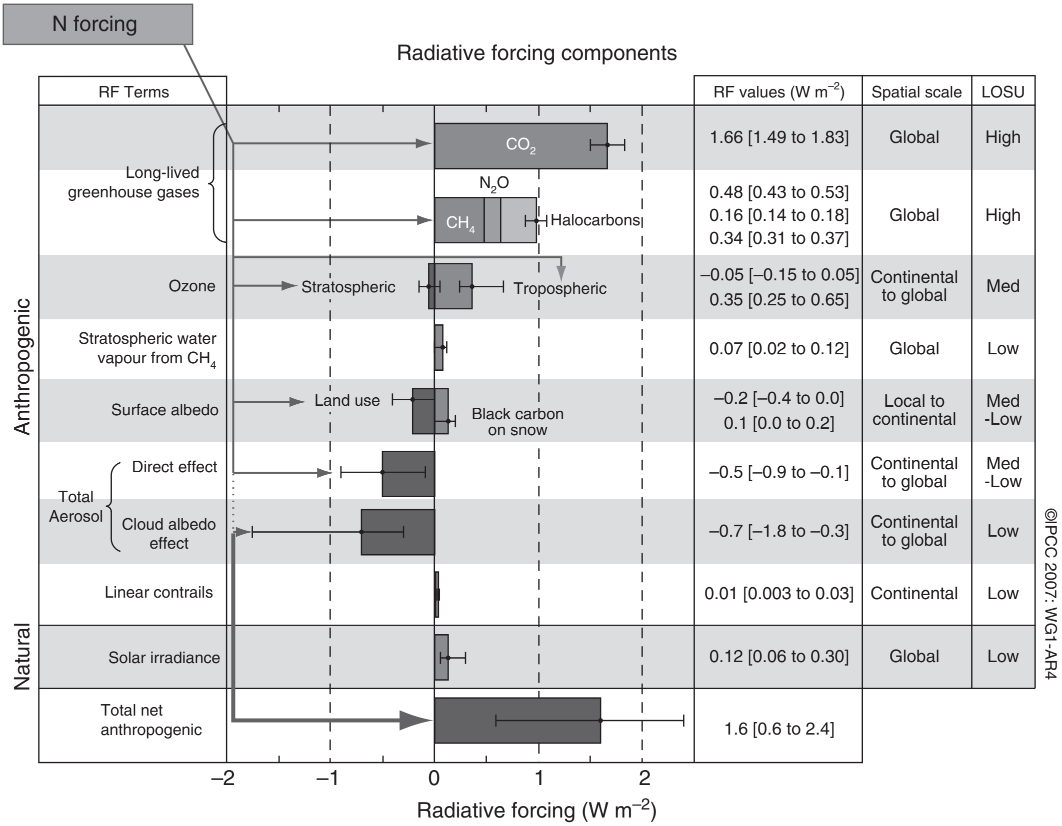


Figure 11.3 Human caused (shown in light gray, including all of the CFC and HCFC bars) and natural (shown in dark gray) contributions to atmospheric carbon dioxide (CO_2), halocarbon, methane (CH_4), nitrous oxide (N_2O), and tropospheric ozone (O_3) sources and sinks. For CO_2, soils contribute to both the land use CO_2 emissions and to the land based sink. For CH_4, microbial production and uptake in soils contribute to both the source and sinks. For N_2O, microbial production and uptake in soils are the dominant source and an important sink respectively. For O_3, microbial production of NO_x in soils is an important source of catalyst for O_3 formation and destruction.
From Denman et al. 2007, figure 7.1.

concentration of carbon dioxide is now 379 parts per million (ppmv) and methane is over 1774 parts per billion (ppbv), both very likely much higher than any time in at least 650,000 years (during which carbon dioxide remained between 180 and 300 ppmv and methane between 320 and 790 ppbv). The recent rate of change is dramatic and unprecedented; increases in carbon dioxide never exceeded 30 ppmv in 1,000 years—yet now carbon dioxide has risen by 30 ppmv in just the last 17 years. It is very likely that the increase in the combined radiative forcing from carbon dioxide, methane and nitrous oxide has been at least six times faster between 1960 to 1999 than over any 40 year period during the two millennia prior to the year 1800. On average, present-day tropospheric ozone has increased 38% since



RF Terms	RF values (W m^{-2})	Spatial scale	LOSU
Long-lived greenhouse gases: CO_2	1.66 [1.49 to 1.83]	Global	High
N_2O CH_4 Halocarbons	0.48 [0.43 to 0.53] 0.16 [0.14 to 0.18] 0.34 [0.31 to 0.37]	Global	High
Ozone	–0.05 [–0.15 to 0.05] 0.35 [0.25 to 0.65]	Continental to global	Med
Stratospheric water vapour from CH_4	0.07 [0.02 to 0.12]	Global	Low
Surface albedo	–0.2 [–0.4 to 0.0] 0.1 [0.0 to 0.2]	Local to continental	Med -Low
Total Aerosol: Direct effect	–0.5 [–0.9 to –0.1]	Continental to global	Med -Low
Cloud albedo effect	–0.7 [–1.8 to –0.3]	Continental to global	Low
Linear contrails	0.01 [0.003 to 0.03]	Continental	Low
Solar irradiance	0.12 [0.06 to 0.30]	Global	Low
Total net anthropogenic	1.6 [0.6 to 2.4]		

Figure 11.4 The IPCC 2007 summary radiative forcing figure (SPM.2) modified to indicate how changes to the global nitrogen cycle, show indicated by arrows on the left side of the figure, influence the climate system.

pre-industrial times, and the increase results from atmospheric reactions of short-lived pollutants emitted by human activity.” Soils play an important role in the exchange of all of the top five greenhouse gases (Figs. 11.3 and 11.4). For carbon dioxide, methane, NO, and some halocarbons (e.g. methyl bromide and methyl chloride) soils are both an important sink and source. Microbial production of NO in soils is an important precursor for tropospheric ozone production, which has increased 38% since the preindustrial era (Denman et al. 2007) and may become quantitatively more important in the future as industrial sources of NO_x decrease (Kim et al. 2006).

11.3 The Carbon Cycle

In 1968, Woodwell and Whitakker published a carbon cycle model that remains fundamental to models of carbon cycling at ecosystem to global scales:

$$NEP = GPP - ER = NPP - HR$$

Where NEP is net ecosystem production; GPP is the gross primary production (photosynthetic carbon gain); ER is the ecosystem respiration (the sum of heterotrophic and autotrophic respiration; (HR+AR) and NPP is the net primary production.

As was so clearly stated by Chapin et al. 2009, p. 841, this model limits our ability to model C dynamics across the full range of dynamics. The model is adequate only when (1) NPP and decomposition (and thus HR) are tightly linked, "such that C inputs to soil control decomposition and/or such that decomposer activity controls C inputs to vegetation, 2) biologically mediated CO_2 flux is the only large C flux in the ecosystem and 3) C balance is the most important ecosystem feedback to the climate system." Other areas that require more attention in coupled terrestrial ecosystem models are (1) nutrients and factors that influence the balance between "photosynthetic C inputs and respiratory C outputs", particularly the representation of soil processes; (2) ecosystem fluxes other than CO_2 (e.g. nitric and nitrous oxide, volatile organic carbon [VOC] compounds and methane) that influence the climate system; and (3) climate feedbacks in addition to C balance, including increases in atmospheric CO_2, atmospheric N deposition, land cover change, hydrology and ozone inhibition of carbon uptake (Sitch et al. 2007). The list articulated by Chapin et al. (2009) also serves as a list of needed improvements in biogeochemical cycles within Earth system models.

The AR4 was the first "Earth System" report because some of the climate system models used for making climate projections now included an interactive carbon cycle and carbon cycle feedbacks, in what was called the "Flying Leap" by Inez Fung (Fung et al. 2005). Cox et al. (2000) conducted an early experiment focusing on climate carbon cycle coupling that highlighted the acceleration of climate warming with carbon cycle feedbacks including the drying and subsequent die-back of the Amazon rainforest. A subsequent intercomparison study of climate-carbon cycle models called the Coupled Climate–Carbon Cycle Model Intercomparison Project (C^4MIP; Friedlingstein et al. 2006; Fig. 11.5) showed a wide range of potential feedback responses across the 11 models run for the A2 scenario of carbon dioxide emission. The Cox et al. model (2000) had the most sensitive carbon climate feedback, and the Fung et al. (2005) model had one of the least sensitive feedbacks. The Cox and Fung coupled carbon-climate models differed in their prediction of 2100 atmospheric carbon dioxide concentration by 220 ppm CO_2, more than 2.5 times the approximately 100 ppm rise in atmospheric carbon dioxide over the last 100 years. There is clearly much that needs to be done to evaluate and improve the carbon cycle models within the climate system, including improved representation of soil carbon dynamics (Denman et al. 2007; Chapin et al. 2009; Randerson et al. 2009,). Increased CO_2 in the atmosphere will produce greater warming and climate warming will weaken the capacities of the ocean and terrestrial biosphere to store anthropogenic carbon during the twenty-first century (Cox et al. 2000; Friedlingstein et al. 2001; Fung et al. 2005; Denman et al. 2007; Randerson et al. 2009).

Randerson et al. 2009 have undertaken a remarkable synthetic effort to set up a system that facilitates comparison of the global terrestrial carbon models with observations called the Carbon Land Model Project (CLAMP; Figs. 11.6 and 11.7). Two carbon models, CASA and CN, which operate within larger Community Climate System Model effort (http://www.ccsm.ucar.edu/), were compared against a broad range of observational data, (http://www.climatemodeling.org/c-lamp/). The seasonal cycle of net carbon uptake, shown in Figure 11.7, was underestimated in temperate and boreal ecosystems by both models compared to the Ameriflux eddy covariance data of net ecosystem exchange and NOAA's Global Monitoring

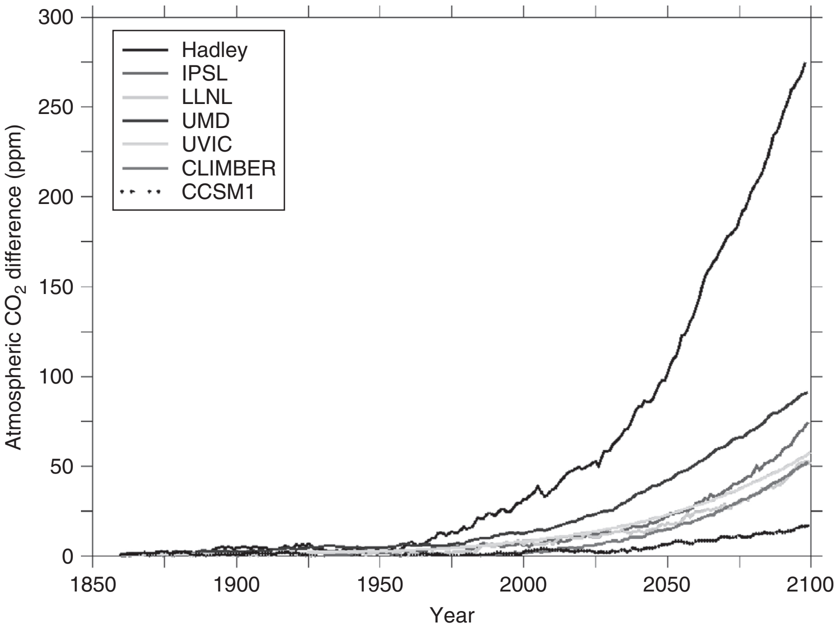


Figure 11.5 Projected differences in atmospheric CO_2 concentrations for a subset of seven models from C4MIP study run for the IPCC A2 scenario (Friedlingstein et al. 2006). The upper black line, indicated as the Hadley model, is the Cox et al. model (2000) and the lowest black line, indicated as the CCSM1, is the Fung et al. model (2005) demonstrating the range of climate-carbon dioxide sensitivities.

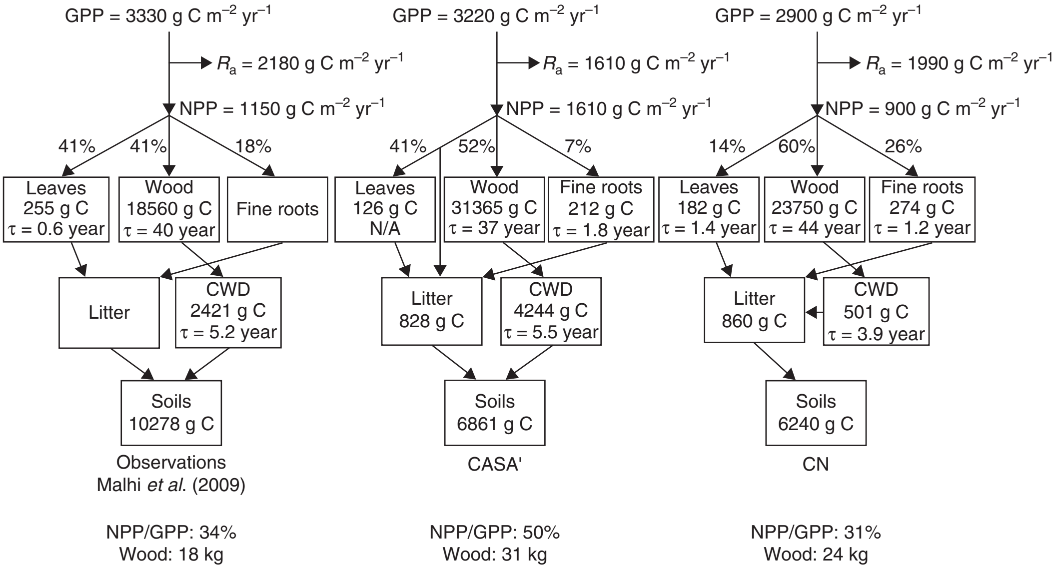


Figure 11.6 Comparison of modeled carbon pools and fluxes to a synthesis of Amazonian observations.
Mahli et al. 2009.

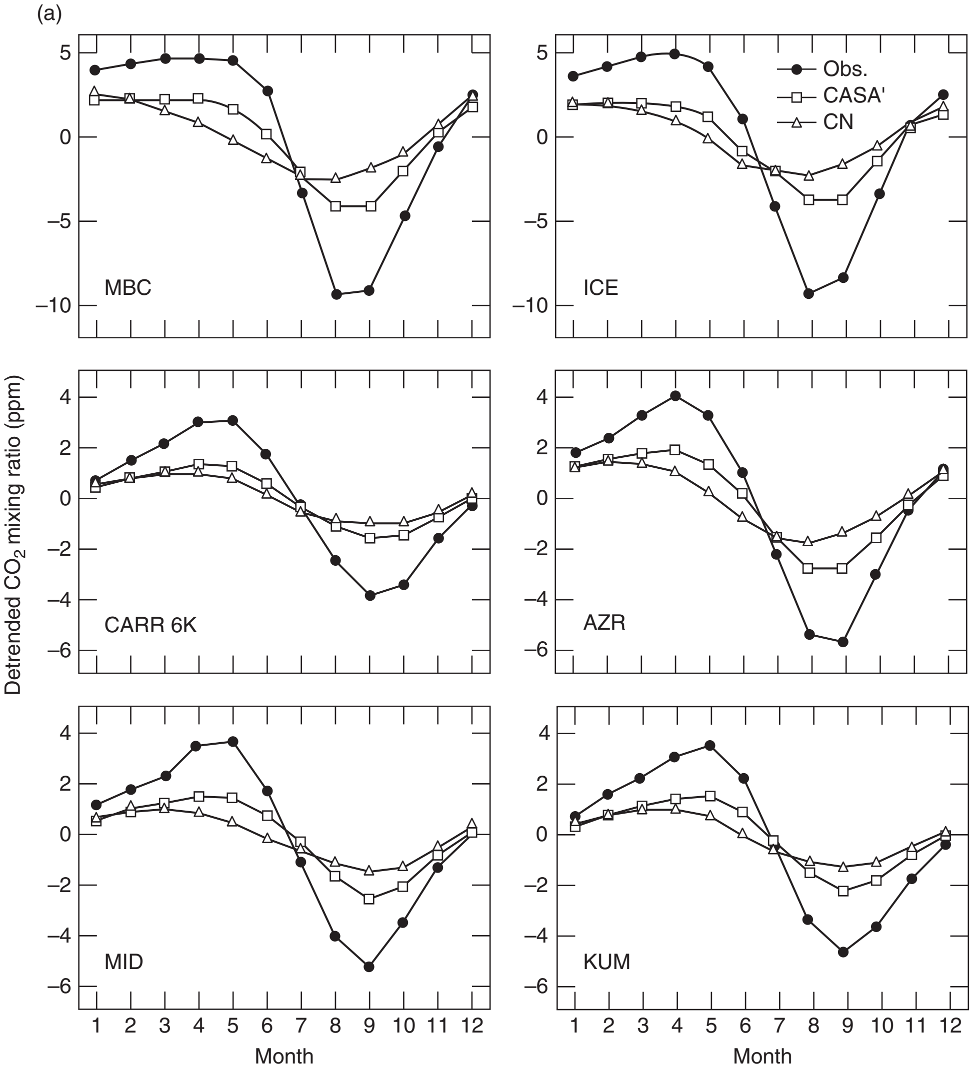


Figure 11.7(a) Modeled and observed seasonal cycle of carbon dioxide from six different sites, Mould Bay Canada (MBC 76°N), Storhofdi Iceland (ICE, 63°N), Carr Colorado, (CARR, air craft samples from 6km masl, 41°N), Azores Islands (AZR, 39°N), Sand Island, Midway (MID, 28°N), and Kumakahi, Hawaii (KUM, 20°N).

Division atmospheric CO_2 measurements. In high latitude and moisture limited savanna ecosystems, maximum leaf area simulated by the models lagged MODIS observations of maximum leaf area. Both models overpredicted the allocation to woody biomass and underpredicted autotrophic respiration compared to available carbon budgets for the Amazon (see Fig. 11.6; Mahli et al. 2009). Much of the emphasis to date has been on the evaluation of modeled atmospheric and aboveground metrics.

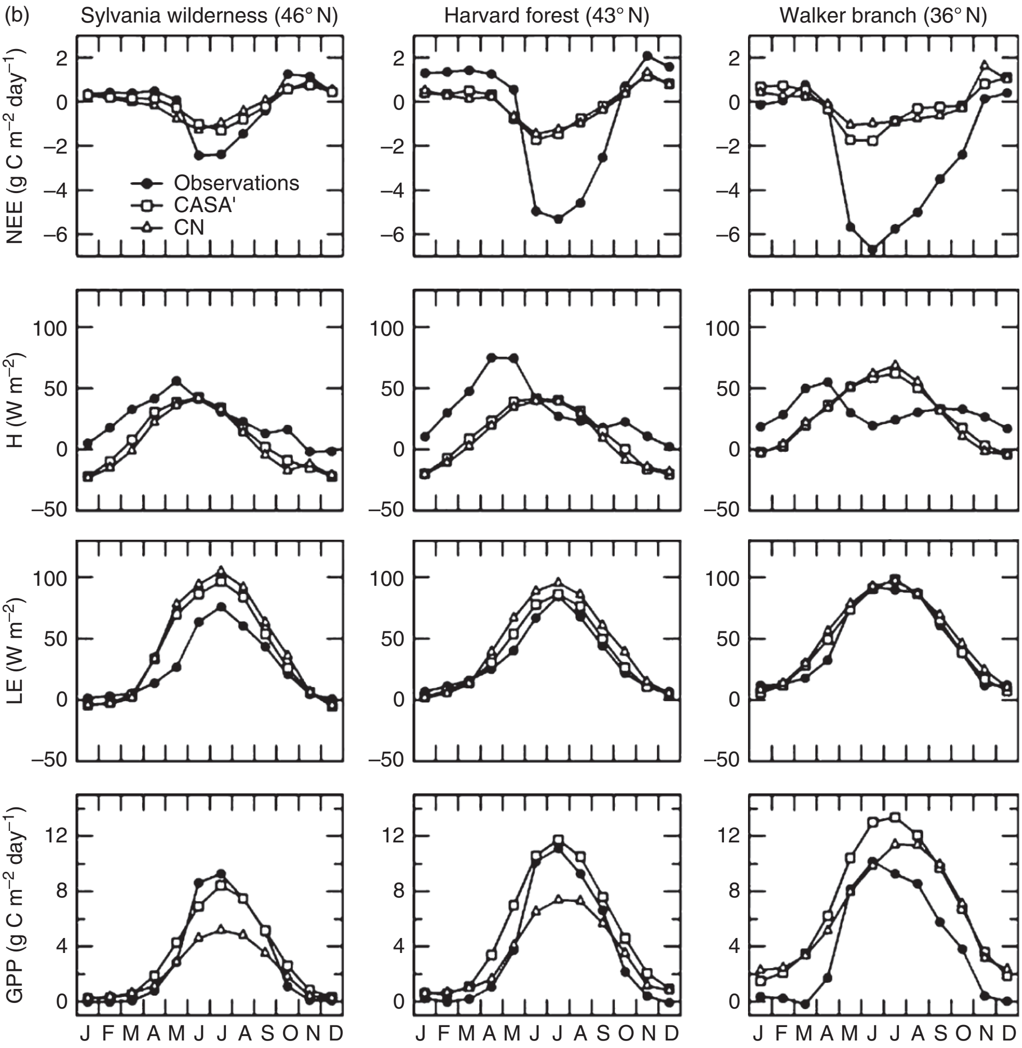


Figure 11.7(b) Comparison of eddy flux measurements of Net Ecosystem Exchange (NEE), Heat (H), Latent Energy (LE), and Gross Primary Production (GPP) for three sites: Sylvania Wilderness (Desai et al. 2005), Harvard Forest (Barford et al. 2001), and Walker Branch (Wilson & Baldocchi 2001) from the Ameri-flux network.
Both figures are from Randerson et al. (2009).

11.4 The Nitrogen Cycle

Like the carbon cycle, the global nitrogen cycle is characterized by large gross fluxes with relatively small net differences that show up as sources or sinks (Fig. 11.1b; Galloway et al. 2004). Unlike the carbon cycle that can be characterized largely by CO_2, with smaller contributions by methane, carbon monoxide, and VOC compounds, the nitrogen cycle must be characterized by considering a number of different reactive chemical species (Fig. 11.8). The most abundant nitrogen species is the ubiquitous triple bonded N_2 that constitutes much of

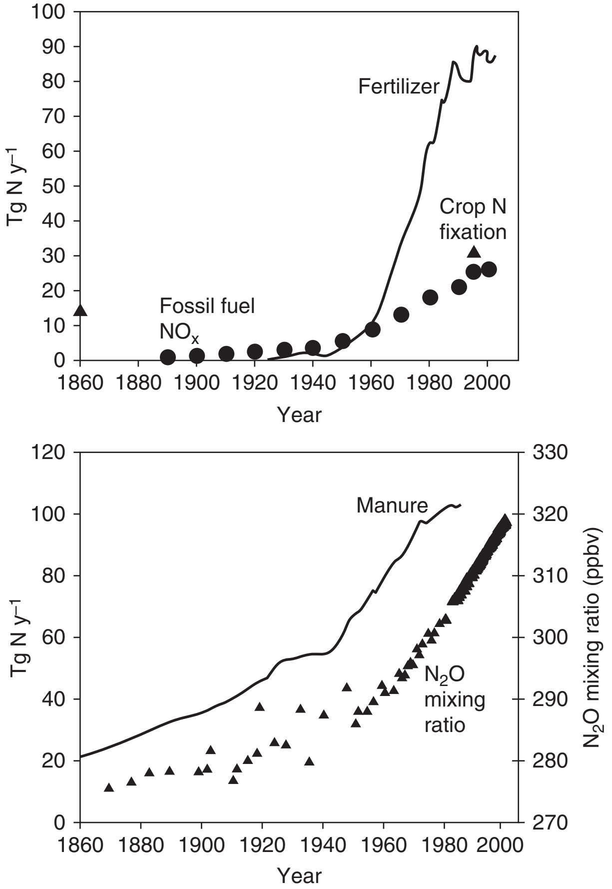


Figure 11.8 Changes to the global nitrogen cycle since 1860. Nitrous oxide serves as a long-lived atmospheric tracer that constrains our understanding of changes to the global nitrogen cycle.
From Holland et al. 2005; Denman et al. 2007; for data: http://ww-eosdis.ornl.gov.

the atmosphere. Alterations to and acceleration of the global nitrogen cycle focus on reactive nitrogen, those nitrogen species that are not N_2, including N_2O with an atmospheric lifetime of 117 years, NO_x:NO+NO_2, and NH_x: NH_3+NH_4^+ with atmospheric lifetimes of 1 day to 1 week depending on their height in the atmosphere, NOy: odd nitrogen, NO and the sum of it atmospheric oxidation products, and organic nitrogen species (Denman et al. 2007).

Reactive nitrogen plays an important role in human and ecosystem health and is central to sustaining our Earth through maintaining soil, ecosystem, and human productivity (Vitousek et al. 1997; Galloway et al. 2004; Townsend & Howarth 2010). N limitation of plant growth is widespread, with an average 29% plant growth response to N addition across temperate and tropical forests, grasslands, wetlands, and tundra (Lebauer & Treseder 2008). N inputs encourage the growth of invasive species, changing plant and animal composition, herbivory, and ecosystem structure (Vitousek et al. 1997). Excess N inputs can contribute to forest die-back and can result in N saturation of ecosystems and the export of N to hydrologic systems and the atmosphere (Schulze et al. 1989; Schulze 2000). Excess N inputs are key contributors to the annual dead zone in the Gulf and Mexico and around the world (Rabalais et al. 2009;

Potter et al. 2010). NO regulates stratospheric ozone abundance (Ravishankara et al. 2009), and NO_x emitted by soils contributes to tropospheric ozone formation (Jeaglé et al. 2005). Reactive N species are atmospheric pollutants: Nitric Acid (HNO_3) is a key constituent of acid rain, and N_2O and N containing aerosols (PM2.5 and 10) are EPA regulated air pollutants. N in water is a pollutant and can cause eutrophication of lakes and streams. High nitrate in water can cause blue baby syndrome. N is needed to grow our food, but excess N consumption in protein can contribute to obesity (Townsend et al. 2003). Managing the global N cycle requires a finely tuned balance to provide nitrogen to grow the food we need for nourishment and not so much as to pollute the planet we live on (Galloway et al. 2008; Vitousek et al. 2009).

The N cycle is implicit in many parts of the climate system but is not yet addressed explicitly beyond N_2O (see Fig. 11.4). NO ranks as five out of five among the top greenhouse gases, and as first in the list of ozone depleting substances through which it plays a role in stratospheric cooling (Ravishankara et al. 2009). Reactive N influences the climate system by playing a role in regulating atmospheric CO_2 concentrations through N limitation of carbon uptake (discussion to follow), through NO_x emissions which catalyze tropospheric ozone concentrations, and shorten the atmospheric lifetime of methane (Prather et al. 2001). Atmospheric NO_x and ammonia form aerosols. Changing agricultural patterns and nitrogen fertilization impact surface albedo and its associated radiative forcing.

The Third and Fourth IPCC reports from WG 1 have emphasized the need to address nutrient limitations of CO_2exchange (Prentice et al. 2001; Denman et al. 2007). An interesting paper by Hungate et al. 2003 described the gap between the N needed to sustain the carbon uptake predicted by the carbon models in the Third Assessment report and the available N. The gap underscored the need to incorporate carbon and N modeling into Earth system models, but the coupled models were not ready for the AR4 and the C^4MIP study. A number of models that couple the carbon and N cycle for Earth system models have been released since the AR4 including studies by Sokolov et al. (2008), Thornton et al. (2009), Jain et al. (2009) Gerber et al. (2010), Zaehle et al. (2010a, 2010b), Zaehle and Friend (2010) and the integration of the nitrogen cycle into dynamic global vegetation models (Ri & Prentice 2008).

The impact of the coupled carbon and N cycle on atmospheric CO_2 has been more challenging to interpret than the thoughtful simplicity of the Hungate et al. 2003. N limitation of CO_2 fertilized plant uptake, is about 50%, or 324 Pg of carbon, consistent with the Hungate et al. 2003 analysis. Increased temperatures stimulate N turnover and availability thus stimulating terrestrial carbon uptake by 49Pg C with the greatest impact in mid-latitude ecosystems, according the Zaehle et al. (2010c). The net result was a 48 ppbv increase in atmospheric CO_2 with an uncertainty range of 41 to 45 ppbv for 2100. The corresponding radiative forcing was 0.29 (0.28–0.34) W m^{-2} (Zaehle & Friend 2010).

11.5 Future of Earth System Models

Coupled biogeochemical cycle modeling of carbon, N, and phosphorus, including the soil processes, within Earth system models is clearly a much needed expansion area that will receive considerable attention for the next decade and beyond. There is a strong need for systematic evaluation of modeled belowground and soil dynamics against the available globally observed of soil organic matter carbon, N, and phosphorus, litter production and decomposition, and nutrient availability (Chapin et al. 2009; Randerson et al. 2009).

A next challenge for Earth system models is to include aspects of agriculture beyond the land surface changes (i.e. cropping season, crop type and extent, crop management, fertilizer use, and the accompanying biogeochemistry). For example, global fertilizer use spans orders of magnitude along developmental trajectories: undeveloped areas (e.g. West Africa receives relatively small inputs of fertilizer, 7 kg N ha-1 y-1); areas undergoing rapid development trying to feed fast growing populations (e.g. China receives inputs of fertilizer exceeding 588 kg N ha^{-1} y^{-1}); and areas trying to solve the environmental problems associated with widespread use of fertilizer over many decades (e.g. the United States has scaled their fertilizer use back to 93 kg N ha^{-1} y^{-1}) (Vitousek et al. 2009). Spatially explicit fertilizer data sets like the one assembled by Potter et al. 2010 will be invaluable in the next phases of model development. Understanding agriculture in the climate system will require understanding the changing land use, land surface, and carbon and N alterations all together (Bonan & Levis 2010).

The representation of soils, their processes, and feedbacks in global scale Earth system models, and their role in sustaining the Earth system to support life for all beings remains a critical challenge for the coming decades.

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12 Net Agricultural Greenhouse Gases

Mitigation Strategies and Implications

Claudia Wagner-Riddle and Alfons Weersink

12.1 Introduction

Increased concentration of atmospheric carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) over the last 50 years have been linked to global climate change (Intergovernmental Panel on Climate Change [IPCC] 2007). Due to their ability to absorb long-wave radiation, atmospheric increases of these gases enhance the greenhouse effect and can lead to positive changes in the Earth's energy balance. Despite their much lower atmospheric concentration, increases in CH_4 and N_2O are estimated to have a disproportionately larger effect than CO_2 in this radiative forcing because on a mass basis their global warming potential is 23 and 296 times larger than CO_2, respectively (IPCC 2007). This effect is taken into account in greenhouse gas (GHG) inventories by considering these warming potentials and expressing non-CO_2 emissions in CO_2 equivalents (CO_2-eq).

Agriculture is a net source of GHG contributing on average 8% (1.3 Gt CO_2-eq yr^{-1} in 2002–2004) to total GHG emissions for countries members of the Organisation for Economic Co-operation and Development (OECD 2008a) and 5.1 to 6.1 Gt CO_2-eq yr^{-1} worldwide (2005 values; 10–12% of total) (Smith et al. 2007). Total agricultural GHG emissions in OECD countries are apportioned to N_2O from soils (46%), CH_4 from enteric fermentation (30%), CH_4 and N_2O from manure storage (14%), and CO_2 from direct energy use (10%) (OECD 2008a). Globally, CH_4 emission from rice paddies is a more significant source than animal manure (United States Environmental Protection Agency [USEPA] 2006). Soils emit large amounts of CO_2 due to microbial and root respiration, but agro-ecosystems also take up CO_2 during photosynthesis closely balancing emissions so that global net CO_2 emissions from agriculture (excluding energy use in this sector) are estimated at only 0.04 Gt CO_2-eq yr^{-1} (Smith et al. 2007). Minimizing soil carbon loss and enhancing the carbon uptake by agro-ecosystems through storage in soil organic matter have potential to offset fossil fuel CO_2 emissions until alternative energy sources are developed (Lal 2004). Hence, agricultural soils play an important role in the direct production and emission of GHG and indirectly through the production of feed (e.g. pasture, grains) for livestock. Consequently, mitigation practices for reduced net GHG emissions from agriculture should consider linkages between animal production, crop, soil, and manure management.

In this chapter proposed mitigation practices for reduction of GHG emissions from agriculture are briefly reviewed. Then, two case studies using experimental data comparing GHG emissions for (1) composted versus untreated liquid swine manure and (2) conventional versus best management practices (BMP) for soils and crops are discussed. The policy options to encourage

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the deployment of these mitigation measures are then discussed and the importance of considering both the biophysical consequences of the farming practice and the incentives facing the farmer regarding the adoption of the practice are highlighted.

12.2 Mitigation Practices for Reduction of Net GHG Emissions

Several comprehensive reviews have assessed the opportunities for GHG mitigation at the global scale (Oenema et al. 2001; Vergé et al. 2007; Van Groenigen et al. 2008; Smith et al. 2008). Practices to reduce agricultural GHG emissions can be classified into: (1) reduction or avoidance of emissions, (2) enhancement of sinks, and (3) replacement of fossil fuel with biomass-derived sources. The most recent literature for each source within these three categories is briefly reviewed. Linkages among mitigation practices are then discussed.

12.2.1 Reduction or Avoidance of Emissions

Methane Emissions from Enteric Fermentation Enteric CH_4 is derived from microbial fermentation of hydrolyzed dietary carbohydrates, and in some cases from amino acids, in the intestinal tract of ruminants and nonruminants (Kebreab et al. 2006). Domesticated ruminants, particularly cattle and sheep, are the main contributors accounting for the vast majority of global CH_4 emissions derived from enteric fermentation (USEPA 2006). Animal nutritional strategies are the main mitigation measures that have been proposed to reduce the CH_4 emissions from this source. Beauchemin et al. (2008) reviewed *in vivo* studies and concluded that replacing roughage with concentrate, adding lipids to the diet and use of ionophores were the most promising techniques. Improved diets through use of concentrates result in increased CH_4 production per animal, but due to productivity increases, the resulting CH_4 production per unit of output (milk or meat) is lower (Lovett et al. 2006). Modern dairy practices involve fewer animals and resources used per unit of milk produced according to a recent analysis comparing US dairy production in 2007 to 1944 (Capper et al. 2009). However, because of population growth and changes in diet, overall number of methane-producing animals has increased dramatically in the last 30 years and is projected to continue increasing (Steinfeld et al. 2006). This has prompted the consideration of future scenarios where fewer animal numbers would be needed through a reduction of consumption of livestock products (Garnett 2009). However, Peters et al. (2007) caution that complete diet models need to be used to assess how human food preferences affect the environmental footprint of animal agriculture.

Methane and Nitrous Oxide Emissions from Animal Manure Feces, urine, bedding, and wash-water are collected and managed as manure in animal feeding operations (National Research Council [NRC] 2003). Manure storage and handling facilities, placed inside or outside buildings, are a direct source of CH_4 and N_2O, while urine and excreta deposited in pastures contribute to emissions from soils (Kebreab et al. 2006). The majority of emissions from manure management historically have originated from OECD countries, but future projections are for increased contributions from non-OECD countries (USEPA 2006). Proposed mitigation practices include improved feed efficiency and diets for reduced nitrogen (N) and carbon excretion, covering of storage tanks, aerobic composting, and capture of biogas in anaerobic digesters (Smith et al. 2008).

Nitrous Oxide Emissions from Soils N_2O is produced in soils by the microbiological processes of nitrification and denitrification (Firestone & Davidson 1989) and comprises the majority of GHG released by agro-ecosystems (USEPA 2006). Nitrogen application to soils in the form of inorganic fertilizer, crop residues, and manure result in increased direct N_2O emissions from soils (Rochette et al. 2008). Nitrogen fixation by legumes *per se* is not considered a significant N_2O source any longer (Rochette & Janzen 2005). Nitrogen that is lost from agricultural soils through ammonia (NH_3) volatilization and nitrate leaching can also lead to N_2O production and emission, an indirect N_2O source (Mosier et al. 1998). The latter effect is part of what has been termed the "N cascade," in which reactive forms of the same N atom can cause multiple effects in the environment (Galloway et al. 2003). Trends in population growth and estimates that approximately one third of the protein in human diets derives from synthetic nitrogen fertilizer (Smil 1997) determine the future continued importance of N_2O in GHG emissions from agriculture.

The suggested mitigation options for reducing N_2O emissions center on increased nitrogen use efficiency by crops, that is, adjusting nitrogen input rates according to soil reserves and matching the time of application to crop uptake (Mosier 1994). Slow-release fertilizer forms, precise placement of fertilizer into the soil, or eliminating nitrogen application have also been suggested (Smith et al. 2008).

Carbon Dioxide from Energy Use Use of farm machinery and other on-farm activities consume energy directly during crop and livestock production and also indirectly for production of farm inputs such as fertilizers, herbicides, and pesticides (OECD 2008a). Improved energy efficiencies and reduced use of inputs through soil, crop, manure, and animal management are strategies that can result in reduced CO_2 emissions from energy use in agriculture (Schneider & Smith 2009).

12.2.2 Enhancement of Sinks

Long-lived carbon storage in plant biomass and soils can be achieved through increased carbon uptake or reduced decomposition rates (Johnson et al. 2007). Improved crop and nutrient management, reduced or no-tillage, agro-forestry, use of cover crops, reduced soil erosion and degradation are practices with potentials ranging from 50 to 1000 kg C ha^{-1} yr^{-1} globally (Lal 2004).

12.2.3 Replacement of Fossil Fuel Emissions with Biomass-Derived Sources

Agriculture is projected to expand its contribution to biomass-derived energy, chemicals, and materials in addition to food, feed, and fiber during the twenty-first century (Eaglesham et al. 2008). Carbon dioxide emissions resulting from the use of biomass-derived fuels and products do not contribute to the enhanced greenhouse effect because they recycle carbon that was recently fixed into organic matter through photosynthesis. Hence, reductions of GHG emissions and reduced dependence on fossil energy have been the drivers of recent government support for biofuels and bioproducts (OECD 2008b).

12.3 Net GHG Reduction

Use of a specific mitigation practice may have unintended consequences for GHG emissions upstream or downstream in the agricultural system. Recognition of interactive effects has led to calls for whole-system studies to evaluate net GHG reductions of a combination of mitigation practices (Oenema et al. 2001; Lovett et al. 2006; Beauchemin et al. 2008; Stewart et al. 2009). The main potential interactive effects that have been highlighted in the literature are:

- Increased use of dietary concentrate to reduce enteric CH_4 emissions would require growing, processing, and transporting more grains, leading to direct CO_2 and N_2O emissions that may offset the reduced CH_4 emissions in some cases (Beauchemin et al. 2008). Soil CO_2 emissions from any land clearing associated with growing of such feedstuff (Garnett 2009) and potentially higher GHG emissions from the manure associated with changed diets need to be considered.
- Treatments to reduce or avoid CH_4 emissions from manure, such as composting and anaerobic digestion, need to consider effects on N_2O and NH_3 emissions, the latter leading to indirect N_2O emissions. In addition, direct and indirect N_2O emissions after land spreading of treated manure should be evaluated in comparison to untreated manure (Clemens et al. 2006; van der Meer 2008).
- Fossil fuel savings due to biofuel use can be offset by global warming contributed by N_2O emissions from production of agricultural crops as feed-stocks for biofuels at current N use efficiencies (Crutzen et al. 2008). Soil CO_2 emissions from indirect land use change caused by deforestation and conversion of grasslands to agricultural lands may also offset reductions in GHG emissions from biofuels (Fargione et al. 2008; Searchinger et al. 2008). However, there is controversy on when and how such displacement effects should be considered as there is large uncertainty in linking biofuel production and land use change elsewhere (Börjesson 2009).
- Improved crop and grassland productivity and no-tillage may result in greater soil carbon storage, but can be offset by higher soil N_2O emissions and CO_2 emissions from fertilizer manufacture (Smith et al. 2008).

The interacting effects discussed previously emphasize the importance of studies that consider net GHG emissions and a combination of management practices for GHG mitigation. While whole-system evaluations rely on modeling approaches due to the complexity of agricultural systems, field studies that test a combination of suggested measures are also needed (Oenema et al. 2001). In addition, there is agreement in the literature that mitigation practices are likely to be site specific, so that studies need to be carried out considering local conditions to evaluate the magnitude of GHG reduction associated with technical options. In the next two sections results from two field studies are discussed and then nontechnical aspects for implementation of these measures are considered.

12.4 Case Study 1: GHG Emission Mitigation through Composting of Liquid Swine Manure

The evaluation of liquid swine manure composting as a mitigation strategy for GHG emissions requires measurements during various stages of manure treatment and after field application of manure using flux measurement methods applicable for each situation (Fig. 12.1). To compare emissions, measured CH_4 and N_2O fluxes were scaled taking duration of each stage and volume

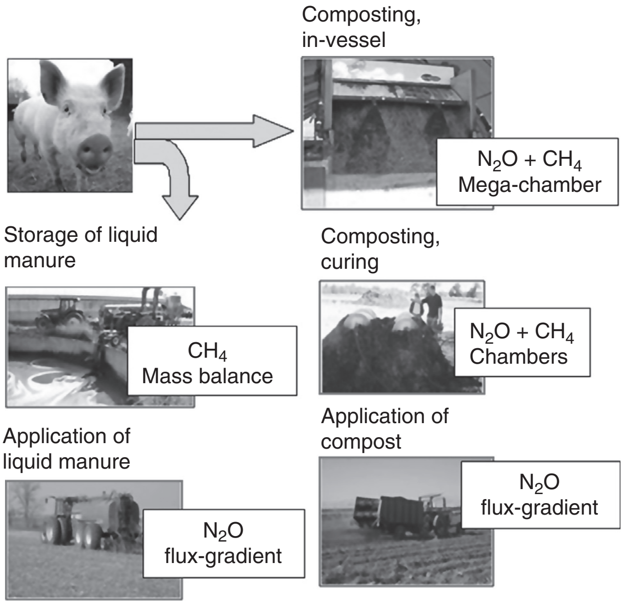

Figure 12.1 Stages of liquid swine manure treatment, storage and land application considered in Kariyapperuma (2008). Greenhouse gas emissions measured at each stage and method of measurement are also shown.

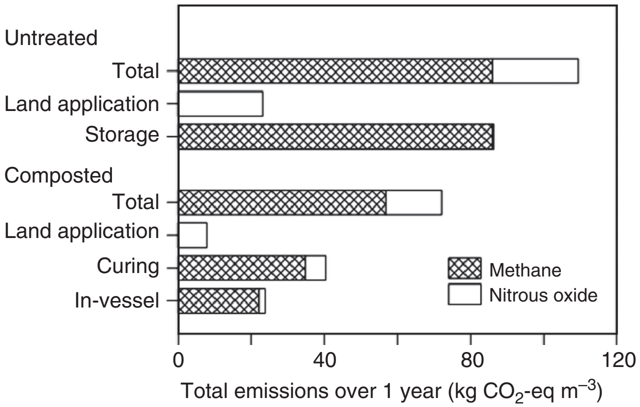

Figure 12.2 Greenhouse gas emissions as methane and nitrous oxide for untreated and composted liquid swine manure for each stage depicted in Figure 12.1.
Drawn from data reported in Kariyapperuma (2008).

of manure treated into account and then expressed in kg CO_2-eq per m^3 of manure treated (Fig. 12.2). The magnitude of fluxes and the duration of each stage determined the total for each phase. CH_4 dominated GHG emissions for both treated and untreated manure. N_2O emissions during composting increased relative to storage of liquid manure, but this increase was off-set by lower CH_4 emissions during composting. Overall emissions were decreased by 40 kg CO_2-eq m^{-3} or a 35% reduction through composting.

Experiments such as the one described can provide the technical potential of a given mitigation practice. To translate these research results to achievable mitigation estimates, socio-economic

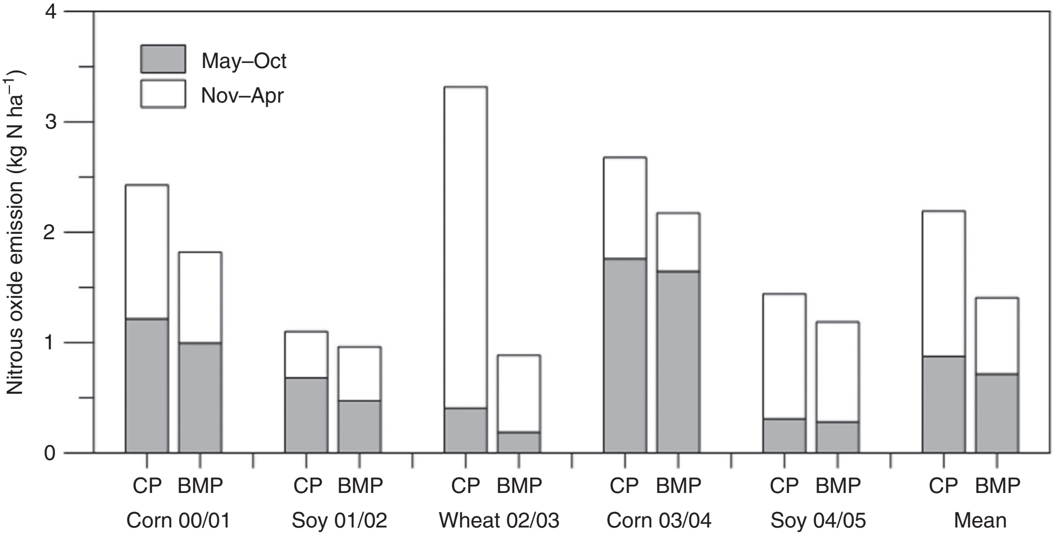

Figure 12.3 Nitrous oxide emissions for plots managed using conventional (CP) and best management practices (BMP) during the growing season (May to October) and nongrowing season (November to April) over five years (May 2000 to April 2005). Label on *X*-axis indicate which crop was grown each year and when mean value over five years is displayed.
Graph drawn using data from Wagner-Riddle et al. (2007).

and behavioral factors need to be considered. Composting facilities require greater capital and operational costs than manure storage. There are also learning costs and time commitments associated with operating a composter, which producers may not be willing to undertake. Proper operation of a composting facility has important implications for GHG emissions. Thompson et al. (2004) found that, when a producer decided to not turn on the active aeration system, composting elevated emissions up to an estimated 330% of liquid manure storage. In addition, other environmental impacts should also be considered, in particular the high carbon (as CO_2) and N losses (as NH_3) which occur during the composting process (Larney et al. 2006).

12.5 Case Study 2: Direct and Indirect N_2O Emission Reduction through Soil Tillage and Nitrogen Fertilizer Management Practices

No-tillage has the potential for carbon sequestration as well as several other environmental benefits (Holland 2004). Mitigation practices for N_2O emission reduction, such as applying N fertilizer according to soil N reserves and matching the time of application to crop uptake, interact with no-tillage practices.

Wagner-Riddle et al. (2007) compared N_2O fluxes from two management systems: conventional (CP) and best management practices (no-tillage + reduced fertilizer better timed for crop uptake (BMP)); applied to a corn (*Zea mays* L.), soybean (*Glycine max* L.), and winter-wheat (*Triticum aestivum* L.) rotation in Ontario, Canada, over May 2000 to April 2005 (Fig. 12.3). Annual N_2O emissions under BMP were reduced on average by 36% or by 383 kg CO_2-eq ha^{-1} yr^{-1}, an effect that was mostly associated with lower spring thaw emissions associated with no-tillage due to less winter soil freezing (Wagner-Riddle et al. 2007). An additional reduction of 286 kg CO_2-eq ha^{-1} yr^{-1} was associated with lower fuel emission and fertilizer processing requirements under the BMP system (Meyer-Aurich et al. 2004). Carbon sequestration may occur through no-tillage as well, although long-term studies at this site have shown no net gain (Yang & Kay 2001).

Cumulative nitrate leaching loss in this experiment was reduced by 51% from 133 kg N ha^{-1} in CP to 68 kg N ha^{-1} in BMP over May 2000 to October 2004, while crop yields were either not different or higher for BMP (Jayasundara et al. 2007). Lower inputs meant a 9% reduction in costs, with fixed and variable costs about Cdn$30 per ha less under the BMP (Meyer-Aurich et al. 2004). When averaged over the analyzed period of 4 years, net returns per hectare were 42% greater for the BMP system as compared to the conventional system. In summary, the technical mitigation options (reduced N rate, better timing of application, no-tillage) evaluated for conditions in Ontario, Canada, appeared to constitute a win-win situation, leading to reduced environmental impact and economical benefits to farmers. In the latter half of this chapter, the issues in designing policies to encourage or coerce farmers to adopt the fertilizer practices that reduce GHG emissions are examined.

12.6 Designing Policies for Reduced Nitrogen Fertilizer Use

The previous section presented the results of a field experiment highlighting the role of fertilizer management in reducing environmental N emissions. Some studies have suggested that cutting fertilizer levels is the cost-effective means of cutting net GHG emissions because it may enhance, rather than cut, farm profit and because it is easily adopted (Weersink et al. 2005). Despite the apparent win-win predictions stemming from calls for lower fertilizer rates, many farmers continue to apply more than the recommended rate (Sherrif 2005; Agriculture and Agri-Food Canada [AAFC] 2000). In this section, policy options to reduce GHGs emissions through a reduction of fertilizer rates are assessed and the importance of considering both the biophysical consequences of farming practices and the behavior underlying the adoption of those practices is highlighted.

12.6.1 Farmer Choice of Fertilizer Rates

The level of fertilizer that a farmer chooses to apply on a given field depends on the objective of the farmer, the yield response of the crop to fertilizer, and relative prices. Assuming the farmer desires to maximize net returns and that the yield response and prices are known with uncertainty, the profit maximizing fertilizer rate is where the incremental return from adding another unit of fertilizer is equal to the incremental cost of that unit.

The concept of the profit maximizing fertilizer rate is illustrated in Figure 12.4. The nonlinear curve is the total value produced (TVP) per unit of land from the application of alternative fertilizer rates (N). The return from fertilizer is the product of the response function ($f(N)$) and the price of the crop (P_C). Because farmers are generally price takers, the shape of the total value product is the same as the underlying yield response curve. The shape of the curve in Figure 12.4 is quadratic implying there is a fertilizer rate that maximizes yield (N_Y) and output falls with applications beyond this rate. Other common specifications for the production function include a linear-plateau, quadratic plateau, and Mitscherlich. The linear line in Figure 12.4 is the cost of fertilizer application (TC) which is the product of the fertilizer price and the amount applied ($TC=P_N*N$).

The difference between the total value product and the fertilizer cost is the net return to the application of fertilizer. Profits are zero when the lines cross (i.e. at $N=N_0$) and positive when

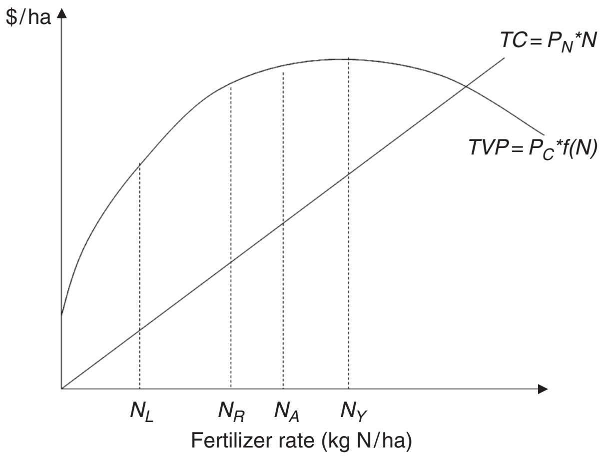

Figure 12.4 Total value product (TVP) and total nitrogen cost (TC) for alternative nitrogen application rates.

TVP is greater than *TC*. The maximum profit occurs when the distance between the two curves is greatest, which is when the slopes of the curves are equal. At this fertilizer rate, N_R, the change in crop yield from another unit of fertilizer is just equal to the cost of that extra unit. Increasing the rate of application up to N_R increases the level of profits. Afterward, profits are still positive but decrease with the levels of fertilizer until N_0 is reached.

The profit maximizing rate, which is the recommended rate by agronomists (N_R), and the yield maximizing rate (N_Y) are two possible application levels that can be chosen by farmers. Two others are illustrated in Figure 12.4 and serve as comparisons when highlighting the importance of understanding farmer behavior in setting policy mechanisms to control GHG levels from farm activity. One is the actual rate applied by farmers (N_A), and it is often greater than the recommended rate. The other is lower than the recommended rate (N_L). Because the response function is generally flat around N_R, the costs of reducing application levels to N_L are small but the potential reductions in residuals such as N_2O emissions are significant. Thus, N_L may be a target for agri-environmental policy.

12.6.2 Public: Private Benefits Framework

The socially optimal application rate of fertilizer suggested previously (N_L, N_R, N_A, or N_Y) and the policy mechanism to induce the optimal rate are examined within a framework developed by Pannell (2008). The socially optimal strategy is one in which the farmer not only considers the actual cost of the fertilizer relative to its return but also the environmental damages that may result. There are no property rights associated with air and water quality, so the costs associated with higher N_2O in the atmosphere or nitrate in the groundwater are not considered by the farmer in making fertilizer management choices. The socially optimal choice internalizes those environmental costs.

Pannell's framework illustrated in Figure 12.5 captures the private and public aspects of practices that could affect the environment. The horizontal axis represents the private net benefits to the farmer of changing fertilizer application from the current rate (N_A). Movements

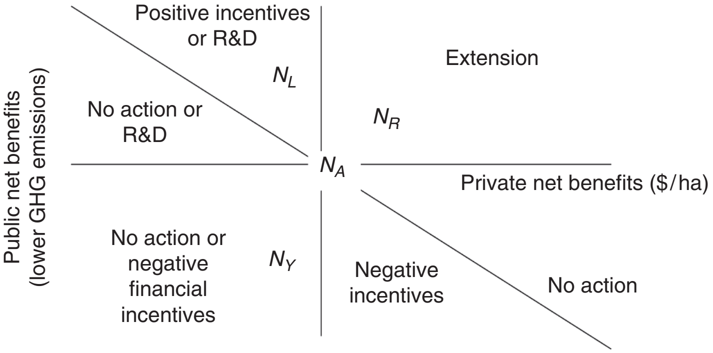

Figure 12.5 Public and private net benefits from alternative nitrogen application rates (N) and policy mechanism. Adapted from Pannell (2008).

to the left (right) of the origin indicate expected returns that are less (greater) than from the present strategy. The choices represented in Figure 12.5 of a potential target for agri-environmental policy (N_L) and the yield maximizing rate (N_Y) imply lower profits than the actual rate and are to the left of the origin. In contrast, applying the recommended rate (N_R) generates higher returns and, consequently, it is situated to the right of N_A in Figure 12.5. Note that at this stage of the analysis, factors influencing net benefits such as risk and amenity value of an aesthetically pleasing crop are not considered but only the deterministic yield and prices used in Figure 12.4.

Public net benefits, the other aspect of the socially optimal management choice, are represented on the vertical axis in Figure 12.5. Movements up (down) from the origin represent improvements (reductions) in environmental quality relative to the current situation. The measurement unit for public net benefits would ideally be in monetary terms so that a comparison can be made relative to the private net benefits of the farmer, which are also measured in dollars. It would also allow for a comparison across resource management choices to prioritize sites or environmental problems for action. Nonmarket valuation techniques provide estimates of the dollar value that society places on the changes in environmental quality. However, for the purpose of this analysis, the axis is measured in terms of GHG emissions, which are assumed to be directly correlated to the levels of fertilizer application. Thus, the low and recommended rates (N_L and N_R) are above the actual rate (N_A) while the yield maximizing rate (N_Y) is below N_A in Figure 12.5.

12.6.3 Policy Options

Determining the socially optimal fertilizer management strategy requires understanding of the biophysical implications of the practices as discussed in the first part of this chapter and the profitability of those practices for the farmer. The resulting estimates of the public and private net benefits allow each strategy to be placed within the grid of Figure 12.5. Pannell (2008) uses the location in the grid to determine the appropriate policy mechanism.

The recommended rate strategy (N_R) is a win-win scenario as both public and private net benefits are higher than the current application method. Because the farmer must be unaware of the greater profitability, or else N_R would equal N_A, the appropriate policy mechanism is to provide information. Education programs promote environmental objectives by enhancing the farm sector's awareness of the contribution of their current practices to environmental problems and the management practices to reduce those problems (OECD 2003). Technical assistance programs are popular across many countries because they meet with little political resistance and are relatively inexpensive to implement, as they are often combined with existing government extension efforts. Another advantage is that these advisory efforts can have wide spillover effects since a broad suite of environmentally-friendly practices addressing a host of pollutants are generally promoted.

The number of practices that fall within the upper grid of Figure 12.5, for which extension efforts are the appropriate policy mechanism, is limited. Although there may be some more profitable application methods, it is in the farmer's best interest to seek and employ those methods. Consequently, the number of practices that can generate higher returns of which the farmer is unaware is likely limited. Rather than being the result of insufficient information, nonadoption is more likely due to costs not incorporated into the preceding analysis. These costs include learning costs, adjustment costs in switching practices, and risk, which will be discussed in more detail later.

Extension efforts can still be effective in achieving an environmental objective even without profitable practices if the environmental impacts of individual actions can be clearly demonstrated to the producers causing these damages (Horan & Ribaudo 1999). An example is the application of the yield-maximizing rate in the lower left quadrant of Figure 12.5, (N_Y). GHG emissions are reduced and farm profits are higher if the producer lowers rates to either N_R or N_A. Information on the public and private net benefits from lowering rates could prompt the switch if the producer is unaware of the value to lowering fertilizer rates. If the producer is aware, then extension efforts are ineffective and negative incentives may be necessary to induce the switch in practices.

Incentives, both positive and negative, can be imposed either on the acceptable levels of pollutants (performance-based) or on the type of practices or equipment that can be used (design-based). An additional categorization of the policy mechanisms is direct regulation versus economic instrument. The former, also called command-and-control, sets limits on emissions or practices, whereas the latter creates incentives for farmers to act in the desired manner. The incentives could be in the form of charges (negative incentives), which forces the firm or individual to pay for the right to pollute, or in the form of subsidies (positive incentives), which forces the government to pay for the right to a clean environment.

Negative incentives to induce the farmer to reduce N_Y include forcing the farmer to cut GHG levels (performance-based standard) or to cut fertilizer application levels (design-based standard). Performance-based standards are rarely used in agriculture due to the diffuse nature of most residuals from farming but design-based policies are common. Design-based standards for agriculture were initially targeted toward pesticides and most countries have regulatory authorization processes that assess the environmental and human health impacts of inputs before granting approval or reapproval for their use. In terms of fertilizer, governments could limit the availability, impose limits on how fertilizers are used through licenses to purchase and restrict timing of application. It is easier to observe farming practices than the level of emissions so measurement costs are significantly less with design-based standards as compared to performance-based standards. The targets are clear and easily understood, which reduces the transaction costs of implementation.

Negative economic instruments include charges on either emissions (performance-based) or inputs (design-based). As with emission standards discussed above, fees levied on the discharge of pollutants are rarely used in agriculture since individual emissions cannot be measured at a reasonable cost for most agricultural residuals that travel by diffuse and indirect pathways over a potentially long period of time to the receiving resource. An exception is the levy assessed on surplus N and phosphorus from manure application in the Netherlands (Hanegraaf & den Boer 2003).

Instead of taxing the residual directly, a charge can be levied on inputs that indirectly generate the pollutant. There are environmental charges on fertilizers in Sweden and some US states (OECD 2003). The intent of taxes is to raise the price of the polluting inputs and subsequently cause farmers to decrease their use. For example, in the case of N fertilizer, a tax will encourage a more conservative application rate and cause a shift in cropping patterns away from relatively N-intensive crops and towards N-fixing crops such as soybeans and alfalfa. However, the charges actually levied on farm inputs appear designed primarily to generate revenue for other environmental programs and education efforts rather than to alter producer behavior. The inelasticity of farm input demand implies the tax rates must be high to cause the desired reduction in input use—so high that they are likely to be nonfeasible politically (Burrell 1989).

The negative incentives in the form of standards or taxes on either emissions or practices are also appropriate for the bottom half of the lower right quadrant in Figure 12.5. The 45-degree line represents points when the increase in net farm profits is equal to the absolute value of the reduction in public net benefits in comparison to the current situation. If the value of the improvements in environmental quality is greater than the abatement costs from changing practices, then negative incentives are appropriate to force the farmer to reduce their application rates. If the practice is in the upper half of the 45-degree line, then no action is required because the gain in environmental quality is less than the reduction in net farm benefits.

The final quadrant of Figure 12.5, the upper right, illustrates several policy options. Positive incentives are appropriate in the upper half of this quadrant where the increase in public net benefits is greater than the abatement costs, or reductions in net benefits, to the farmer. The most common agri-environmental policy measure is to offer financial incentives encouraging the adoption of inputs or a set of practices that have a more benign effect on the environment. Financial assistance normally takes the form of grants, loans, or tax allowances and is popular with the benefiting farm community. The major limitation of these positive incentives is their universal availability and the resulting cost ineffectiveness.

An additional policy mechanism for practices located in the upper left quadrant of Figure 12.5 is technology development. Research could expand the set of management options by either improving the profitability of environmentally friendly practices or reducing the environmental damages caused by current profitable practices. In addition to technological developments, research into better understanding the impacts of farming practices would aid in the design of environmental policies.

12.6.4 Do Farmers Overapply Fertilizer?

The location of the actual vs recommended rates in Figure 12.5 suggests that farmers with full information are irrational because profitability can be enhanced by lowering rates. Not only are there private net benefits to lowering rates to the recommended level, but public net benefits are also increased. The reluctance to switch to the apparent win-win scenario may be due to issues discussed by Pannell (2008) such as the cost of learning, lags in adoption, and the adjustment costs of moving from one system to another. These costs are not included within the static assumptions of Figure 12.4.

There are other reasons why farmers are apparently applying more fertilizer than a crop can use. Sheriff (2005) suggests several reasons: (1) perception that the general recommendations are not appropriate for their individual situations, (2) uncertainty about soil quality, N content, and weather, (3) uncertain effectiveness of chemical fertilizer substitutes (i.e. manure) and complements (i.e. irrigation), and (4) hidden opportunity costs of farmer time and equipment.

Rajsic and Weersink (2008) and Rajsic et al. (2009) empirically examined the validity of those reasons by estimating the differences in *ex-post* optimal and *ex-ante* recommended application rates of N to corn on field trials over several years. Their results suggest farmers are not "wasting" fertilizer and that the overapplication is a rational economic response due largely to risk.

Rajsic and Weersink (2008) found a high degree of variability in the *ex-post* optimal N rates, especially across years, due to differences in weather. While the *ex ante* recommended rate may be close to the *ex post* optimal on average, the large variability could erode a farmer's trust in a single N recommendation value, and induce them to follow their own judgment (Rajsic & Weersink 2008). The number of years in which the recommended rate was higher than the *ex-post* optimal was approximately equal to the number of years in which the reverse was true. However, in those other years when the recommended rate is lower than the *ex-post* optimal, it is much lower because there is potential for large yields in good growing conditions with sufficient N that is not adequately captured by the recommendations based on average yield potential. The benefits of overapplication in the good years are greater than the costs of excess fertilizer in the poor years. The expected benefits and expected costs are not symmetric so it pays for risk neutral farmers to apply a little extra just in case (Rajsic et al. 2009).

Rajsic et al. (2009) also found a relatively flat payoff functions to N, which suggests a low payoff to variable rate application technology. However, there does appear to be significant value to forecasting the likelihood of weather events during the growing season so that N rates can be adjusted accordingly. The flat payoff function also suggests that the other potential values from overapplication such as the amenity value of an aesthetically pleasing crop and the opportunity costs of time may justify the costs of applying more fertilizer than the recommended.

12.7 Conclusion

The design of effective policies to mitigate GHG levels requires understanding of the biophysical relationships between farm practices and environmental quality along with the reasons for farmers' behavior. The potential for mitigation from the composting of liquid swine manure and through tillage and N fertilizer management were highlighted. The biophysical implications from these practices along with the impacts on farm profitability determine the public and private net benefits of the mitigation measures and the subsequent policy options. The example of the reluctance by farmers to reduce N fertilizer, which appears to be a profitable mitigation measure, highlights the need to better understand producer incentives when estimating the potential for GHG reduction.

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13 Overview on Response of Global Soil Carbon Pools to Climate and Land-Use Changes

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13.1 Introduction

Soil organic carbon (SOC) levels are governed by soil texture, climate, the input of organic material, and by the rate at which various SOC pools decompose. The response of SOC dynamics to climate change and to ecosystem productivity changes remains poorly understood (e.g. Jones et al. 2005; Davidson & Janssens 2006; Bond-Lamberty & Thompson 2010). The mechanisms and factors that govern global formation and decomposition of SOC and their relative regional importance are uncertain as well. Long-term in-situ measurements are sparse and difficult to upscale, whereas remote sensing techniques are only partially effective and no remote sensing observation directly measures SOC (Valentini et al. 2000; Baldocchi 2008). A number of carbon (C) cycle modeling studies attempted to quantify and predict the SOC distribution and its response to climate (McGuire et al. 2001; Cao et al. 2002; Zeng et al. 2005; Peylin et al. 2005; Friedlingstein et al. 2006; Sitch et al. 2008; Piao et al. 2009a). However, few of these models did separate the contribution of changing climate drivers such as carbon dioxide (CO_2), temperature and precipitation from the one of land-use change.

In this chapter, the implications of changes in climate and in land cover for the global and regional balance of SOC are reviewed. The historical period 1901–2000 using models and observations and the period 2000–2100 using a simplified model only are review.

A presentation of the SOC global distribution is given in section 2. The SOC vulnerability to climate and land-use is discussed in section 3. Historical changes in SOC induced by climate, CO_2 and land cover change are analyzed for different regions in section 4, and future projections in section 5. Uncertainties are discussed in section 6.

13.2 Global Distribution of SOC

SOC is the largest C pool of the land. The global mass of SOC is at least 2300 PgC. It is ~75% of the total land biosphere reservoir given that litter and vegetation stocks amount to only 850 PgC (Houghton et al. 2007). SOC consists of a wide range of organic compounds with different physical and chemical properties. SOC is formed by input from plant litter and marginally from charcoal formation after fire (0.005–0.27 Pg $C.yr^{-1}$ according to Kuhlbusch and

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Table 13.1 Soil organic carbon stock (down to 3 m) distribution among main terrestrial biomes.

Biomes	Area (Mha)[1]	SOC stocks (PgC)[2]	Vegetation C (PgC)[3]	SOC density (MgC ha^{-1})[4]
Deserts and sclerophyllous shrubs	2650 (*2770–4550*)	332 (*159–191*)	8–10	125 (*42*)
Crops	1400 (*1350–1600*)	248 (*128–165*)	3–4	177 (*80*)
Tropical savannas	1500 (*2250–2760*)	345 (*247–264*)	66–79	230 (*117*)
Temperate grasslands	900 (*1250–1780*)	172 (*176–295*)	9–23	191 (*236*)
Tundra	800 (*560–927*)	144 (*115–121*)	2–6	180 (*127*)
Tropical forests	2450 (*1755*)	692 (*213–216*)	212–340	282 (*123*)
Temperate forests	1200 (*1038*)	262 (*100–153*)	59–139	218 (*96*)
Boreal forests	1200 (*1372*)	150 (*338–471*)	57–88	91 (*344*)
Peatlands	350	400–500	15	1140–1430
Permafrost[5]	1878	1024	—	545

[1] Jobbagy and Jackson (2000) except for peatlands (IPCC 2000) and permafrost (Tarnocai et al. 2009). WBGU (German Advisory Council on Global Change 1988 in IPCC, 2000) and MRS (Mooney, Roy and Saugier 2001 in IPCC 2000) estimates are given in brackets.

[2] Jobbagy and Jackson (2000) except for peatlands (IPCC 2000) and permafrost (Tarnocai et al. 2009). WBGU (German Advisory Council on Global Change 1988 in IPCC 2000) and IGBP (International Atmosphere-Biosphere Program in IPCC 2000) estimates are given in brackets.

[3] Calculated from erman Advisory Council on Global Change and Mooney, Roy and Saugier estimates (IPCC 2000).

[4] Calculated from Jobbagy and Jackson (2000) except for peatlands and permafrost (Tarnocai et al. 2009). WBGU estimates (IPCC 2000) are given in brackets.

[5] Permafrost partly includes peatlands, borela forests, and boreal grasslands.

Data were gathered from Jobaggy & Jackson (2000), IPCC LULUCF (2000), Davidson & Janssens (2006) and Tarnocai et al. (2009).

Crutzen [1995]). SOC is removed from the soil by microbial decomposition (heterotrophic respiration), by river export of dissolved organic carbon and by ecosystem disturbance, such as fire, and by wind and water erosion. Human removal of SOC is localized to peat mining for agriculture and fuel. Finally, erosion displaces SOC horizontally at landscape scales, acting on longer time scales than the former processes (Van Oost et al. 2007).

Table 13.1 summarizes the SOC distribution among the main biomes. It should be noted that SOC stocks estimates presented in Table 13.1 are generally higher than those given in the Intergovernmental Panel on Climate Change (IPCC) LULUCF report for the top 1 m of soil (IPCC 2000) because they were estimated down to 3 meters (Jobaggy & Jackson 2000). This difference is particularly apparent for tropical forests (about +480 Pg C).

Table 13.1 shows that the contribution of SOC to total ecosystem C stock differs greatly between biomes. The fraction of SOC to total ecosystem C represents roughly 60 to 80% in forests and more than 80% in grasslands. In tundra soils, peatlands, and permafrost C deposits, SOC represents nearly 100% of total ecosystem C stocks. Peatlands and permafrost have the highest stocks and highest stock densities mainly because of cold temperature and anoxic conditions limit microbial decomposition. In other biomes, SOC stock is determined by the interaction between factors controlling decomposition and plant litter inputs. Therefore, SOC differences between these biomes are not obvious to understand. Generally, the mean residence time of SOC, defined as the ratio of stock to heterotrophic respiration loss (Mahli et al. 2002), is longer at high latitudes for boreal forest and tundra (Bird et al. 1996; Trumbore 2000), whereas litter input reflecting primary production is higher for tropical forests (Zhao et al. 2004).

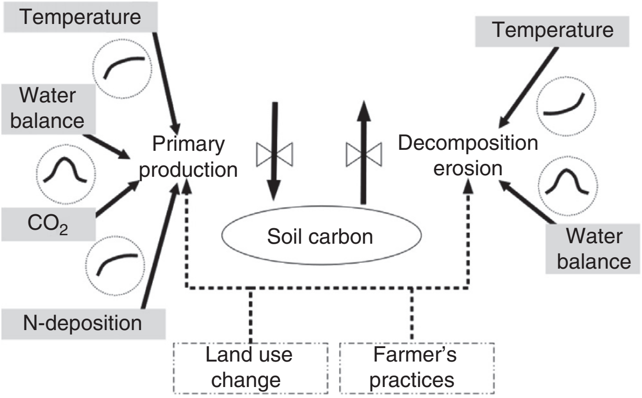

Figure 13.1 Response and potential vulnerability of soil C to climate, land-use change and farmers' practices. Adapted from Reichstein 2008.

13.3 Global Vulnerability of SOC to Climate and Land-Use Change

13.3.1 Vulnerability of SOC to Climate Change

The response of SOC to climate change is schematized in Figure 13.1. The SOC stock can be increased by increasing litter input, which is driven by increases in net primary production (NPP). Rising CO_2, warming in temperature-limited ecosystems or increased rainfall in drier ecosystems, and extra-nitrogen deposition in nitrogen-limited areas, and the combination of these factors are the main causes of increased NPP (Piao et al. 2006). On the other hand, changes in climate directly impact microbial processes. In models, this results in wetter and warmer conditions acting to accelerate soil C losses. Generally, soil C respiration rate is multiplied by roughly a factor of two for a 10°C warming (Davidson & Janssens 2006; Raich & Schlesinger 1992; Reichstein et al. 2005; Mahecha et al. 2010). The soil C vulnerability in response to climate warming thus results from the generally opposing effects of increased productivity input and increased decomposition and respiration.

Neither SOC input nor output fluxes are linear functions of climate (see Fig. 13.1); thus, these responses are uncertain, making the future SOC evolution difficult to assess. Generally speaking, decomposition is increasing exponentially with temperature (Raich & Schlesinger 1992; Lloyd & Taylor 1994) and decreases with decreasing pool/substrate size. Productivity is a saturating function of climate as it can be limited by resource availability. Both productivity and decomposition decrease if warming creates water stress (Angert et al. 2005). Conceptually, above a certain degree of warming, the increase of respiration will not be offset by an equivalent productivity increase, and soils will lose C. This response is observed in simulations of the climate-carbon coupled system; for instance, in the widely cited study of Cox et al. (2000) where Amazon forest productivity drops, causing a large forest die-back and a loss of soil C in the end of the twenty-first century, ultimately acting as a positive feedback to global warming.

The potential loss of soil C under future IPCC warming scenarios could be up to six times larger than the current soil C sink (Reichstein et al. 2008). There are large uncertainties associated to this estimate, both in the amount and spatial distribution of warming, which depends on climate scenario, and in the processes that determine the climate response of SOC.

13.3.2 Vulnerability of SOC to Land-Use Change

In addition to climate factors, land cover and land-use changes also alter the soil C balance by acting on both decomposition and input. Land-use change has accompanied human history. It consisted mostly of expanding cropland and pastureland, and more recently of urbanization. Today land-use change is concentrated in the tropics, where forest clearing is taking place at a high rate (13 Mha yr^{-1} in Houghton 2003). Tropical forest clearing is estimated to cause a direct loss of C in biomass of 1.4 Pg C yr^{-1} over 2000 to 2008, but it also causes an indirect or delayed, loss of SOC (Houghton 2003). In newly deforested areas for agriculture, the fate of SOC after a change in land use will depend on agricultural practice. Intensive agriculture will quickly deplete the former SOC pools within two to three decades (Arrouays et al. 1995, Jolivet et al. 1997; Reeves et al. 1997), whereas sustainable pasture management may stabilize them to a value similar to the former tropical forest (Trumbore et al. 1995). A key question is whether SOC contains recalcitrant compounds that are not affected by land-use change. A recent study by Barré et al. (2010) suggests that for European arable soils, even a total suppression of input leaves a fraction up to 30% of SOC that remains undecomposed even after 80 years.

13.4 Historical Land Cover, Agricultural Management, and Climate Change Effects on SOC

To separate land use and climate effects on SOC regionally, the results of a global biosphere model over 1901–2002 were analyzed. This process-based global ecosystem model called ORganizing Carbon and Hydrology In Dynamic EcosystEms (ORCHIDEE) model, (Krinner et al. 2005) was driven by variable climate, atmospheric CO_2 concentration, and annual land cover (Piao et al. 2009a).

13.4.1 Global Land Cover Change and SOC Balance

Figure 13.2 represents the modeled global evolution of SOC, in response to observed CO_2 and climate changes, and in response to changed CO_2, climate and land cover. If only CO_2 and climate are accounted for, NPP increases and thereby biomass (Fig. 13.2). SOC decreases globally from 1901 until 1960, due to warming in Europe and in temperate North America. Elsewhere, the modeled CO_2 fertilization effect on NPP increases soil C input by litterfall in excess of increased decomposition from warming. Therefore, the SOC balance is slightly positive over the twentieth century.

By contrast, when land cover changes are prescribed to the same model, SOC decreases globally between 1900 and 1960. This land use induced decrease is opposed by NPP increases elsewhere, ending up only in a small net loss of SOC, $\delta SOC = -7.3$ PgC by year 2000. This net change represents an insignificant 0.3% decrease of the initial stocks in 1901. The essential point here is that land-use change has a negative effect on SOC between 1901 and 2000 that just opposed the positive effect of climate and CO_2.

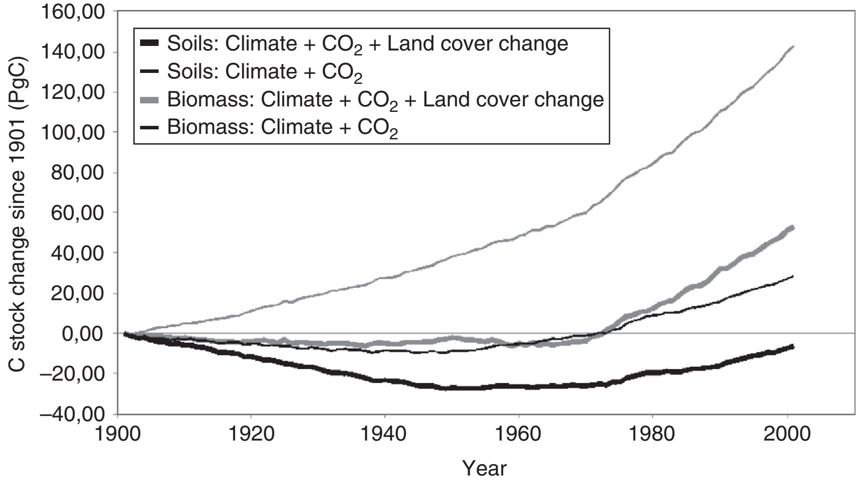

Figure 13.2 Simulated evolution of global soil and vegetation C stocks in response to combined effects of atmospheric CO_2 concentration and climate and to combined effects of atmospheric CO_2 concentration, climate, and land cover change from 1901 to 2002.

It is also noted that a change in land cover affects (in the model as in the reality) biomass immediately and SOC with a delay, owing to changes in litter input and decay of former SOC. The change in litter input following forest clearing is not as large as the direct loss of biomass (δVEG), and so the impact of land cover change is more drastic on biomass than on SOC pools. In our analysis of the Piao et al. ORCHIDEE simulation, land cover change modifies biomass globally from + 140 to −51 PgC and SOC from +27 to −7.3 PgC.

When combining effects of land use, climate, and CO_2 changes on the SOC balance at regional scales, it can be seen in Figure 13.3 a different behavior between tropical and temperate/boreal regions. In temperate/boreal regions, the effect of land cover change on SOC stocks is larger than in the tropics, while the loss of biomass is greater in the tropics.

In the former Soviet Union (FSU) and North America, forest clearing took place during the first half of the twentieth century but continued later to impact the SOC balance with inertia, owing to the long residence times of SOC (Figs. 13.3c and 13.3d). In FSU, the modeled difference between SOC stocks with climate and CO_2 only (S1) and with land-use changes (S2) continues to increase with time. In North America, this difference remains rather constant after 1970, indicating that the lagged effect of former deforestation and natural grassland ploughing on SOC stocks is stabilized. In Europe and China (Figs. 13.3e and 13.3f), no major change in forest area took place during the twentieth century (most of deforestation having already occurred earlier than that date). The SOC difference between simulations S2 and S1 in these two regions is thus small, indicating that SOC stocks did not change due last century land cover change. However, we will see below that SOC stocks in China and Europe have declined during the twentieth century if the intensification of agriculture is accounted for.

In summary, the effect of land cover change on SOC stocks to the one of climate and CO_2 is compared. The results of this comparison are shown for different regions of the globe in Figure 13.4 In the ORCHIDEE model simulation, climate and CO_2 have increased SOC stocks everywhere but in Africa (because of drought that decreased NPP) and in Canada (because increased NPP did not compensate warming increased heterotrophic respiration). In contrast,

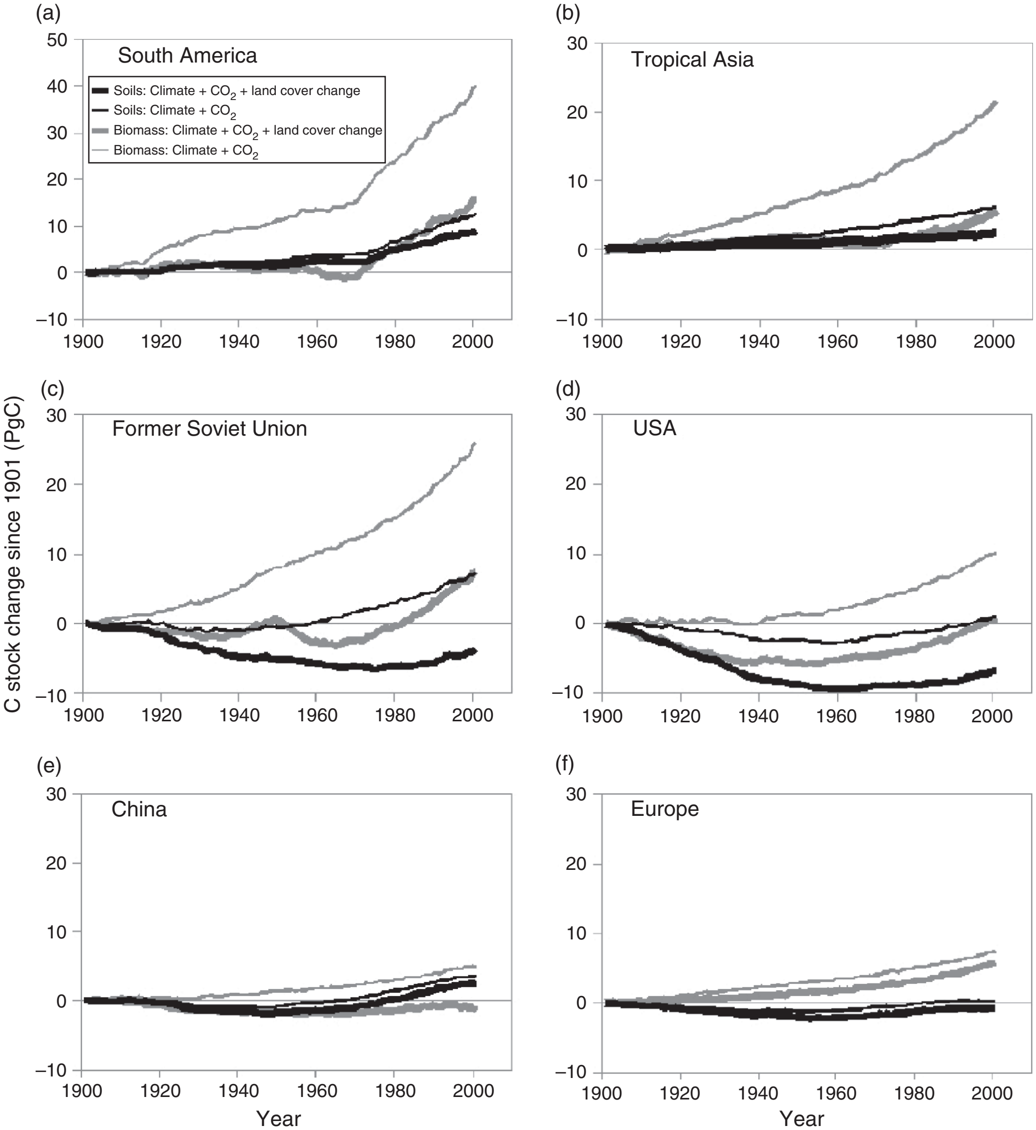

Figure 13.3 Simulated evolution of regional soil and vegetation C stocks in response to combined effects of atmospheric CO_2 concentration and climate and to combined effects of atmospheric CO_2 concentration, climate, and land cover change from 1901 to 2002.

land cover change has diminished SOC stocks everywhere. Therefore, the effect of land cover change on SOC balance between 1901 and 2000 is opposite to the one of climate and CO_2. Regions where land cover induced SOC losses dominate over climate and CO_2-induced SOC accumulation are the United States, the FSU, and Europe. These regions thus experienced a net loss of SOC since 1901. Oppositely, regions where a net SOC gain since 1901 is modeled are tropical Asia, China, and South America. Despite deforestation going on in tropical Asia and South America after 1950, the CO_2 and rainfall induced increase of NPP in intact forests (Lewis et al. 2009) has driven the pantropical SOC balance positive.

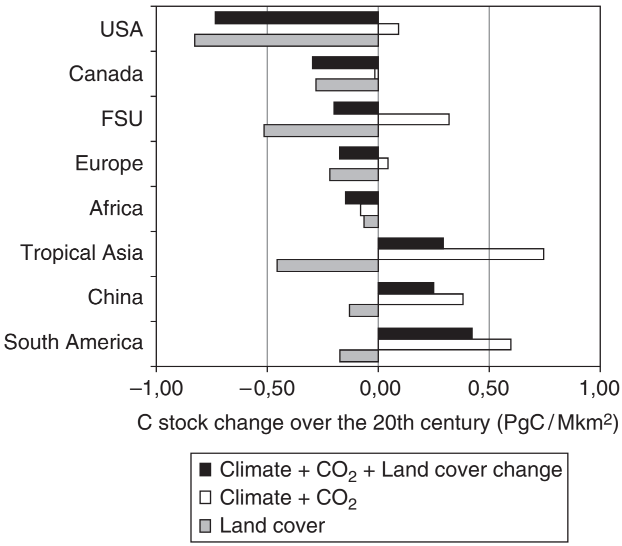

Figure 13.4 Partitioning of the regional SOC changes from 1901 to 2000 between land cover change, climate, and CO_2 effects.

13.4.2 Agricultural Intensity and SOC Balance

Not only land cover change but also land-management-intensity change matters for changes in SOC stocks. Cultivation practice, changes in the fate of harvest residue, such as straw and stubble, changes in tillage, and erosion of arable soil, all have strong impacts on SOC stocks (Paustian et al. 1998, 2000; West & Post 2002; Van Oost et al. 2007). Numerous agricultural-site local measurements show declines of SOC (Burke et al. 1989; Paul et al. 1997), but there is no large-scale survey to monitor SOC change over arable lands, except for few regional detailed inventories (Mäkelä-Kurtto & Sippola 2002; Sleutel et al. 2003; Bellamy et al. 2005).

In North America, changes in agricultural practices during the last 30 years are generally considered to have increased SOC sequestration. Ogle et al. (2003) estimated using the IPCC method (Houghton et al. 1997) that conservation tillage practices on cropland, reduced use of bare fallow, and conversion of annual cropland to grass and trees in the Conservation Reserve Program (CRP) resulted in a net gain of 10.8 TgC year^{-1} from 1982 to 1997. Most of this gain was due to setting-aside lands in the CRP. Using the ISAM-2 model, Jain et al. (2005) estimated a 868 TgC increase (i.e. 43.4 TgC yr^{-1} from 1980 to 2000) in North American soils due to no-till practices. In the United States, irrigation may have also played a significant role. For example, Parton et al. (2005) estimated with the CENTURY model that the increase in irrigated agriculture in the Great Plains since 1950s has resulted in a net carbon storage of 21.3 TgC.

In China, a continuous decline in SOC levels for a wide scope of Chinese agricultural soils has been observed since the 1950s (Qiu et al. 2009), mainly caused by the reduction of crop residue incorporation and manure amendments (Qiu et al. 2009). New policies have been launched during the past decades to encourage Chinese farmers to add organic matter to the soil and some agricultural fields have shown SOC sequestration (Huang & Sun 2006; Yan et al. 2007). In addition, increased application of mineral fertilizer, irrigation in the arid areas, expansion of straw incorporation, and shallow plowing have also led to an increase in SOC in

China croplands (Huang & Sun 2006). Preliminary estimates suggested that along with the increase of agricultural productivity and less removal of biogenic material for energy purposes for humans, between 0.02 and 0.04 PgC yr^{-1} is potentially fixed in cropland soil (Lal 2004; Huang & Sun 2006; Piao et al. 2009b).

In Europe, the ORCHIDEE-STICS model, initialized with (reconstructed) ancestral farming practice and crop varieties in 1900 and integrated over the past century, provides a net change in agricultural SOC, $\delta SOC = 0.01 \pm 0.06\, tC\ ha^{-1}\ yr^{-1}$ between 1901 and 2000. This insignificant gain is mostly due to agricultural intensification (Gervois et al. 2008). During the twentieth century, a strong loss of SOC is modeled when agriculture became mechanized in the 1950s, but this loss trend was reversed in the 1970s and SOC increased thereafter, with arable soils being modeled to be a small sink over the last decade. The few regional SOC inventories give a small SOC loss (Mäkelä-Kurtto & Sippola 2002; Smith et al. 2005a; Bellamy et al. 2005), except for Flanders where a large SOC loss is obtained (Sleutel et al. 2003). When corrected for erosion, which displaces SOC from arable lands to floodplains, and soil horizons where it is more stable (Lal 2003; van Oost 2007), the inventory indicated that SOC balance was comparable to results from the ORCHIDEE-STICS model within the errors of both.

13.5 Future Changes in Climate and Land Use and the SOC Balance

Unfortunately at this stage, few global terrestrial carbon model projections have integrated both land-use climate change effects on the SOC balance during the twenty-first century. For climate and CO_2 effects alone, we analyzed the results from an ensemble of recent coupled climate–carbon C4MIP models (Friedlingstein et al. 2006). For land-use change and climate effects, a coarse resolution terrestrial C model OSCAR (Gitz & Ciais 2004) divided into four global regions and six biomes was integrated.

13.5.1 Effect of Climate and CO_2 Changes

Cox et al. (2000) suggests that the SOC balance is highly sensitive to climate warming. The drying of the Amazon region leads to forest die-back in the TRIFFID vegetation model used by Cox et al. accompanied by decreased NPP and subsequently by a large SOC loss of about 170Pg C between 2000 and 2100. This SOC loss in tropical forests feeds back to increase CO_2 and temperature by the end of the twenty-first century.

Table 13.2 presents the SOC changes simulated by the 11 models of the C4MIP model ensemble (Friedlingstein et al. 2006) between 2000 and 2099. One common scenario of CO_2 anthropogenic emissions (Special Report on Emission Scenarios [SRES] A2 scenario) was used to drive all these coupled carbon-climate models. Even though the models are broadly consistent with the current global land carbon sink, their responses differ markedly. The predicted change in global SOC stocks ranges between −45.8 PgC (HadCM3LC) and 310 PgC (MPI) between 1990 and 2100. In most models, soil is projected to gain C during the twenty-first century due to increasing NPP. Only for two of the eleven coupled models (HadCM3LC used by Cox et al. [2000] and UMD), tropical (30° S–30°N) and temperate (30° N–60°N) soils lose C between 1990 and 2100. This discrepancy between models is partly explained by differences in soil and vegetation model parameterizations (number of SOC pools, Q10, plant respiration). For example, the use of a single-pool SOC model (HadCM3LC) increases the sensitivity of SOC stocks to both changed litter input and to warmer temperature (Jones et al. 2005). In this study,

Table 13.2 Simulated change of the regional SOC from 2000 to 2099 in the C4mip model intercomparison (Friedlingstein et al. 2006). SOC changes are expressed in PgC.

	Global	30° S–30° N	30° N–60° N	60° N–90° N
HadCM3LC	–45,8	–44,9	–32,9	23,5
UMD	–17,3	–11,4	–8,8	3,4
FRCGC	46,8	11,19	6,6	11
CLIMBER	109,1	59,5	25,5	14,9
Uvic-2,7	109,2	52,3	38,5	6,5
BERN-CC	132,2	59	45,8	21,6
IPSL-CM2-C	134,03	45,3	66,1	10,5
CSM1	140,1	81,2	48,6	5,8
IPSL-CM4-LOOP	206,2	43,7	109,8	48,9
LLNL	215,9	111,1	31,2	42,1
MPI	310,4	163,2	114,2	12,2

no consensus emerges among the C4MIP models for attributing SOC sensitivity to either changes in NPP or in respiration (Friedlingstein et al. 2006).

Large uncertainties on the future fate of SOC due to plant geography and anthropogenic CO_2 emissions were also evidenced by Sitch et al. (2008) using five Dynamic Global Vegetation models or DGVMs (Hyland, Triffid, LPJ, ORCHIDEE and Sheffield), four SRES scenarios of CO_2 emission (A1F1, A2, B1, B2), and a common climate model. As for the C4MIP study, the SOC change modeled by Sitch et al. (2008) over the twenty-first century differs markedly between models. The range of DGVM responses to climate change increases with more intensive CO_2 emission scenarios. The global SOC stocks change was predicted to range between a gain of 169 Pg C (Sheffield DGVM with A1F1 scenario) and a loss of 58 PgC (LPJ model with A1F1 scenario). Again, major differences between DGVM are localized in the tropics. For the most intensive fossil fuel emission scenario (A1F1), three of the five DGVMS (Hyland, LPJ, TRIFFID) simulate forest dieback and soil carbon loss in both the Amazon and African tropical forests whereas there is a small increase of SOC stocks for ORCHIDEE and Sheffield. The DGVM results also differ qualitatively in the boreal forest region where, contrarily to the four other DGVMs, LPJ simulates a large SOC reduction.

13.5.2 Effect of Future Agricultural Change

Using the OSCAR global simplified carbon model the IPCC A2 climate and future land-use scenario (Gitz & Ciais 2004), we estimated potential SOC changes between 2000 and 2100. The results split into four large global regions are given in Figure 13.5. It can be seen that land cover change (SRES A2 with land use from the IMAGE2.0 model [Alcamo 1994]) is opposing climate change in driving the net SOC balance to be negative in Asia and Africa and Latin American regions. On the other hand, in all other regions, warming induced increases in NPP dominates over warming induced increases in decomposition, resulting into a net SOC gain.

Over Europe, Smith et al. (2005b) using the Roth C model estimated that projected climate change up to 2080 might have limited impact on cropland carbon balance due to the balancing effects of increased losses due to faster decomposition and increased inputs due to choice of crops/harvestable fraction and improved technology. They attributed uncertainties in future projections mainly to differences in projected climate by four IPCC climate scenarios, and

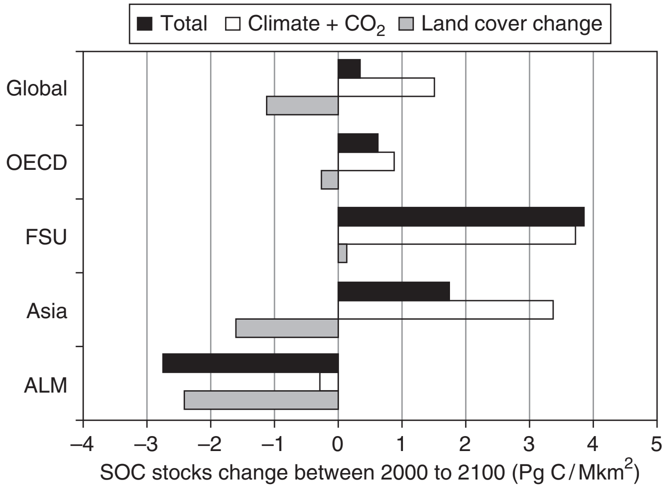

Figure 13.5 Simulated change of the regional SOC from 2000 to 2100 distributed among land cover change and climate and CO_2 effects using the OSCAR model. OECD includes North America, Japan, OECD Europe, and Oceania. FSU stands for Former Soviet Union, and ALM includes Africa, Middle East, and South and Central America.

differing assumptions about the implementation of technology. Smith et al. (2005b) also suggested that croplands could become a net carbon sink under improved technology, but the uncertainty was also large.

13.6 Discussion: Uncertainties and Future Directions

Many sources of uncertainties affect SOC change prediction in the context of atmospheric CO_2 increase, climate change, and land-use change. These uncertainties include both relevance of scenarios for future land-use and land management and incomplete understanding of basic biogeochemical processes.

First of all, the effects of agricultural practices on SOC turnover and stability are still poorly understood. For example, even the increased C sequestration under less intensive tillage practices is currently *questioned* (Baker et al. 2007). It is now argued that conservation tillage does not accrue SOC stock but redistributes it within the soil profile (Baker et al. 2007; Angers & Eriksen-Hamel 2008). Future evolution of agricultural technology and practices is also a large source of uncertainties. Indeed, changes of agricultural practices since the 1950s may continue during the next century because of new environmental and agricultural policies and the need for new land-use types such as biofuel production. In forests, future management is also difficult to anticipate; on the one hand, more and more forest stands are either put into protection or certified under a sustainable forestry label, both of which limit the amount of wood that can be harvested. On the other hand, the rising demand for wood-energy and the increasing risk of increased natural disturbance may provide economic incentives to intensify management and shorten forest rotation length. Pussinen et al. (2009) show that if felling is increased in European forests to meet the increase in wood demand, SOC will be reduced by about 10 tC ha^{-1} in 2100 compared to maintaining current felling rates. In their model however, this decrease is offset by an increase in litter input when the positive effect of climate change on tree growth is taken into account.

Secondly, some potentially important processes are not incorporated in the current generation of DGVMs models. Among the most important are (1) the “priming effect”; (2) temperature sensitivity of different SOC pools; and (3) the role of the mineralogy in SOC stabilization. For the priming effect, several studies reported that fresh organic matter input to soil can stimulate SOC mineralization (e.g. Fontaine et al. 2004, 2007). This process could provide an important negative feedback in the carbon cycle-climate system (Heimann & Reichstein 2008). Indeed, if fresh litter C inputs stimulate SOC mineralization, enhanced inputs due to increased NPP will also increase SOC mineralization. Accounting for priming, the soil C sink would be smaller than currently estimated by DGVMs. Second, the vulnerability of each different SOC pools to warming is highly debated. Some authors reported that labile compounds are more sensitive to warming (Liski et al. 1999), others that recalcitrant compounds are more sensitive (Fierer et al. 2005) or that both compounds are equally sensitive (Fang et al. 2005). At the moment, DGVM models assume that all pools will respond uniformly to warming. Third, several studies observed that most of the SOC is stabilized through interaction with mineral surfaces (Mikutta et al. 2006; Basile-Doelsch et al. 2009) and that mineral types have a major impact on SOC storage and turnover (e.g. Torn et al. 1997; Feller & Beare 1997). Consequently, it may be necessary to take soil mineralogy explicitly into account in soil C models. These three examples are not exhaustive and illustrate that further breakthroughs in soil biogeochemical research may lead to the modification of the architecture of soil C models in DGVMs, which would change predictions.

Finally, temporal changes in soil water deficit, wind speed, air temperature, and humidity will modify the risk frequency and severity of forest fires or insect outbreaks and the consequent rapid loss of carbon from the biosphere (Kurz et al. 2008; Heimann & Reichstein 2008). Using the Biome-BGC model, Bond-Lamberty et al. (2007) estimated that the C balance of the Canadian boreal forest was mainly driven by fire disturbances from 1948 and 2005. Increase in fire disturbances during this period resulted in carbon losses of 6.8 ± 1.0 gC m^{-2} yr^{-1}. But fire may in the long term be a driver for SOC increase because it converts a substantial proportion of plant biomass to stable black carbon compounds (e.g. charcoal) (Wardle et al. 2008; Marris 2006). Hence, the net effect of fire on soil C balance remains uncertain. Less well documented are the impacts of insect outbreaks on the global carbon balance. Climate change will likely influence insect distribution and abundance (Kurz et al. 2008). For example, it is predicted that outbreaks of mountain pine beetle in Canada will increase in both scale and severity due to the expansion of its habitat and may have an impact on annual CO_2 emissions equivalent to fires (Kurz et al. 2008). Insect outbreaks may temporarily increase SOC stocks because of the large transfers of biomass to dead organic matter pools. But contrarily to fire, no black or stable carbon is produced.

13.7 Conclusions

Over the past century, climate and land cover change both significantly changed the regional balance of SOC. Globally, according to factorial simulations with the ORCHIDEE DGVM model, these two effects are opposite in direction and have nearly offset each other between 1900 and 1990. Tropical soils have gained carbon because CO_2 and rainfall-induced NPP increase dominated over the sum of warming-increased decomposition and deforestation. Oppositely, boreal and temperate regions have lost carbon particularly in North America and FSU due to early twentieth-century Century forest conversion into arable lands. Though mechanization of agriculture in the 1950s has likely caused SOC losses in croplands, development of carbon-sequestering practices over the past decades (i.e. irrigation, reduced use of bare fallows, land conservation program, increased crop residue incorporation) seem to have limited SOC losses in the recent years, yet with large uncertainties. Nowadays, croplands do probably not represent a strong source of CO_2 to the atmosphere in Europe, China, and United States. But regional, systematic inventories of the SOC balance of arable lands are basically lacking to verify this.

In the future, climate change may induce a SOC release into the atmosphere. According to the results of five DGVMs integrated by Sitch et al. (2008), increased litter input may no longer compensate warming-increased decomposition during the period 2000–2100. Neither future climate change, nor human land-use changes are likely to sustain large SOC storage in the future. The timing and magnitude of projected SOC changes are considerably uncertain. Although most carbon-cycle climate coupled models predict that the net SOC balance will still remain positive for the twenty-first century, several models simulate a fast SOC release in the late twenty-first century leading in some regions to a negative SOC balance. The most vulnerable regions are tropical forests because of drought-induced forest dieback. But large high-latitudes SOC losses could also be expected because of permafrost thawing (the DGVMs discussed in this review do not include permafrost). A better incorporation into models of biogeochemical processes affecting SOC balance together with the identification of the most relevant future anthropogenic CO_2 emissions and land-use scenarios are needed to reduce the uncertainties associated with the predictions of future SOC changes.

13.8 Methods

Brief description of the model tools used in this study

ORCHIDEE-LUC

The ORCHIDEE model (Krinner et al., 2005) is a dynamic global vegetation model (DGVM) representing key vegetation processes governing terrestrial biogeochemistry and biogeography. In this study, however, we switched off the vegetation dynamic simulation module because there are large uncertainties in DGVM modeled vegetation distribution (Krinner et al. 2005; Sitch et al. 2008). ORCHIDEE distinguishes 12 plant functional types with different photosynthetic, phenological, and morphological characteristics. Heterotrophic respiration parameterization is taken from CENTURY (Parton et al. 1988). The current version of ORCHIDEE takes into account the effects of land-use change on terrestrial C cycle as described in Piao et al. (2009a). In this study, it was hypothesized that SOC was at steady-state equilibrium in 1901. This is a rather crude assumption because human-induced land-cover change has occurred way before the twentieth century particularly in Europe and in East Asia (Pongratz et al. 2008). It is estimated that about 5 million km^2 were transformed to cropland or pasture between 800 and 1700 AD. Pongratz et al. (2009) have shown in a modeling study that these preindustrial land conversions have probably led SOC stocks to a significant disequilibrium in 1900. For example, they estimated that, whereas vegetation lost about 100 Gt C from 800 to 1900, global SOC stocks increased by about 30 Pg C due to additional plant material added to the soil pools from the converted natural vegetation. The steady-state assumption underlying the ORCHIDEE simulation results implies that the effect of land-cover change on SOC stocks during the twentieth century are likely to be overestimated.

ORCHIDEE STICS

ORCHIDEE-STICS is an evolution of the ORCHIDEE ecosystem model that is coupled to the STICS agronomy model describing crop phenology. More details of the model and applications can be found in de Noblet-Ducoudre et al. (2004) and Gervois et al. (2004, 2008). ORCHIDEE-STICS was used to simulate changes in the European croplands C balance between 1901 and 2000. This simulation included winter wheat and maize and ignored summer C3 crops (Gervois et al. 2008). The soil carbon decomposition module of ORCHIDEE-STICS is similar to the CENTURY model equations (Parton et al. 1988). Starting from ancestral farming practice and crop varieties in 1901, the model was driven over Western Europe by rising CO_2 and reconstructed climate at a resolution of 10 km, and by evolving agricultural technology. The technological evolution is reconstructed by Gervois et al. (2008) and includes the use of shorter growth cycle varieties, increased harvest index, increased N-fertilizers and decreased manure applications, maize irrigation, and increased tillage which accelerates SOC decomposition.

OSCAR

OSCAR is a global carbon cycle model including a reduced-form ocean model to quantify the ocean-atmosphere CO_2 exchange and a terrestrial carbon cycle model to account for the fluxes between land and atmosphere (Gitz & Ciais, 2004). The parameterization of the biosphere was derived from the spatially-explicit CASA-SLAVE model (Friedlingstein et al. 1995). The terrestrial cycle integrates a detailed land-use module that allows for conversions of biomes and calculates both the land-use related net CO_2 emissions following anthropogenic disturbances as well as the terrestrial uptakes over the remaining undisturbed ecosystems at each time step. The global land cover is based on a simplified vegetation map, which is regionalized into four world regions as defined by the Intergovernmental Panel of Climate Change Third Assessment Report (IPCC 2000) and shown in Table 13.2: OECD-1990 (North America, Europe, Japan, and Australia), former Soviet Union, ASIA, ALM (Africa, Latin America, and Middle East). In each region, six natural biomes are defined, plus three crop types (boreal, temperate, and tropical) and cohorts of lands in transition between two biomes. Icy and hot desert were excluded. For each region, a biome has separate biophysical characteristics and is assigned one surface area in the model.

C4MIP

In the context of the Coupled Climate–Carbon Cycle Model Intercomparison Project (C4MIP), seven coupled Ocean-Atmosphere General Circulation Models (OAGCMs) and four models of intermediate complexity performed coupled climate–carbon cycle simulations over the historical period and the twenty-first century (Friedlingstein et al. 2006). All models used observed anthropogenic fossil fuel emissions for the historical period (Marland et al. 2005) and the IPCC Special Report on Emissions Scenarios (SRES) A2 emission scenario for the period from 2000 to 2100. Most models included land-use-associated CO_2 emissions provided by Houghton and Hackler (2002) for the historical and by the Integrated Model to Assess the Global Environment (IMAGE)-integrated model for the twenty-first century (Leemans et al. 1998). Land-use-associated emissions are seen here as an external forcing. More details on the models used in this study are presented in Friedlingstein et al. 2006.

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14 Potential Impacts of Climate Change on Microbial Function in Soil

The Effect of Elevated CO_2 Concentration

Paolo Nannipieri

14.1 Introduction

Terrestrial ecosystems play a fundamental role in the biosphere, and concerns about the effects of climate change on the biosphere have therefore stimulated research on the potential impacts of climate change on soil functioning. In addition, soil can be a source and sink of gaseous compounds, such as carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4), which are responsible for the greenhouse effect (Drigo et al. 2008). Straightforward predictions are difficult due to the complexity of the soil system. Although this arises through several physical, chemical, and biological properties, microbiological properties are considered to be most sensitive to changes of management practices and environmental factors (Nannipieri et al. 2003), but both composition and functioning of microbial communities of soil are difficult to monitor.

Soil as a biological system has unique properties. The biological space occupied by soil organisms accounts for a small proportion (less than 5%) of the overall available space because only a few microhabitats possess the right set of conditions; these microsites represent oases in a desolate land (Nannipieri et al. 2003). The lack of colonization of soil microsites may result from temporary lack of suitable conditions for microbial life, such as the lack of water and nutrients. An example of soil "hot spots" is the rhizosphere, where beneficial and detrimental microorganisms can affect plant growth. Despite the low volume of the biological soil space, microbial biomass is huge; for example, bacterial biomass and fungal biomass can range, respectively from 1 to 2 and from 2 to 52 tons ha^{-1} (Nannipieri et al. 2003). Microbial diversity is also high, and Gans et al. (2005) have hypothesized that diversity exceed 10^6 prokaryotes per gram of soil. The use of molecular techniques based on the extraction of DNA, amplification of 16S rRNA genes, and separation of amplicons has allowed detection of unculturable microorganisms, but despite progress arising from these techniques, determination of microbial diversity in soil is still a problem.

Microorganisms are involved in most of the important soil functions such as nutrient transformations, degradation of organic compounds including xenobiotics, humification, formation of soil structure, and son. Several assays are available to measure microbial activity (i.e. basal respiration, N mineralization, enzyme activities) in soil and expression of functional genes (e.g. those involved in denitrification, nitrification, methane transformation) has now been studied in parallel with measurement of associated processes (Metcalfe et al. 2002; Nannipieri et al. 2008; Nannipieri & Paul 2009).

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It is not possible to cover here all of the extensive bibliography concerning the effects of climate change on microbial functions in soil. Discussion will therefore focus on the effect of elevated atmospheric CO_2 concentration on soil microbial functions because not only has it been most extensively studied, but also the relatively vast bibliography shows the complexity of the subject, the methodological and conceptual problems, and the future research needs, which apply also to other environmental factors related to climate change. The effect of increased air temperature and desiccation on soil microbial functions involved in the storage of organic carbon (C) in soil and its role in counteracting the increase in atmospheric CO_2 concentration will also be discussed.

14.2 Effect of CO_2 Concentration on Plant C Inputs including Rhizodeposition to Soil

The CO_2 concentration of the pore space of soils with active biological activity is much higher (2,000–38,000 ppm) than that of the atmosphere and thus direct effects of elevated atmospheric CO_2 concentrations on soil microbial communities are probably negligible compared to potential indirect effects as modulated by plants (Drigo et al. 2008). The increase in CO_2 concentration of the atmosphere can change the organic C dynamics by increasing the photosynthetic activity of C_3 plants, with increases in rhizodeposition and consequent stimulation of soil respiration (due to stimulation of both root and microbial respiration). Therefore, indirect effects due to greater belowground C allocation, through root exudation and turnover are possible and these indirect effects may change the size and activity of soil microbiota. The changes in plant inputs to soil are important because the majority of soil microorganisms are heterotrophic and generally C-limited. Drigo et al. (2008) assumed that modification of plant C allocation particularly affects fine roots, which can account for 33% of the global annual net primary production. With high turnover rates, fine roots are thought to be especially sensitive to elevated atmospheric CO_2 concentration. In addition C_3 plants are more affected than C_4 plants due to the peculiar C-fixing metabolism of the latter.

Other indirect effects caused by the greater belowground C allocation are: (1) improvement of soil structure due to higher concentrations of organic binding agents and (2) increased uptake of nutrients and water by enhanced plant growth (Drigo et al. 2008). The latter effect can create both nutrient- and water-limited conditions in soil. For example, nitrogen (N)-limited conditions have been observed with possible negative effects on microbial activity and on the ability of the plant to respond to increased atmospheric CO_2 concentration (Hu et al. 2001). Microbial degradation of organic matter in grassland soils was reduced after exposure to elevated CO_2 concentration (Jongen et al. 1995; van Ginkel & Gorissen 1998; van Ginkel et al. 2000; Hu et al. 2001), probably as the result of N-limitation to soil microorganisms. In contrast, improved soil structure can have positive effects on the response of plants and soil microorganisms to elevated CO_2 concentration.

In addition to quantitative changes, qualitative changes in litter and root-derived products have been shown (Zak et al. 1993; King et al. 1997; Cotrufo et al. 1998; Zak et al. 2000; Pendall et al. 2004). Carbon/nutrient ratios, such as the C/N or lignin/N ratios, and nonstructural materials and C-based secondary compounds, such as phenolics and tannins of plant litter, were affected under elevated CO_2 concentration, and these changes influenced decomposition rates (Gebauer et al. 1997; Cotrufo et al. 1998; Korner 2000; Zak et al. 2000). Therefore, plants can decrease the allocation of N-rich metabolites and increase the allocation of C-rich metabolites, but the type of plant is important. Phillips et al. (2006) found that growth of axenic cultures of wheat and medic (C_3 plants) was stimulated at elevated CO_2 concentration without altering amino acid efflux. The larger root surface promoted higher root exudation. In contrast root or shoot growth in C_4 plants was not stimulated but the efflux rate of 16 amino acids increased by 44%. However, study of the amount and quality of rhizodeposition is problematic because, generally, studies are based on the collection of samples in hydroponic solution. This does not reflect the in situ conditions because in soil, for example, root-derived compounds, such as amino acids, are degraded by soil microrganisms or adsorbed by surface-reactive soil particles and both processes can affect release of these compounds by roots.

The effects of rate of addition and quality of aspen leaf litter was studied by Liu et al. (2009). The leaf litter was obtained by growing aspen at ambient and high (560 ppm) CO_2 concentrations. The elevated CO_2 concentration decreased litter N but did not alter other components analyzed. Total C and new C (C from added litter) in the whole soil and in the high density soil fraction (HDF) increased linearly with increases in litter rate, despite higher C losses by respiration. In addition, the increased litter rate increased total N retained in the whole soil and in HDF and new C per unit of accumulated N. Changes in litter biochemistry were only important at the highest litter addition rate and decreased total C in HDF, new C in the whole soil, and total N in the whole soil and HDF. The increase in soil total C was probably related to higher inputs of slowly degrading compounds by increasing litter addition rates whereas the increases in microbial respiration and humification were probably due to increased inputs of labile compounds.

14.3 Effects of Elevated CO_2 Concentration on Activity, Size, and Composition of Soil Microbiota

It is obvious from the previous section that the rhizosphere soil is affected much more by increased atmospheric CO_2 concentration than the bulk soil. Carbon dioxide production in the rhizosphere by roots and soil microorganisms is stimulated by elevated CO_2 concentration (Drigo et al. 2008) and may be higher than the increase in root biomass (Cheng & Johnson 1998; Hungate et al. 1997; Drigo et al. 2008). Two mechanisms have been proposed for stimulation of soil respiration by elevated CO_2 concentrations (Cheng & Gershenson 2007): (1) roots have a higher turnover rate and release more organic C and these two processes increase total rhizosphere respiration. The validity of this mechanism is weakened by the fact that N concentration in roots may decrease with consequent decrease in root turnover (Cotrufo et al. 1998; Pregitzer et al. 2000; Wan et al. 2004); (2) rhizosphere microbial activity per unit root growth is higher and this is associated with increases in mycorrhizal infection (Alberton et al. 2007; Drigo et al. 2007; Staddon 2005) and N_2 fixation (Amone & Gordon 1990; Thomas et al. 1991; Tissue et al. 1996).

Variable effects have been observed for other measurements of microbiological activity (gross N mineralization, microbial immobilization, and net mineralization) under elevated atmospheric CO_2 concentration depending on plant physiological state and plant species (Zak et al. 2000). A five-year elevation of atmospheric CO_2 (720 μmol mol^{-1} versus ambient CO_2–360 μmol mol^{-1}) increased xylanase, invertase, alkaline phosphatase, arylsulphatase, and casein hydrolysing (protease) activities of the 0- to 5-cm soil layer under northern Colorado shortgrass steppe without affecting microbial biomass (Kandeler et al. 2006). It was suggested that rhizodeposition and new roots increased the pool of easily available substrate in the top soil with stimulation of enzyme synthesis by soil microorganisms. Microbial biomass N was not affected by elevated CO_2 but was significantly increased by the posttreatment effect (when the elevated CO_2 was eliminated in autumn 2002) probably due to lower competition between plants and soil microorganisms for N in this N-limited ecosystem. Most enzyme activities showed a significant post-CO_2 effect in spring but not in summer and autumn 2002, probably due to depletion of substrates. It was suggested that the additional belowground C input mainly entered the fast cycling C pool and contributed little to long-term C storage in the semi-arid grassland.

Microbial measurements based on adenosine triphosphate (ATP), phospholipid analysis, chloroform fumigation assay, or total cell counts have shown that quantitative alterations in C supply can decrease, increase or have no effect on microbial biomass of soil collected under different plants (*Lolium perenne, Trifolium repens,* poplar, tall grass prairie) (Drigo et al. 2008; Huntgate et al. 2000).

Generally the increase in C availability in soil by elevated CO_2 concentration increases fungal biomass more than bacterial biomass (Drigo et al. 2007; Jones et al. 1998). Higher ^{13}C enrichment of fungal phospholipid fatty acids (PLFA) biomarkers was attributed to faster utilization of new plant C by the fungal community than by bacterial community of rhizosphere (Denef et al. 2007). Increased fungal biomass at elevated CO_2 concentration may also depend on lower N availability because fungi have a greater C:N ratio than bacteria and thus a lower N requirement. The major effect on fungal rather than bacterial communities can have marked effects on soil functionality due to the role of fungi in soil structure, nutrient cycling and organic matter degradation. However Carney et al. (2007) did not find an increase in the fungi-to-bacteria ratio under elevated CO_2 concentration but found higher ligninolytic activity and reduced soil organic C content. The increase in available organic C probably stimulated the priming effect with increased microbial degradation of soil organic matter (Hungate et al. 2003).

The response of bacterial biomass to the increase in CO_2 concentration is not clear because increases (Hu et al. 1999; Zak et al. 2000) and no change (Montealegre at el. 2000) have been observed. According to Griffiths et al. (1998) the amount of photosynthetic C allocated to bacteria was not increased in the rhizosphere of *Lolium perenne* by elevated atmospheric CO_2 concentrations whereas the amount of nonmicrobial C in the rhizosphere increased by a factor of 2.6 within 28 days. The effect of increased rhizodeposition on bacteria depends on the species and groups involved. Increased CO_2 concentration increased the number of culturable bacteria but decreased the total bacterial count and nonculturable oligotrophic bacteria dominating in the rhizosphere of *Lolium perenne* (Hodge et al. 1998) and in artificial tropical systems (Insam et al. 1999). At elevated CO_2 concentration, fast-growing r-strategists, which use easily degradable substrates, are favored and their growth may decrease the amount of available N. The growth and activity of slow-growing k-strategists, which use more recalcitrant substrates, are not favored, and consequently these substrates may accumulate. However after an initial increase, the number of fast-growing r-strategists may decrease due to the activity of bacterial grazers, which may prefer these abundant bacteria over the less abundant slow-growing k-strategists (Drigo et al. 2008).

The use of molecular-based methodologies has produced contrasting results, which have been explained by the different plant-soil systems studied and different techniques used. Monteleagre et al. (2000) observed changes in the composition of clover rhizosphere community in response to elevated CO_2 concentration. Changes in the composition of *Pseudomonas* (Marilley et al. 1999) and *Rhizobium* communities (Montealegre et al. 2000) and stimulation of *Proteobacteria* (Jossi et al. 2006 FEMS) were observed underelevated CO_2 concentration, whereas no significant change in the composition of microbial communities of *Lolium perenne* rhizosphere under elevated CO_2 were detected by thermal denaturation, G+C content and PLFA analysis (see review by Drigo et al. 2008). Using DNA-based (detection of the species) and

RNA-based techniques (detection of active genes) Jossi et al. (2006) showed that elevated CO_2 concentration has a higher impact on active than total bacterial communities of *Lolium perenne* and *Molina coerulea*. These results confirm findings reported above on the effect of culturable bacteria. Jossi et al. (2006) also observed some specific responses; for example, actinobacteria were not affected by CO_2 concentration whereas deltaproteobacteria were stimulated by elevated CO_2 concentration only in the vicinity of roots.

The effects of rhizobacteria on plants may change under elevated CO_2 concentration. The percentage of HCN-producing *Pseudomonas* (potential inhibitors of root parasitic fungi) was reduced in the rhizospheres of *Lolium perenne* and *Molina coerulea* growing under elevated (600 ppm) CO_2 concentration compared to normal (360 ppm) CO_2 concentrations (Tarnawski & Aragno 2006)

14.4 Effects of Elevated CO_2 Concentration on Mycorrhizal Infections of Plants

Mycorrhizal fungi form symbiotic associations with plants and depend directly on photosynthetic products from their hosts, and for this reason, an increase in mycorrhizal infection of roots is expected, due to increased demand for nutrients by the plant when C allocation rates to roots are increased. Mycorrhizae can positively affect inorganic P and organic N uptake by plants and modify plant C allocation and architecture. In addition mycorrhizal infection can improve soil structure and increase soil C storage.

Rilling and Allen (1999) and Treseder and Allen (2000) observed an increase in mycorrhizal growth on plants grown under elevated CO_2 concentration but this effect was not observed by Staddon et al. (1999) and Walker et al. (1997). This contrasting behavior probably depended on differences in plant and fungal species studied.

The way CO_2 concentration increase over time can be important too. For example, an increase from 350 to 550 ppm changed AMF community structure and activity, whereas changes were not observed following gradual increases over 21 generations (Klironomos et al. 2005). This is an interesting observation because most of the reports on the effects of elevated CO_2 concentration on microbial functions of soil are based on sudden changes in CO_2 concentration, limiting extrapolation of results to the in situ situation because the increase in atmospheric concentration is gradual.

14.5 Effect of Elevated CO_2 Concentration on Biotic Interactions and on the Rhizosphere Microfauna

Changes in the composition of root exudates can also affect "molecular crosstalk" between plant roots and soil bacteria. Haase et al. (2007) found that short-term effects of elevated $^{14}CO_2$ stimulated release from roots of sugars and malate acting as a chemo-attractant for rhizobia in 0.5–1.5 cm apical root zones of *Phaseolus vulgaris L.* The release of *nod*-gene-inducing flavonoids (genistein, daidzein, and coumesterol) was also stimulated under elevated CO_2 and nodule number, biomass and the proportion of leghaemoglobin-producing nodules were also enhanced.

The presence of mycorrhizae decreased protozoal number in rhizosphere soil of pea plants (*Pisum sativum L*) grown under elevated CO_2 concentration (Rønn et al. 2002), probably due to decreased bacterial abundance and consequent reduced grazing. Increases in fungal and bacterial activities can stimulate their respective grazers such as protozoa and microarthropods at elevated CO_2 concentration (as reviewed by Drigo et al. 2008). Therefore, the C allocation at elevated CO_2 concentration may increase grazing, with higher microbial turnover and faster recycling of nutrients from microbial biomass. At elevated CO_2 concentration the additional N increased collembolan, which prefer nonmycorrhizal fungi (Kliromonos et al. 1997). Elevated CO_2 concentration can change the composition of nematode, protozoa, and collembola communities but not the relative numbers and these changes depend on changes in soil moisture rather than on changes in availability of C resources (Drigo et al. 2008).

Elevated atmospheric CO_2 concentration increased root-feeding *Longidorus elongatus* on a sheep-grazed pasture after four and nine years and, to lesser extent predacious nematodes, and only slightly decreased microbial-feeding nematodes in the 0- to 10-cm soil layer. The different responses of soil fauna to elevated CO_2 concentration probably depended on the unique combination of soil, plant, and soil biological conditions (Yeates & Newton 2009).

14.6 Effects of Increased CO_2 Concentration, Global Warming, and Changes in Soil Moisture on Microbial Functions Related to C Sequestration in Soil

The increase in soil respiration due to increased CO_2 can have a potentially negative effect on C sequestration by soil, but increased atmospheric CO_2 has led to increased global ecosystem C storage (Schimel et al. 2000). Indeed, the combination of water stress and elevated CO_2 can stimulate the transfer of organic C from labile to recalcitrant pools (Cheng et al. 2007) with positive implications for greater storage of organic C by soil. Both C and N pools of soil under 15 years old loblolly pine *Pinus tadea* increased exponentially when exposed to elevated CO_2 atmosphere (200 uL L^{-1} above ambient concentration) in Duke Forest Free-Air CO_2 Enrichment (FACE), but the increasing rates decreased between six and nine years and the soil C and N pools seemed to stabilize (Lichter et al. 2008). Because soil respiration was not affected it was hypothesised that the higher accumulation under higher than ambient CO_2 concentration was due to the higher litter input to soil and higher root turnover.

Increased temperature can stimulate any microbial process, including microbial oxidation of soil organic matter and thus CO_2 evolution. The temperature sensitivity of bulk soil organic matter and its fractions is probably one of the most important factors regulating the response of terrestrial carbon balance to climate warming. It has been suggested that the temperature sensitivity of soil organic matter depends on: (1) its stability; (2) substrate availability, as affected by input of organic matter, its stabilization by soil colloids, and its mineralization; (3) the efficiency of substrate utilization by soil microorganisms and the optimal temperature of the associated processes; and (4) environmental factors, such as pH, availability of oxygen and nutrient, affecting stabilization and destabilization processes (von Lutzow & Kogel-Knabner 2009).

Van't Hoff formulated the empirical rule that the ratio (the Q_{10}, the temperature coefficient of reaction) of reaction rates at an interval of 10°C is of the order of 2 to 3. If Q_{10} is constant over the temperature range considered, the increase in reaction velocity with temperature is exponential. This was the case for microbial respiration of soils sampled from a successional glacier foreland in Svalbard islands when the temperature was increased from 2 to 20°C at 3–4°C intervals (Bekku et al. 2004). According to Insam and Haselwandter (1989) the metabolic quotient (the ratio between respiration rate and microbial biomass C) decreased with the progress of primary succession on a glacier forefront in Austria due to the shift from "r" strategists to slower-growing "K" strategists, which can degrade the recalcitrant organic matter fractions. The Q_{10} values were higher (except for the youngest site, where it was 2.2, compared to 3.9, 4.1 and 3.0 at three older sites) than those of temperate ecosystems (average 2.4; Raich & Schlesinger 1992). This seems to confirm the general tendency for higher Q_{10} values in colder than warmer ecosystems (Ross & Cairns 1978; Lloyd & Taylor 1994; Kirschbaum 1995) and the implication that temperature increases at the global scale should have more impact in cold than warm environments. However, contradictory results have been reported. Nadelhoffer et al. (1991) showed that Q_{10} values were ≤ 1 at low (3–9°C) temperature and 3 at higher (9–15°C) temperatures for tundra soils. Lipson et al. (2002) reported higher Q_{10} values (3.6) in summer than winter (2.3) in alpine dry-meadow soils.

When studying the effects of temperature on microbial biomass the choice of method is important, as microbial biomass C did not change during incubation of an arable and a grassland soil (sampled from two field plots of the High-field Long Term Ley-Arable experiment at Rothamsted) at 0, 5, 15, or 25°C for 23 days whereas the ATP content (also used to determine microbial biomass in soil) increased linearly with temperature (Contin et al. 2000).

The effect of temperature on soil microbes degrading native organic C substrates is difficult to study because it involves processes that may have different temperature sensitivities. According to Ågren and Wetterstedt (2007) the effect of temperature on microbial degradation of litter or soil organic matter could be simulated by modeling: (1) the rate at which decomposers take up substrate at their surface; (2) the rate by which substrate diffuses to the surface of the decomposer; and (3) the rate at which substrate is made available in the environment.

Insam (1990) sampled soils from 21 North American sites differing in climatic regimes but with a cropping history long enough to have a content of organic C close to equilibrium. Microbial biomass, determined as substrate-induced respiration, was as an average $50\,\mu g\ C_{mic}\ g^{-1}$ at 20°C and $500\,\mu g\ C_{mic}\ g^{-1}$ at 5°C, with a negative relationship represented by the equation: microbial biomass ($\mu g\ C_{mic}\ g^{-1}$)$=590.1-21.5x$ where x is the mean annual temperature. The C_{mic}:C_{org} ratio reached a minimum when the precipitation-to-evaporation ratio was equal to 1. It was suggested that this trend depends on the decrease of microbial decomposition under soil saturation by water particularly at high temperatures, whereas, high values of the C_{mic}:C_{org} ratio were observed under drought conditions because soil microorganisms were only active for a short period. Apart from moisture, several other factors (substrate quality, composition of soil microflora, etc) can determine C_{mic} or the C_{mic}:C_{org} ratio.

The effects of soil moisture on size and activity of soil microbiota are rather complex. Dijkstra and Cheng (2007) separated soil-derived and plant-derived CO_2-C by growing sunflower or soybean under depleted ^{13}C-CO_2 and studied the effect of soil moisture. The presence of plants induced the priming effect in both sandy loam soil (pH 5.8) and clay loam soil (pH 7.1) and the greatest effect was found in the high soil moisture treatment (85% versus 45% of the water holding capacity). It was suggested that the higher production of root exudates at high moisture stimulated microbial decomposition particularly in the sandy loam soil.

Severe desiccation after prolonged hot dry periods in summer can decrease soil microbial biomass (Van Gastel et al. 1992). Laboratory experiments with ^{14}C-labeled plant material suggested that decrease in labeled microbial biomass was higher than that of unlabelled microbial biomass, probably because actively growing microorganisms are more sensitive to desiccation than slow-growing microorganisms (Van Gastel et al. 1993). It was suggested that desiccation resistance was determined mainly by intrinsic properties of soil biota such as cell wall characteristics.

In conclusion, the effects of climate changes on the organic C content of soil are difficult to study and the complex picture of the underlying mechanisms prevents straightforward predictions. More insights may be obtained by establishing methods to determine pools of soil organic matter differing in their sensitivity to global warming and to measure microbial groups differing in their capacity to degrade the relative organic pools and their response to increased temperature. Another complicating factor is the need to separate the effects of soil desiccation and temperature increase, which can have opposite effects on the studied microbial function.

14.7 Conclusions

It is not possible to make straightforward predictions about the effects of elevated atmospheric CO_2 on soil microbial functions because soil is a complex biological system and knowledge of activity and composition of microbial communities of soil is still limited, despite recent progress made through use of molecular techniques. The effects of increased atmospheric CO_2 on soil microbial functions are indirect, through increased photosynthetic activity of C_3 plants, rhizodeposition, and consequently, soil respiration The changes in plant inputs to soil are important because the majority of soil microorganisms are heterotrophic and generally C-limited (Drigo et al. 2008). Other indirect effects caused by greater belowground C allocation concern the improvement of soil structure due to the higher concentration of organic binding agents and increased uptake of nutrients and water by enhanced plant growth (Drigo et al. 2008). Increased plant N uptake and microbial activity in rhizosphere soil can lead to N-limited conditions and the overall effect can be the reduction in plant growth. Mycorrhizal infections of plant roots under elevated CO_2 concentration is probably stimulated due to the increase in C allocation rates to roots. However, future research should concern the central role of mycorrhizae in the context of global change, as they appear to be a keystone in the CO_2-related response.

Some future research needs and some methodological problems have been highlighted by studies on the effects of elevated CO_2 concentration on microbial functions of soil. Most experiments have been performed in young developing ecosystems where microorganisms appear to be regulated by relatively large pools of soil organic matter (Jones et al. 1998) rather than by additional input of organic substrates under elevated CO_2. Usually sudden changes in CO_2 concentration have been tested whereas the increase in atmospheric concentration has occurred over the years (Klironomos et al. 2005) and the effect of the reversibility of the CO_2 on microbial processes over a long period is poorly known (Kandeler et al. 2006). The study of the resilience is important because it is expected that the elevation of CO_2 will probably decrease due to political reasons. The distance between CO_2 fumigated and control plants is another critical aspect since carbon originating from fumigation was incorporated into SOM located at a distance of 9 m (Heim et al. 2009).

The different responses of soil microorganisms and complex adjustments in the food web structure reported under elevated CO_2 concentration suggest that it is needed to understand better C flow from the plant, through the mycosphere, to the rhizosphere, and into the soil food web. More attention should be paid to the response of the microbiota to elevated CO_2 concentration of the rhizosphere, particularly plant-growth-promoting rhizobacteria and their production of metabolites and antibiotics.

The modellng of the effect of climate changes on microbial functions of soil has not been discussed. Modeling soil processes, such as the turnover of organic matter, can predict and quantify the release of important nutrients such as N in soil, increasing understanding and improving management of the terrestrial C cycle. However, the modeling approach has drawbacks, such as the distance between theoretical and analytical representation of organic matter heterogeneity; indeed, as mentioned previously, methods are not available to determine pools of, for example, recalcitrant and labile organic matter, which are used in modelling the turnover of organic matter (Nannipieri & Badalucco 2002; Paustian 2001).

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15 Impacts of Climate Change on Forest Soil Carbon

Uncertainties and Lessons from Afforestation Case Studies

Philip J. Polglase and Keryn I. Paul

15.1 Introduction

Forests dominate terrestrial carbon cycles. Prentice et al. (2001) summarize data that estimate the world's forests (including savannas) to contain about 520 Gt of carbon in live vegetation, which is about 92% of the total store of carbon in all vegetation (note that the Food and Agriculture Organization [FAO] 2010 figure is somewhat less than this, highlighting the difficulty in obtaining accurate information). Net primary production (NPP) is the net amount of carbon that is exchanged between plants and the atmosphere—the difference between photosynthesis and autotrophic respiration. Globally, terrestrial NPP is about 63 Gt C yr^{-1} of which forests contribute about 44 Gt yr^{-1} (Prentice et al. 2001). This compares with the 7.6 Gt C yr^{-1} released from fossil fuels between 2000 and 2006 (Canadell et al. 2007). The amount of carbon stored in the atmosphere is about 750 Gt and accumulated at an average rate of about 4.1 Gt yr^{-1} in the period from 2000 to 2006 (Canadell et al. 2007). The terrestrial fluxes to and from the atmosphere are therefore large, small changes in which can have potentially significant consequences for net accumulation of atmospheric carbon dioxide (CO_2).

Globally, the stock of soil carbon is estimated to be about 1900 Gt to 1 m depth (Prentice et al. 2001), or more than three times that contained in live vegetation and about two and a half times the amount in the atmosphere. Although such figures are cited widely to implicate the important role of soil carbon in terrestrial carbon balances, it should be recognized that: (1) global soil carbon stocks may be much larger if depths greater than 1 m were considered, and (2) it is only that carbon which is, or potentially is, in exchange with the atmosphere that is of interest and this generally is a small proportion of total stocks (most carbon being in a highly stable form). Nonetheless, soil represents a significant proportion of the total global carbon that can be lost or added to the atmosphere depending on a range of site, management, and climatic factors. For the purposes of this discussion, soil carbon is defined as dead particulate matter (i.e. excludes live roots) that lies under the litter layer of forests and includes any discrete, humified layers, such as found in coniferous forests.

Forest plantations are an important consideration in the development of international and some national government policies. Under Article 3.3 of the Kyoto Protocol, afforestation or reforestation is an eligible activity for mitigating greenhouse gas emissions, providing that the trees are planted on land that had been cleared before 1 January 1990, are at least 2 m tall, have 20% cover, and are greater than 0.2 ha in area. The reasons for including afforestation as an eligible activity are straightforward: when planted on cleared land, trees can provide a substantial, measurable, and additional carbon sink, the amount being the difference between

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an assumed zero rate of change in the preceding agricultural phase (which may not be strictly true if the land system was not in equilibrium) and that accumulated subsequently in the live components of trees, allowing for any changes in soil carbon.

The area of planted forest globally was estimated to be about 289 M ha in the year 2005 (FAO 2010), and their potential for sequestering carbon can be profound. For example, China established about 20 M ha of new plantations after 1980 that was claimed to help offset a significant proportion of national fossil fuel emissions in 2000 (Wang et al. 2007).

Accounting for increases in forest carbon is relatively simple. Tree dimensions such as height and diameter can be readily measured and trees can be harvested (including roots) to directly estimate changes in carbon stocks. In contrast, measuring changes in soil carbon is difficult because (1) the changes are often small compared with a large initial amount, especially over short time frames, and (2) soil is heterogeneous making it difficult to sample accurately, even in the upper soil layers. Thus, a well verified modeling approach is often the most effective means by which to estimate change in soil carbon.

Despite the potential usefulness of plantations in sequestering carbon and their eligibility in international protocols, what matters globally is the total net flux of CO_2 to the atmosphere, which is given by the combined change in carbon stocks from plants and soil in all terrestrial ecosystems. Climate variability and change, through its influence on terrestrial carbon stocks, may have profound impacts on terrestrial emissions.

The importance of climatic and atmospheric change in driving terrestrial emissions, now and most importantly into the future, is given by some recent examples (Schapoff et al. 2006; Sitch et al. 2008). Results highlight the importance of potential feedbacks caused by changes in both the climate (temperature and rainfall) and increasing concentrations of atmospheric CO_2. However, the predictions are highly uncertain. For example, Sitch et al. (2008) compared five models of global, terrestrial carbon balance and showed that they all predicted a cumulative net uptake of carbon in the twenty-first century, but the amount differed greatly between models. Soil carbon was predicted to be either a source or a sink, depending on the models being tested, assumptions contained within them, and the scenarios used to drive emissions and climatic change.

Such variability in predictions highlights the need to have model constructs that properly reflect the sequential pathways for carbon flows in terrestrial ecosystems—the capture of carbon by plants, its allocation to various plant components, generation of plant residues, and processes of decomposition that lead to input of carbon to soil and its subsequent turnover.

Models of soil carbon turnover had their origin in the agricultural literature. The two best known and most widely used are the RothC model (Jenkinson 1990) and CENTURY (Parton et al. 1987). The models are similar in that they simulate multiple pools of carbon that vary in turnover times from a few months to hundreds of years or which are considered inert. The models transfer carbon from fresh plant residues directly to soil where it undergoes decomposition and exchange between the various pools. In forest ecosystems the situation is more complex. Surface litter provides a major pathway for transfer of carbon to soil and can also be highly heterogeneous in structure and decomposition rates, consisting of leaves or needles, twigs, small branches, or whole stems from fallen trees. Belowground, tree residues include fine roots that turnover on a relatively fast basis to coarse, woody roots that turnover slowly or only enter the soil pool when the tree dies.

Linking models of forest growth and turnover to models of soil carbon in a robust way is therefore a key challenge if such models are to be used for predicting the impacts of climate change on soil carbon stocks with any confidence.

Research (e.g. Kirschbaum 1999; Paul et al. 2003a) has attempted to develop models that specifically link transfers of carbon between trees and soil. Here, we focus on the RothC model and its incorporation into the FullCAM model, developed by the Australian Government to estimate greenhouse gas emissions from the land sectors. In particular, the FullCAM model has been developed and tested to estimate the impacts of afforestation on change in soil carbon. The objectives here are to:

- Review some of the factors impacting on the change in soil carbon after afforestation.
- Describe how these factors can be embodied in a modeling framework that lends some confidence to linking plant and soil carbon.
- Show how the resultant model(s) can be used to predict the impacts of climate change on soil carbon.
- Discuss some of the uncertainties in modeling forest soil carbon, implications for predicting the impacts of climate change or management at a range of scales, and further policy and research needs.

15.2 Afforestation Overview

As part of developing a capability for estimating change in soil carbon after afforestation for the Australian Government, Polglase et al. (2000) and Paul et al. (2002) reviewed the global literature and developed a conceptual framework for explaining changes. The main findings were that when trees were established on pasture, on average there was an initial decrease in soil carbon followed by a longer term increase (Fig. 15.1). Ten sequential processes were identified that explained this pattern but in summary:

- Under pasture, fine roots are continually turned over, maintaining the stock of soil carbon. When trees are established, the grasses are shaded out. Trees, unlike grasses, do not cast their residues annually, rather most of the carbon is stored in long-lived components so that trees accumulate carbon for a long period. This diverts carbon away from the soil cycle, at least during the initial phase after afforestation. Soil carbon thus decreases.
- Once the forest canopy closes, litter in the form of leaves (or needles), branches, and roots are shed, and the litter is more lignified and resistant to decay than grass residues. Soil carbon thus accumulates in the longer term.

Polglase et al. (2000) and Paul et al. (2002) also showed that this generalized pattern of decrease followed by increase in soil carbon was reasonably reproduced by the RothC model in FullCAM. The analysis also showed that after afforestation, the changes in soil carbon (negative or positive) were small relative to the accumulation of carbon in trees. This reinforces the notion that direct measurement of changes in soil carbon, especially over short time intervals and as part of an emissions trading scheme, would be costly and carry a high degree of uncertainty due to methodological problems.

Verified modeling offers a useful alternative to direct measurement of change in soil carbon. The models are best tested against long-term data sets and where there has been a significant change in soil carbon, usually due to a perturbation such as a change in land use or other management. The long-term studies should have archived soils so that all samples collected can be analyzed at the one time and all of the soil, including the greater than 2-mm fraction, should have been sampled. Soil bulk density also needs to be measured at each sampling to account for any changes in soil mass that could affect calculations.

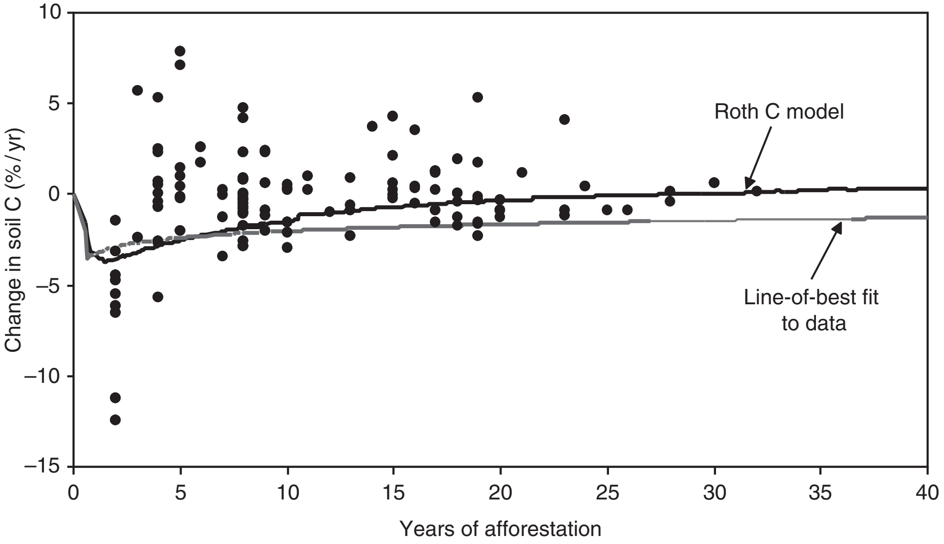

Figure 15.1 Observed percentage change in soil carbon (0–30 cm) from a global review of the literature, with fitted line and the RothC model prediction.
From Paul et al. 2003a.

In agricultural situations, there are many examples of such long-term data sets that satisfy the preceding criteria. Often, they are studies in which land has been cleared of trees followed by intensive cropping in which a large proportion of the NPP is taken off site in harvested products (Dalal & Chen 2001). This generally causes a long-term and often large decline in soil carbon due to the decrease in the amount of residue entering soil carbon pools.

Such large changes provide a useful test of the ability of models to predict temporal patterns of total soil carbon. As with nearly all models that have some degree of complexity, it is possible (if not probable) to be able to get the right answer for the wrong reasons. That is, errors in more than one of the model parameters or input assumptions can cancel out and lead to the model correctly reproducing the pattern of long-term observations. One way to overcome such inherent difficulties is to have several calibration data sets, or better, to test the model independently against validation data sets where the model is run without further adjustment. Ideally, model calibrations may be best constrained by comparing predictions against more than one type of observation in each calibration data set.

For example, comparing model predictions against total soil carbon is a useful starting point, but it is even better if the various pools of soil carbon can be isolated for model testing. To this end, Skjemstad et al. (2004) developed a fractionation procedure to estimate the five pools of soil carbon represented in the RothC model, namely decomposable plant material (DPM), resistant plant material (RPM), humus (HUM), microbial biomass (BIO), and inert organic matter (IOM), which is largely considered to be charcoal (sometimes referred to as char or back carbon). Quantifying the IOM pool was a major advance because it often persists in a fine form in soil that is not visible to the naked eye (Skjemstad et al. 1999). It is important accurately estimate this pool because it can be a large proportion of total soil carbon.

Paul and Polglase (2004b) applied this fractionation method to two forest studies as a further test of the RothC model. In one study, trees were planted on an ex-pasture site at Wagga Wagga, Australia, that has a hot dry climate and then irrigated with municipal sewerage effluent. After two years of irrigation, there was a significant and measurable loss of soil carbon of 3.1 t C ha^{-1} (21% of the initial amount) from the 0- to 5-cm layer (Polglase et al. 1995). This was primarily due to the effect of irrigation, causing soil conditions to go from hot and dry to hot and continually wet, thus stimulating rapid decomposition and loss of soil carbon. The results from the fractionation procedure of soils collected over nine years showed that the loss (and subsequent recovery) of soil carbon was entirely from the particulate pool (equivalent to RPM in the RothC model). This pool of carbon is made up of plant residues that are yet to fully undergo decomposition and which can be a large proportion of the total soil stock. In the Wagga experiment, the particulate pool was initially 9 t ha^{-1} and decreased to 4 t ha^{-1} after 2 years, before recovering. The FullCAM model reasonably predicted the pattern of change and that decreases in soil carbon came from the particulate pool, the amount of humus remaining relatively constant. This gives further confidence that the model has a sensible construct and that, for these studies, an adequate calibration.

In forest ecosystems, a good proportion of NPP each year is cast off in litterfall where it decomposes on the forest floor. During decomposition, most of the carbon will be lost to the atmosphere as CO_2, but over time, a small proportion will enter the soil carbon pool. Being able to quantify the role of aboveground forest litter and its contribution to soil carbon is a key challenge in understanding the forest carbon cycle and thus in model development.

There is a rich literature that reports studies of litter decomposition in forests and the environmental and chemical factors that control rates of breakdown. Here, it is important to separate coniferous from broad-leaved forests. Much of the early literature comes from European studies in coniferous forests in which decomposition of needles is controlled mostly by fungi, the substrates undergoing little comminution—the fragmentation of litter by microfauna—at least during the early stages of decomposition. In broad-leaved forests, in contrast, leaves are readily consumed by a rich microfuana, and the processes of decomposition may be greatly different to coniferous forests. Studies in coniferous forests have thus focused on chemical controls over litter decomposition, highlighting the importance of the relative components of lignin, carbohydrates, and ratios of carbon to nitrogen in litter as the main determinants of fungal activity. Such concepts are also embodied in models such as CENTURY, GENDEC (Moorhead & Reynolds 1991) and CenW (Kirschbaum 1999). Although this makes sense for reasonably uniform substrates, such as pine needles or agricultural and grassland residues, it presents something of a problem for the diverse range of substrates that are present in forests in general, and broad-leaved forest in particular.

Paul and Polglase (2004a) compiled the results from 385 litter decomposition studies globally and compared a simple model that separated litter into decomposable and resistant pools only with the more complex GENDEC model that includes detailed consideration of substrate chemistry. Half of the data were used for model calibrations and the other half were used as an independent test of validation. The simple, empirical model was better at predicting rates of litter decomposition across the range of litter types than the complex model. The results show that the type of substrate (e.g. leaf, needle, twig, wood) is a logical predictor of rate of decomposition when combined with simple climatic drivers such as temperature and moisture availability. In that sense, simple models are preferable because they need less data, such as chemical analyses, to calibrate them and the more simple a model, the less prone it is to yielding misleading results when applied to data sets other than the ones to which it is calibrated.

In further work, Paul et al. (2003b) studied the sensitivity of changes in soil carbon predicted by the FullCAM to model parameters and inputs. Results indicated that predicted change in soil carbon was most sensitive to parameters determining:

a. Estimates of NPP.
b. Rate of decomposition of litter.
c. The split of carbon in litter that is undergoing decomposition into that which is lost to the atmosphere as CO_2 and the proportion that is transferred to soil (microbial efficiency).

That NPP exerts such an influence should be no surprise. It may be many years before carbon that is captured by plants finds its way into soil (and it is usually only a small proportion of total NPP), but it highlights the fact that all flows of carbon in the plant and soil system will follow NPP. In other words, if NPP is not predicted correctly then no matter how well constructed the models are for describing soil carbon dynamics, they will not be able to predict with confidence any changes to the soil carbon pool. Estimating correctly the inputs to soil is an essential first step.

And that leads onto the controlling factors b and c identified above. Together they define the amount of carbon that enters soil during litter decomposition. Point c is the microbial efficiency, and it is also one of the hardest parameters to measure in forests. In agriculture, studies of plant residue decomposition have used isotopically labeled plant material to estimate microbial efficiency. Usually, the whole plant is labeled with carbon-13 isotope during its growing phase and the fate of the isotope tracked during subsequent decomposition. In contrast, labeling mature trees and all the substrates of interest, including leaves, branches, stem, and roots is technically problematic. In the absence of such detailed information, the most appropriate solution for forests is to calibrate models as far as possible against a wide range of data sets that involve properly sampled field sites, where there is a measurable change in soil carbon and as many other forest stocks and flows are known, such as rates of biomass accumulation, litterfall, and litter decomposition.

15.3 Implications for Predicting Climate Change Impacts

Predicting impacts on forest carbon balances and including soil carbon require well-constructed models that accurately, as far as possible, represent the major flows of carbon. From the preceding discussion it can be seen that predicting correctly the impact of climate on the plant response is a necessary first step. Logically, that needs to be followed by describing the allocation of carbon captured by plants to their various components (such as leaves, roots, and stems), the longevity of those components, their rates of decomposition once they are cast off as residues, the amount of carbon that enters soil, and finally rates of soil carbon turnover and loss through respiration. Errors further up the chain of carbon flows may therefore compound by the time soil carbon dynamics are considered.

A further difficulty with predictions is that any future change in global carbon storage is likely to be due to relatively small changes per hectare of forest spread over a large area. This means that model predictions will be attempting to describe a change in existing stocks that is often only marginally different from the current state. For example, Schapoff et al. (2006) showed that predicted changes in carbon stocks between 2071 and 2100, when the potential influences of climatic change are likely to be high, averaged about 0.26% yr^{-1} for vegetation and 0.05% yr^{-1} for soil carbon. Having a model that can predict with reasonable confidence such subtle changes presents something of a problem. Models need to strike a balance between correctly describing the main flows of carbon and controlling factors including interactive effects but avoid such complexity that predictions are hard to substantiate due to a myriad of internal feedbacks and constraints on carbon flows. As a starting point, parsimony in model construction is desirable providing that it adequately represents the main pathways for carbon flows. For example, models of soil carbon need to have about four pools of varying turnover rate to correctly capture the temporal response of soil to perturbation (Polglase, unpublished data). With fewer pools represented, the model can return to the same future equilibrium condition as the four-pool model but the transient response will be quite different.

The uncertainty in model predictions is highlighted by the results of Sitch et al. (2008) who compared five “Dynamic Global Vegetation Models (DGVM),” whereas Schapoff et al. (2006) used one DGVM and five different General Circulation Models to generate a range of inputs for temperature increase and changes in precipitation. The latter study showed that, during 2001 to 2100, predictions for net change in terrestrial carbon stocks ranged from −106 to +201 Gt depending on the climatic change scenarios used. In the model comparison of Sitch et al. (2008), the net change in terrestrial carbon varied from +11 to +505 Gt for 2001 to 2100 for one emission scenario, depending on the DGVM that was tested. Despite the large variation in results, some consistent patterns do emerge, such as boreal forests being a future source of $CO_{2,}$ and there is a suggestion that, as of about 2050, the terrestrial biosphere on average will flip from being a sink for CO_2 to a source.

Future changes in temperature and precipitation are important because they drive the NPP and soil carbon response, but in different ways. Soil organic matter decomposition can continue at low levels of soil water that plants cannot access. This means that soil respiration can continue when photosynthesis shuts down (no longer accumulates carbon). Thus, several studies have inferred that forests (or indeed any terrestrial ecosystem) can flip from being a strong sink for carbon, when it is relatively cool and wet, to a strong source of carbon when it is hot and dry (Tian et al. 1998).

Under increasing CO_2 the water balance of soils may also change. Plant stomata partially close in response to increased concentrations of atmospheric CO_2, and in nonwater limited environments, may therefore transpire less amounts of water, leaving a greater proportion in the soil (e.g. Gedney et al. 2006). Other feedbacks that impact on the soil-water balance are also possible, such as increasing CO_2 causing a growth response and hence greater area of forest canopy that in turn intercepts more of the incoming rainfall, leaving less available as an input to soil.

Ambient changes in climate need to be translated into soil conditions of temperature and water availability to properly drive soil respiratory response. In forests, this is particularly important because of the potential role of the litter layer in modifying soil temperature and water due its mulching effect. Paul et al. (2003c, 2004) showed that depth and mass of litter could greatly influence soil temperature, evaporation of water from soil, and hence the rate of organic matter decomposition in soil.

The preceding sections have: (1) used examples from studies of afforestation to highlight some of the important issues to be considered when constructing coupled models of forest and soil carbon, (2) discussed the importance of climatic inputs as differential drivers of NPP and heterotrophic respiration, and (3) described the way in which different model constructs and varying climatic inputs can alter predictions depending on the assumptions used. The next section illustrates further some of the uncertainty in models using as an example the impacts of afforestation on soil carbon under a changing climate.

15.4 Modeling the Impacts of Climate Change on Soil Carbon

To illustrate the impacts of climate change on processes that control soil carbon, three case studies of *Eucalyptus globulus* plantations growing in Australia were chosen. The plantations are fast growing and are harvested every 10 years for pulpwood. Three sites selected across

Table 15.1 Differences in NPP and soil carbon pools 90 years after afforestation due to climate change, as predicted by combining outputs of the CABALA plantation growth model with the FullCAM carbon accounting framework. The difference is given as (change in carbon with future climate change—change without future climate).

Site and conditions	Climate (1940–2000)		Climate (2000–2100)[1]		Difference in carbon due to climate change 1997–2100 (t C ha^{-1} yr^{-1})	
	MAR (mm)	MAT (°C)	MAR (mm)	MAT (°C)	NPP	Soil C
WA (Western Australia) Nutrient limited, future climate drier and hotter	995	16.4	935	17.3	+0.56	+0.16
TAS (Tasmania) Temperature limited, future climate wetter and hotter	944	12.6	1001	13.8	+1.71	−0.11
VIC (Victoria) Water limited, future climate drier and hotter	745	14.2	676	15.7	−4.33	−0.23

[1] To derive climatic projections, climate data from 2000–2015 were based on current data, 2016–2045 was adjusted centered on 2030 from Hadley Mk2, and 2056–2085 was adjusted centered on 2070 from Hadley Mk2. MAR, mean annual rainfall. MAT, mean annual temperature.

southern Australia have contrasting climates: (1) growth being either temperature or water limited and (2) future climates were projected to be either wetter and hotter or drier and hotter.

Monthly climatic conditions were generated from 1890 to the present using the recent climatic record. Between the present and 2120, Hadley Mk2 GCM with the Alfi SRES scenario for climatic change were used.

The CABALA model (Battaglia et al. 2004) was used to estimate the potential impacts of climate on NPP and tree growth. CABALA is a linked carbon, water, and nitrogen mechanistic model that has been well calibrated to Australian plantation species and includes the interactive impacts of CO_2 and water. The sites were initialized to a pasture condition so that soil carbon pools were at equilibrium. Plantations were then established as of 1997 and continuously harvested and replanted every 10 years until 2100 under conditions with and without climate change.

Growth increments of all tree components from CABALA runs under present and future climates were entered into the carbon accounting model FullCAM to transfer litter to soil carbon pools that are also affected by prevailing temperature and moisture.

The results (Table 15.1) show the impact of climate change, being the differences for NPP and soil carbon over the 90-year period of afforestation when the model is run with a future climate or the historical climate. Responses by NPP and soil vary according to the particular site. The Tasmania (TAS) site is temperature limited, having reasonably high mean annual rainfall. Under climate change, NPP is expected to increase and amounts of soil carbon are predicted to decrease as the site becomes wetter, stimulating decomposition despite the increase in litter inputs. At the Western Australia (WA) site, which is nutrient limited and is projected to become increasingly dry, soil carbon is predicted to increase slightly. For the Victoria (VIC) site, which has lower mean annual rainfall and which is projected to become increasingly dry and hot, both NPP and soil carbon are predicted to decrease.

Change in soil carbon is thus the result of the differential response by plants and soil to climate, dependent on both the quantity and quality of incoming litter and the changes in temperature and moisture that control organic matter decomposition. All other things being equal, soil carbon is profoundly driven by inputs from NPP. Trying to predict changes in soil

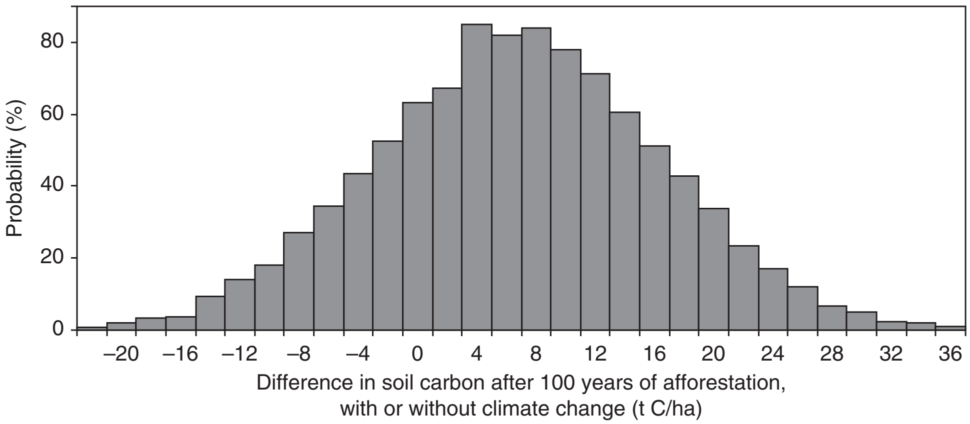

Figure 15.2 Predicted probability of impacts of climate change on soil carbon, 100 years following afforestation at the WA site. Results were generated using a Monte Carlo uncertainty analysis (using 10,000 iterations using the @Risk Program) with assumed uncertainties in key model inputs as described by Paul et al. (2003b). The key inputs contributing to uncertainty were growth increments, turnover of plant residues, allocation of biomass components of the tree, and microbial efficiency during decomposition.

carbon under a future climate is therefore a rather futile exercise unless the way in which climate change affects growth, and hence residue turnover, can be estimated with some degree of confidence.

Add to this the uncertainty in climate change projections themselves and predicting climate change impacts on soil carbon is fraught with difficulties. This can be seen in Figure 15.2 which shows the variation in predictions after running the FullCAM model 10,000 times for the WA site with varied assumed parameter values. Results are for the difference in soil carbon after afforestation in 1997, with and without climate change. There is wide variation in predicted change, from high-positive to high-negative values.

The preceding analysis considers the direct climatic impacts of changes in CO_2, water, and temperature on growth and hence soil carbon dynamics. At a regional level, associated impacts need to be considered such as from fire, cyclone, pests and disease incursions, and prolonged drought (Lewis 2006). Forest fires, for example, can be substantial contributors to the carbon cycle and Canada makes an interesting case study. In 1999, the average area of forest burned by wildfire was about 2.4 mill ha yr^{-1} greater than in 1970, and was commensurate with an increase in mean air temperature (Gillet et al. 2004). The additional fires are of such magnitude that they drive the change in carbon balance of Canadian boreal forests (Bond-Lamberty et al. 2007), more so than the direct atmospheric impacts of climatic change. Exacerbating this impact is recent incursion of mountain pine beetle in these forests, causing widespread mortality of trees and subsequent release of carbon by decomposition (Kurz et al. 2008). It is estimated that in the worst years, emissions from pine beetle outbreak would be about 75% of direct emissions from all fires.

At the global scale, fires are a significant contributor to the carbon cycle. The El Niño years of 1997 and 1998 caused widespread fires, particularly in parts in southeast Asia. The fires released an additional 2.1 Gt yr^{-1} to the atmosphere—that is, an amount that is on top of the annual average emissions of CO_2 from fires (van der Werf et al. 2004). If NPP is a primary determinant of soil carbon dynamics, then accounting for disturbance impacts on forest growth clearly needs close consideration.

15.5 Conclusion

Forests are complex systems. Changes in soil carbon are the balance between inputs from residues and outputs from decomposition. NPP is a major driver of soil carbon because it determines the amount of residue inputs. Because NPP is the precursor to all other forest carbon flows, a first step is to assess the impacts of climate changes on plant growth, carbon allocation, and residue turnover.

Models need to balance the need for complexity with simplicity. They need to describe adequately the main processes controlling carbon flows, but not be so complex as to invoke a range of processes, including feedbacks, that make them hard to verify. Parsimony is a useful default position in model constructs.

Establishing new forests on agricultural land offers one way in which to use trees to mitigate CO_2 emissions and potentially derive other ecosystem benefits. The change in carbon stocks in live vegetation is relatively straightforward to estimate, primarily because the difference in carbon stocks between agricultural land and trees is discrete and tangible – the mass of trees can be measured directly. In contrast, measuring small changes in soil carbon against a large background can be problematic, both from a technical and economic point of view. In an emissions trading scheme, it is likely that the costs of measuring any change in soil carbon would far exceed any payments that might be derived from sequestration credits. Well-verified modeling, therefore, offers the best option for accounting for changes in soil carbon stocks.

Notwithstanding the opportunities for new plantations to offset greenhouse gas emissions, it remains true that native forests represent an enormous store of carbon, small percentage changes in which can contribute greatly to global emissions of greenhouse gases. Under an increasingly changing climate, both the direct atmospheric impacts and associated disturbances from fire, pest, and disease need to be considered.

Models of soil carbon turnover are generally well verified for agriculture but not for forests in which there is much uncertainty as how best to describe the transfer of carbon in surface litter to soil. One of the most important parameters—microbial efficiency during litter decomposition—is also one of the most difficult to measure. Models of soil carbon turnover can provide valuable insights as to how plant-soil systems might respond to climate change. As with all models, their strengths and limitations need to be recognized.

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16 The Effect of Forest Management on Soil Organic Carbon

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and Francesca Scandellari

16.1 Forest Ecosystems and Global Carbon Cycle

Forest ecosystems play a fundamental role in regulating the global carbon (C) balance. An estimated 80% of all terrestrial aboveground carbon is stored in forest ecosystems and the 70% of all the soil organic carbon (SOC) is contained in forest soils (Jobbagy & Jackson 2000). The importance of this C stock becomes evident considering that soil contains more carbon than any other terrestrial carbon pool at the global scale; about twice the carbon present in atmosphere and 2.5 times the carbon stored in the living biomass (Jobbagy & Jackson 2000). The C that is exchanged between the atmosphere and forests each year via respiration and photosynthesis is more than seven times the total carbon dioxide (CO_2) anthropogenic emission (Intergovernmental Panel on Climate Change [IPCC] 2006, 2007). Within this framework, a slight increase in global soil respiration of forest soils, if not balanced by an equivalent rise of soil carbon inputs (i.e. leaf, root, and woody litter), can have important effects on global carbon cycle (Andrews et al. 1999). For this reason, in the last decades, particular attention was given to the effect of climate change on soil organic matter dynamics and soil respiration (Peng et al. 2008). It is generally accepted that soil respiration increases with increasing temperature by an exponential relationship (Lloyd & Taylor 1994). Therefore, for a number of authors, global warming will potentially result in increased soil respiration with a positive feedback of CO_2 release to the atmosphere (Jenkinson et al. 1991; Kirschbaum 1995; Bond-Lamberty & Thomson 2010). However, both heterotrophic and autotrophic soil respiration are also significantly affected by soil water content. The relationship between soil water availability and soil respiration can be properly described as a convex curve (Peng & Thomas 2006). Soil CO_2 flux is low under dry conditions in which the shortage of available water inhibits microbe and root activities and increases with increasing soil water content up to a threshold value. Indeed, in waterlogged conditions the scarcity of oxygen becomes the limiting factor for both autotrophic and heterotrophic activities, and the soil respiration generally decreases (Londo et al. 1999). Other than a general increase of temperature, the majority of global forecasting models (Bates et al. 2008) predict significant changes of rainfall regime in many parts of the globe. Thus, the response of forest ecosystems and especially the soil component to climate change is still uncertain. For instance, little is known about the effect of global warming on the interactions among roots, microbes, and soil, and how forest management can interact by limiting or enhancing the effect of climate change at local and global scales (Wardle et al. 2004; Xu & Chen 2006).

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A better understanding of the interaction between above- and belowground processes is urgently needed to build up provisional models (Peltoniemi et al. 2007) able to predict future changes in soil carbon pools in response to climate and forest management (Lee & Jose 2003). Despite these gaps of knowledge, attention given to the capacity of forest soils to store atmospheric CO_2 has continued to increase. To identify, on the base of experimental evidence, the best forest management practices to sequester atmospheric carbon is now recognized as a global priority (Lal 2005). The Kyoto Protocol (KP) recognized the importance of forest management as tool to offset greenhouse gas emissions (United Nations Framework Convention on Climate Change [UNFCCC] 1997). According to the article 3.4 of the KP, all countries can decide to consider managed forests as possible carbon sinks/sources to calculate the national carbon budget (UNFCCC 1997). In the recent Copenhagen climate conference, although the importance of including forest management in the national carbon budget within the framework of the Land Use Land Use Change and Forestry (LULUCF) issues was recognized, the debate on the accounting rules is still open and far to be concluded (Grassi et al. 2010).

Carbon sequestration in the aboveground biomass can be easily evaluated through the National Forest Inventories, but the estimates of SOC changes are more difficult to obtain. This is because of the high spatial variability of SOC, the high SOC sensitivity to previous land use, and the soil management. Moreover, the process of SOC accumulation is slower than the accumulation of carbon in aboveground biomass.

As proposed by Dixon (1994), forest policy can exploit several strategies to contribute to atmospheric CO_2 sequestration:

1 maintenance of existing forest carbon pools;
2 creation of new carbon sinks and pools;
3 substitution of wood fuels for fossil fuels; and
4 expansion of existing sinks and pools.

16.1.1 Maintenance of Existing Forest Carbon Pools

This strategy consists of reducing deforestation and forest degradation at all latitudes. However, despite the significant international effort to reduce deforestation at the global scale, deforestation continues at an alarming rate. The last report of the Forestry and Agriculture Organization (FAO) of the United Nations (FAO 2006) on the global forest resource states that 13 million hectares per year were deforested during the period from 2000 to 2005. Considering the multifunctional value of the forests, any social, political, and economic action aimed to reduce the global rate of deforestation, especially of primary forests, is, without doubt, the most important and effective strategy to store carbon and maintain forest functions in a vital state.

16.1.2 Creation of New Carbon Sinks and Pools

This strategy—dealing with reforestation or afforestation practices—was largely adopted in Europe and Asia in recent years. In Europe the upper limit for afforestation has been estimated to be 20% of the agricultural land area (FAO 2006). For many European countries already with a significant forest cover, reforestation is limited by land area availability. However, the potential of reforestation remains largely unexploited in many other European and Mediterranean countries as well as in the rest of the world (FAO 2006). As a result of forest planting, landscape restoration, and natural expansion of forests, the net loss of forest area at the global level slowed down during the period from 2000 to 2005 (FAO 2006) in respect to the previous five years. Nevertheless, the net global loss of forest area per year is estimated at 7.3 millions of hectares, equivalent to 200 km^2 per day. For statistical purposes primary forests and new plantations are both considered forest areas, but the different value of these different ecosystems in terms of biodiversity and social functions must be taken into account.

Therefore, afforestation as a compensative activity of primary forest exploitation is a political mistake with negative effects on carbon sequestration and biodiversity conservation.

16.1.3 Substitution of Wood Fuels for Fossil Fuels

The use of woody biomass, a renewable source, for energy or biofuel production can significantly reduce global fossil fuel emissions. About half of the removed wood in the world is fuelwood reaching an annual volume of at least 1.5 billion m^3 (FAO 2006). So, for example, one of the most important challenges in the coming years to counter climate change and guarantee food security will be to provide poor countries with efficient technologies for bioenergy transformation and energy conservation. The conversion of woody biomass in thermal-energy or biofuel by pyrolysis process seems to be an attractive approach (Lehmann 2007). The by-product of pyrolysis process is a biomass-derived black carbon (biochar) that contain up to 90% of the original carbon of the fresh biomass. Consequently, the addition of biochar to soil was proposed as a new approach for reducing net greenhouse gases emissions with a potential positive effect on soil fertility and crop production (Lehmann 2007).

16.1.4 Expansion of Existing Sinks and Pools

Expanding existing sinks and pools is strictly associated with the forest management practices and is thoroughly discussed. In general, large areas of forest ecosystems are not at maximum carbon storage for several reasons. First, most of the tropical forests, considered primary, are actually secondary forests that can sequester carbon in soil and vegetation compartments for a long time if a more stringent protection policy was adopted. Second, it is increasingly more evident that old-growth forests continue to accumulate carbon in the soil at an important rate (Schulze et al. 2000). Third, historically, the forest management strategies were prevalently oriented to timber production and other extra productive functions with little attention to the C stoking potential.

16.2 Effect of Forest Management on Soil Organic Carbon Sequestration

Evaluating the effect of forest management on soil processes and SOC accumulation means to consider all the forestry activities that can alter the soil carbon stock. Among them, thinning regime, chronological structure (uneven- or even-aged structure), harvesting strategies associated with the chosen forest structure (clear cutting, shelterwood cutting, seed-tree cutting, group selection, single tree selection), length of rotation period for coppices and even-aged forests, types of residue management after tree harvesting, and degree of mechanization during harvesting operations are all variables with important implications for soil processes.

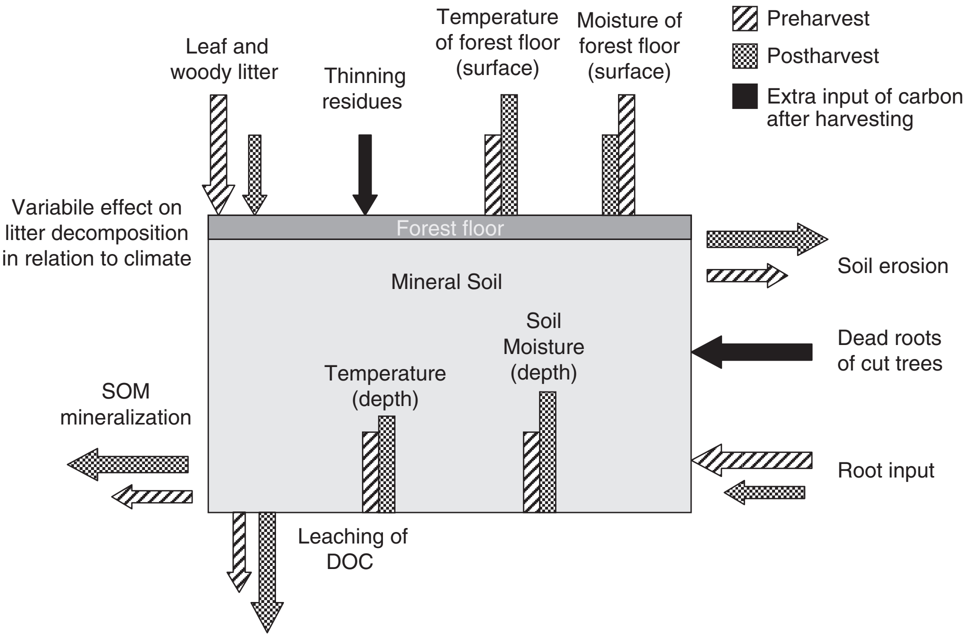

Figure 16.1 Conceptual model of the effect of forest harvesting on soil environmental factors and litter inputs.

16.2.1 Effect of Thinning on Soil Organic Carbon

Forest thinning can be defined as the partial removal of trees of an even-aged forest to improve the physical stability of the stand and the productivity of the remaining trees. Although the impact of thinning on the aboveground net primary production (ANPP) has been largely investigated (Nyland 1996), very few and sometimes contrasting information exists on the effect of thinning on carbon change in the soil. Moreover, the effect of thinning was often evaluated on a single soil layer (i.e. forest floor or mineral soil) without a complete view of the effect on the entire soil profile.

In several studies, in different part of the world and forest typologies, forest floor carbon was found to decrease with increasing thinning intensity, but the intensity of the response varied with climate, soil properties and the amount of thinning residues (Vesterdal et al. 1995; Makineci 2005; Jonard et al. 2006).

In general, the accumulation of carbon and nutrients on the forest floor reflects differences between rates of litter production and rates of litter decomposition (Olsson et al. 1996). Reducing the tree density and canopy cover, leaf litter, and root litter can temporarily decrease as a consequence of thinning. On the other hand this reduction could be balanced by the thinning residues left on the soil surface and by the extra input of dead roots from cut trees. The cumulative effect on forest floor carbon accumulation of these temporary changes in litter input and litter quality is difficult to forecast. The reduction of canopy cover can also change the microclimate conditions of the forest floor toward increased solar and thermal radiation and toward changed water availability as consequence of reduced plant transpiration and increased water evaporation of the superficial soil layer. Thus, especially in humid and cold climates, the microclimate could become more favorable for microbial activity and litter decomposition could increase after thinning (Fig. 16.1).

In a Danish study, Vesterdal et al. (1995) investigated the effect of increasing thinning intensity on forest floor carbon accumulation in three Norway spruce (*Picea abies*) stands differing in soil fertility. They found that the negative effect of increased thinning intensity on accumulated forest floor carbon and nitrogen was statistically significant at two of the three investigated sites. Irrespective of soil fertility, the pH of forest floor tended to be higher, and the C:N and C:P ratios tended to be lower in the heavily thinned plots. So, it seems that, the increased rate of litter decomposition, at least in the heavily thinned plots, can be explained not only by the more favorable microclimate conditions but also by the improvement of litter quality.

How does thinning improve litter quality? Thinning reduces competition between the remaining trees thereby increasing nutrient availability per tree and resulting in a more nutrient-rich and easily decomposable litter. In the study of Vesterdal et al. (1995), the forest floor carbon accumulation was much higher in nutrient-poor soils than in rich soils indicating that (1) nutrient availability can affect the mineralization pattern and (2) the effect of thinning on forest floor carbon can be modulated by soil fertility.

Very few data exist on the duration of thinning effect on microclimate conditions and litter decomposition. In general, it can be hypothesized that, unless the thinning frequency and intensity are excessive, microclimate returns to previous conditions after few years. This “memory effect” of thinning regime on forest floor carbon content thus depends on thinning interval and intensity and the reactivity of the ecosystem to perturbations. However, a general lack of knowledge about the time-course of the response to thinning in terms of SOC variation and belowground processes must be noted.

Few experimental data are available regarding the effect of thinning regime on the organic carbon content of mineral layers. In a Norway spruce stand in Austria, Hager et al. (1988) found that all thinning intensities decreased carbon storage in mineral soil layer 8 years after intervention and that the reduction was not proportional to thinning intensity. More recently, Selig et al. (2008) investigated the effects of thinning on mineral soil carbon storage 14 years after the thinning of an 8-year-old loblolly pine (*Pinus taeda*) plantation in Piedmont Region, Virginia, United States. They found that SOC was higher in all soil layers in thinned stands compared with the unthinned stand. To explain these results, the authors underlined how the soil in thinned stands, unlike the unthinned ones, received two large additions of organic matter. One was the decomposition of root systems of cut trees and the second was the growth, death, and decomposition of opportunistic understory vegetation occurring within a few years after thinning.

Based on these results, it could be hypothesized that the short- and the medium-term response of SOC changes to thinning operations could be opposite. In other words, immediately after the thinning, and for some years after that, SOC concentration declines because of the increased rate of litter decomposition. The duration of this period depends on soil fertility, litter quality, species, and thinning intensity. After this period the decomposition of roots of harvested trees, other than an increased productivity of remaining trees, could cause a significant increase of SOC.

Overall, thinning removes biomass otherwise fated to produce new woody litter. Consequently, the long-term net effect of thinning for carbon accumulation is probably a loss, but this has still to be experimentally verified at an ecosystem scale. To predict the long-term effect on SOC, further studies and more sophisticated ecosystem carbon models, considering for instance the effect of thinning on litter quality, are needed.

Moving our attention to the effect of thinning on ecosystem carbon balance of the forest, in Finland a first commercial thinning of a 40-year-old Scots pine (*Pinus sylvestris*) forest did not change net ecosystem exchange (NEE; Suni et al. 2003) because (1) the reduced net primary productivity (NPP) of trees was balanced by the increased NPP of understory vegetation and

(2) the reduced autotrophic soil respiration was balanced by the increased heterotrophic respiration. A significant reduction of root respiration, proportional to thinning intensity, was also observed in a 19-year-old Japanese larch (*Larix kaempferi*) plantation 4 years after thinning (Son et al. 2004). The effect of thinning regime on total soil respiration was investigated by many other authors with contrasting results (Peng et al. 2008). The high variability of total soil respiration response to thinning operations is probably due to the divergent effect that thinning can produce on root respiration on one hand and on heterotrophic respiration on the other hand. These results highlight how a deeper knowledge of the interaction between aboveground and belowground processes are urgently needed to predict the response of soil processes also to modest aboveground perturbations, such as forest thinning.

16.2.2 Effect of Forest Harvesting and Residues Management on SOC

The impact of forest harvesting on soil processes is greater than that of thinning. Harvesting generally removes biomass, changes the microclimate and disturbs the soil more than forest thinning (Yanai et al. 2003). Despite this greater impact, harvesting and thinning perturb the same soil processes. Whatever the harvest intensity, forest cutting influences soil carbon in several contrasting ways. Harvest residues left on the soil, the decomposition of roots of harvested trees, and a drier soil surface, should increase the soil carbon stock at least in the short term (see Fig. 16.1). On the contrary, reduced leaf and root litters, dissolved organic carbon (DOC) leaching, increased soil temperature and moisture of the deeper layers, and soil disturbances should reduce the soil carbon stock over time (see Fig. 16.1).

Johnson and Curtis (2001) using a meta-analysis approach reviewed the literature on forest management effect on soil carbon and nitrogen, and their results are a further proof of the possible contrasting effect of harvesting on SOC changes. Indeed, they found that forest harvesting, on average, has little effect on soil carbon and nitrogen of both the surface horizon (A horizon) and the whole soil, but the variability of the response was very high, ranging from an increase of 70% to a reduction of 60% of the original SOC (Fig. 16.2). The origin of this high variability was found to be related to the harvest method and to the species composition within the same harvest method. Actually, sawlog harvesting, leaving the residues on the soil surface, caused, on average, a significant soil carbon increase while whole-tree harvesting causes a slight decrease of soil carbon in the A horizon (see Fig. 16.2). No statistically significant effect on B horizon (subsoil) was highlighted. Soil carbon increase after sawlog harvesting occurred only in coniferous forests.

Therefore, the importance of residues management and interaction between residue management and species composition emerges clearly in the Johnson and Curtis (2001) analysis. In recent years, many studies have focused on the effect of residue management on SOC and nutrient availability (Mendham et al. 2003; Mathers et al. 2003; Mathers & Xu 2003; Corbeels et al. 2005; Chen & Xu 2005; Blumfield et al. 2006; Jones et al. 2008; Gomez-Rey et al. 2008; Busse et al. 2009). Most of these studies evaluated the short-term impact on soil carbon and nitrogen of different treatments, whereas only a few studies assessed the impact of treatment beyond 10 years after harvest. The treatments that are commonly compared are sawlog harvesting, whole-tree harvesting, and whole-tree harvesting plus forest floor removal. The majority of the studies on the short-term effects found that leaving the residues on the soil has a beneficial impact on SOC content, whereas all the others treatment significantly reduce the carbon content. On the contrary, studies on the long-term effect (beyond 10 years) highlighted a negligible effect of the different residue management on SOC. Only Thiffault (2006) found a lasting effect in boreal soils with intrinsically low organic matter.

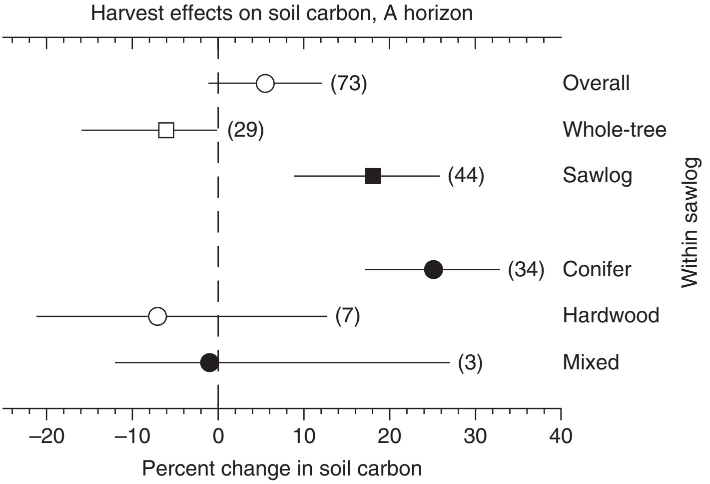

Figure 16.2 Effect of harvest method (sawlog harvest, where bole was removed and residue left on the soil; whole tree harvest, where all aboveground residue and slash were removed), and species composition on SOC change of A horizon after clear cutting. Confidence intervals of 99% and number of studies (in parenthesis) are shown.
Johnson & Curtis 2001.

The different conclusions of short- and long-term effect studies suggest, as we have seen for thinning, that the impact of residue management on SOC, and more generally, of forest harvesting should be temporary. It is to underline that most of these studies focus on the impact of forest harvesting on soil mineral carbon, whereas the effect on forest floor carbon is often ignored. In one of the most influential studies in the history of forest ecology, Covington (1981) suggested that carbon of a hardwood forest floor declines by 50% within 20 years after clear cutting. This was attributed to an acceleration of soil organic matter decomposition and to changes in litter input. The results of Covington's study were often used without any validation in many different climate conditions and forest typologies leading to alarming estimation of global carbon losses as result of forest management. Covington's findings based on chronosequence studies and the analysis of the original data were recently criticized by Yanai et al. (2003). Although, as proved by Yanai et al. (2003), the negative effect of forest harvesting on forest floor carbon was probably overestimated by Covington, the higher sensitivity of forest floor carbon in comparison with soil mineral carbon is commonly accepted and found in many studies (Olsson et al. 1996). According to Jandl et al. (2007), carbon dynamics after forest clear cutting show a sudden carbon loss, with the loss of an important portion of carbon forest floor and labile mineral carbon (Fig. 16.3).

If other perturbations do not occur, then a slow continuous recovery follows. The complete recovery of carbon to preharvest levels can take place if rotation period is long enough (see Fig. 16.3). On the basis of the carbon dynamic proposed by Jandl et al. (2007), the discordant results of the effect of forest management on SOC are in some way accounted for the differences in the length of time following harvest. Very few data exist on the effect of historical forest management on SOC. A prerequisite for these studies is the availability of forests with similar species composition, grown in similar climate and geological situations, but differing for their historical forest management regime. The difficulty in meeting these conditions could be the reason for the lack of data on the effect of historical forest management on SOC. Tonon et al. (unpublished data) did not find any significant difference in soil carbon and nitrogen contents

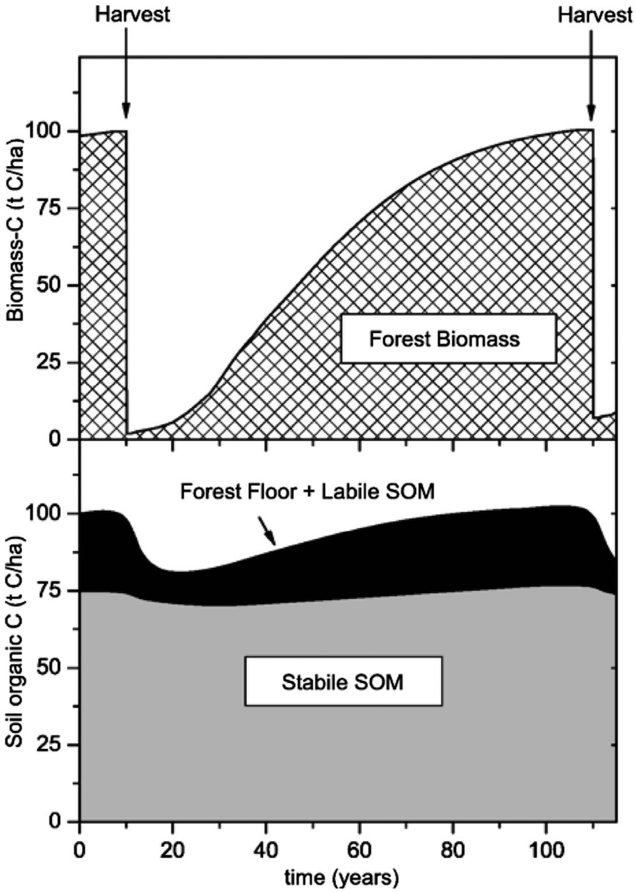

Figure 16.3 Carbon dynamic in the aboveground biomass and soil after clear cutting, as proposed by Jandl et al. (2007) for Central European Norway spruce forest.

of four Norway spruce subalpine forests, managed over centuries by shelterwood or single-tree selection harvesting, and then unmanaged over the last 80 years. Recently, also Waldchen et al. (personal communication) found no effect of historical forest management on present soil carbon stock of shelterwood beech forests, managed during the eighteenth and nineteenth centuries as coppice or as uneven aged forests. On one hand, these results indicate that the current management is more important than the historic management regime in establishing the present soil carbon stock. On the other hand, they highlight the plasticity of forest ecosystems that, irrespective of the previous management history, over some decades under a given forest management reach new soil carbon balance equilibrium.

16.2.3 Effect of Forest Harvesting on Ecosystem Carbon Balance

In general, different forest harvesting strategies affected the net ecosystem carbon exchange more than the soil carbon balance itself. For instance, although single tree selection or group selection cuttings temporarily reduce uptake of CO_2 from the atmosphere until the canopy has

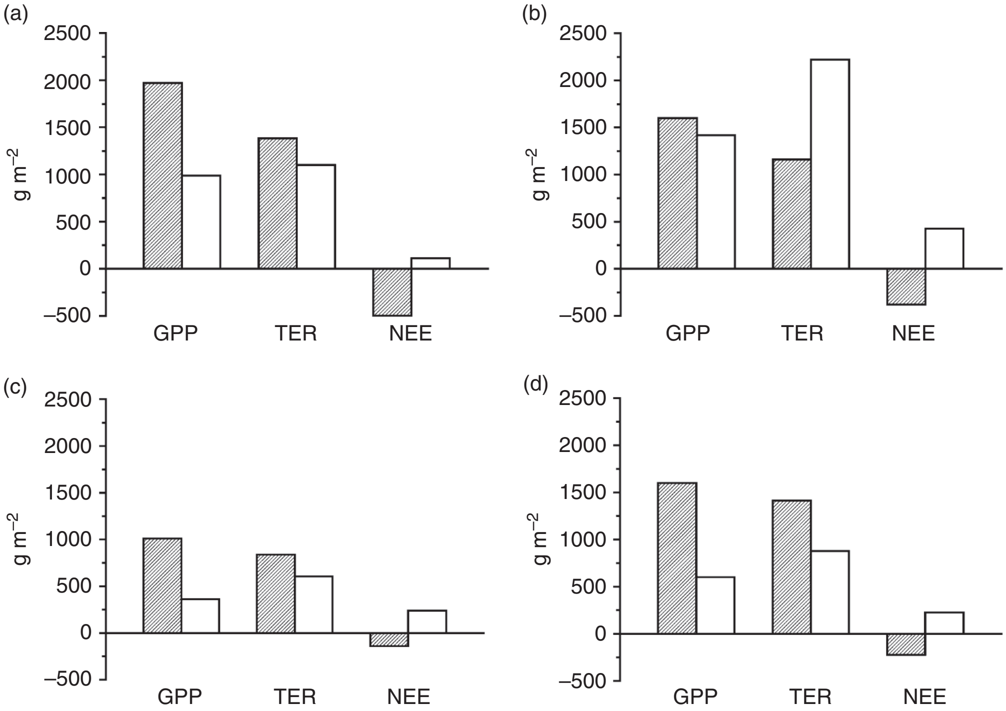

Figure 16.4 Comparison of annual Gross Primary Productivity (GPP), Total Ecosystem Respiration (TER), and Net Ecosystem Exchange (NEE) between mature (*shaded*) and harvested (*clear*) forest sites in (a) UK, (b) Italy, (c) Finland, and (d) France.
Kowalski et al. 2004.

regrown, clear cutting immediately converts the forest from a carbon sink to a carbon source (Jarvis et al. 2005). Clear cutting leads to an immediate loss of sink capacity, whose duration depends mostly on the timing and the promptness of regeneration or revegetation process. Where the soil and climate conditions are unsuitable for natural regeneration or for the development of buffer opportunist vegetation, the forest ecosystem can act as a carbon source for several years. For instance, Schulze et al. (1999) found that Siberian forests remain net sources of CO_2 to the atmosphere for at least 14 years after clear cutting, and that they remain weaker sinks for atmospheric CO_2 than old-growth forests for many years after logging. In another European study the effect of harvest on NEE was examined comparing four pairs of mature/harvested sites through the combination of eddy covariance measurements and empirical modeling (Kowalski et al. 2004). Three sites were high coniferous forests, spruce in the United Kingdom, and pines in Finland and France, whereas a coppice-with-standard oak plantation was examined in Italy. Harvesting converted all forests from carbon sink to carbon source of similar magnitude, but the mechanisms by which this occurred were quite different. A stronger reduction of gross primary productivity (GPP) than ecosystem respiration (ER) for high forest coniferous, and a burst of ER in oak coppice were detected following harvest (Fig.16.4).

In a recent Japanese study, the clear cutting converted a mixed forest from a weak carbon sink to a large carbon source (Takagi et al. 2009). However, the large emission in the year of harvest rapidly decreased in the following 2 years as the GPP increased, whereas the total ER remained relatively stable.

16.3 Forest Management Strategies and Forest Structures Improving Carbon Storage

All the previous examples show how the forest clear cutting strategy, involving the total removal of the canopy, causes an immediate, even if temporary, loss of carbon to the atmosphere. In this context, the use of partial cut (Taylor et al. 2008) or shelterwood strategies or the conversion of even-aged forest to uneven-aged forest by the application of selective harvesting, such as single tree selection or small group selection cutting, could represent a valid alternative for reducing soil carbon losses and for stocking more carbon in the ecosystem. For instance, Scott et al. (2004) in a mixed forest in Maine (United States), found that a shelterwood cut removing 30% of the aboveground biomass reduced the NEE by about 18%, which is less than expected based on basal area and leaf area index changes. Moreover, soil respiration declined following harvest, suggesting no significant soil carbon loss after harvest.

Seidl et al. (2008) in a simulation study compared the effect of four forest management strategies on carbon storage of an even-aged Norway spruce forest in Austria. The four management strategies were: (1) traditional Norway spruce age class forestry (even-aged forest); (2) transition to continuous cover forestry with Norway spruce (uneven-aged forest); (3) conversion to mixed conifer/broadleaved stands; and (4) no management. These alternative forest management strategies were investigated under current climate and two transient climate change scenarios. The results showed that the transition to continuous cover forestry would increase the carbon storage in all the considered climate scenarios compared to the conservation of the even-aged forest structure. Moreover, even-aged management has been recently put under criticism for being unsuccessful in realizing the site-specific production potential (Lahde et al. 2001), producing a large amount of low quality woody products, and being an inefficient strategy for conserving biodiversity (Humphrey et al. 2002). The transition to uneven-aged forest is not possible everywhere because it requires local technical skills, suitable climate conditions to support natural regeneration under the typical uneven-aged forest microclimate and a flexible timber market. However, according to ECCP-Working Group on Forest Sink (2003), 30 million hectares in 15 European Union countries could be converted to selection forest with a significant increase of C stored in the forests.

16.3.1 Length of Rotation Period and Carbon Storage: Learning from the Old-Growth Forests

Where social, economic, technical, or ecological reasons make the conversion to uneven-aged structure difficult or impossible to achieve, the elongation of the rotation period of even-aged forest can be considered a possible measure to promote carbon sequestration in forest ecosystems. It is generally thought that old-growth forests are carbon neutral because the productivity decreases with forest age and heterotrophic respiration counterbalances the NPP. So, the common idea is that old-growth forests have the highest carbon stock, and the younger stands have the larger carbon sink capacity. Some evidence seem to contradict this ecological paradigm. For instance a 250-year old beech forest in central Germany accumulated more than 4 t carbon ha^{-1} yr^{-1} (Knohl et al. 2003), a value of NEE similar to those of many young stands. Similarly, a 220-year old Siberian Scots pine forest sequestered 1.68 t carbon ha^{-1} $summer^{-1}$. Recently, Luyssaert et al. (2008) reconsidered this ecological paradigm by conducting a comprehensive literature analysis. They demonstrated that old-growth forests continue to accumulate carbon at a very high average sequestration rate (2.4 ± 0.8 t carbon ha^{-1} yr^{-1}), and more than half of this carbon is annually accumulated belowground. This seems to occur irrespective of whether forests are boreal or temperate. Several authors showed that old-growth forests transfer into the soil a proportion of NEE higher than young stands; by this allocation mechanism old-growth forests continue to accumulate carbon over the centuries (Harmon et al. 1990; Schulze et al. 2000). Forest stand dynamics can explain this mechanism: if it is generally accepted that aboveground biomass cannot accumulate forever, on the contrary the concept of soil carbon saturation is far to be defined and accepted. Luyssaert et al. (2008) hypothesized that, when the maximum aboveground biomass is reached, the old-growth forests enter in a degradation phase; in a few decades the old trees die due to tree-tree competition or small-scale disturbances and a new recruit is ready to grow. Because the decomposition of tree trunk and branches is a slow process, the CO_2 released from the degradation of dead wood is more than balanced by the growth of new generation. The final effect under constant environmental conditions is a continuous soil carbon accumulation. Before Luyssaert et al. (2008), others authors reached similar conclusions. For instance, Harmon et al. (1990) found by a simulation study that conversion of old-growth forest to young fast growing forests was not an efficient policy to reduce atmospheric CO_2 concentration. Even when carbon sequestration in wooden buildings was considered, timber harvest resulted in a net carbon flux of CO_2 to the atmosphere. Only the production of long-term wood products and a significant increase of the life span of the building could make the mass balance positive. Schulze et al. (2000) stated that replacing unmanaged old-growth forest by young Kyoto forests, will lead a massive carbon losses to the atmosphere. The old-growth forests of the Northern Hemisphere alone sequester annually about 1.3 ± 0.5 Gt of C that is 10% of the global net ecosystem productivity (Luyssaert et al. 2008). The clear conclusion arising from these results is that the protection of the old-growth forests as active carbon sinks and hot spots of biodiversity will be a crucial point of the global forest policy in the coming decades.

Considering the carbon cycle of the old-growth forest, what is the optimal rotation length of the even-aged forest when the carbon sequestration is the aim of the forest management? The debate is still lively and open. In general, short rotation lengths close to the age of maximum mean annual increment maximize aboveground biomass productivity but not carbon storage and NEE. In a Canadian study Peng et al. (2002) found that for a given harvesting intensity, total ecosystem C stock of a boreal forest is highest with long rotations (120 years) and reduced under shorter rotations (60 and 30 years).

Extremely short rotations (30 year) reduce forest productivity by as much as 65%. On the base of their simulation, the authors stated that longer rotations and less intensive harvesting could increase C sequestration to 36/40% in the boreal forest region of central Canada. Liski et al. (2001) through a life cycle analysis in which the life span of woody products and the fossil carbon emission in harvesting and manufacture were considered found that a 30-year elongation of common rotation length was the favorable choice for carbon sequestration in both Scots pine and Norway spruce forests in Finland. Kaipainen et al. (2004) in a simulation study found that the potential carbon sinks resulting from the elongated rotation length was from 2 to 10 times higher than the estimates by the IPCC (2006).

16.4 Conclusions

A new way of considering forest management is needed to conserve and enhance the carbon stocks in the forests, particularly the carbon stocks in forest soil. The best forest management strategy with universal value does not exist. Ecological, historical, and socioeconomic conditions and traditional forest management are crucial elements in establishing the best forest management option for a given landscape. Nevertheless, some general indications arise from this analysis.

Forest thinning of even-aged forest is a preferred silvicultural practice for its potential positive effect on soil organic carbon and because thinning increases stand stability and therefore offers an important control mechanism for the maintenance of carbon storage in forest ecosystems. Thinnings have to be done for long-term silvicultural goals to improve the quality of the final product but also increase NPP and the forest carbon stocks. A deeper analysis should be done on the use of thinning products. From a carbon perspective, if the local market is not remunerative for thinnings or the site of utilization is several hundred kilometers away it would be advantageous to use thinning products to substitute fossil fuel. Regarding the use pyrolysis with the production of biochar, it should be evaluated with great attention both at local and global scale. Leaving residues on soil after thinning and harvesting operation results a crucial practice to conserve soil organic carbon and soil fertility. The use of residues as biofuel for heat or energy generation seems undesirable from a carbon perspective.

Where ecological and socio economic conditions are suitable, the so-called "forestry carbon" should move toward the continuous cover forestry. This is a forest management option with minor impact on soil process and positive long-term effect on soil and forest carbon storage. Old-growth forests are relevant carbon sinks and their protection must be discussed if the conservation of biodiversity and the increment of carbon sink capacity of terrestrial ecosystems will continue to be a crucial priority at global level.

Finally, the elongation of rotation period of coppices and even-aged forests could be a possible measure to increase forest carbon sequestration, but how much this management approach is realistic has to be assessed at regional scale by a full quantitative carbon analysis of the "wood chain" during the management cycle.

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