# Land Use and Soil Resources

Ademola K. Braimoh • Paul L.G. Vlek
Editors

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# Foreword

Soils are considered as increasingly important in global development issues such as food security, land degradation, and the provision of ecosystem services. *Land Use and Soil Resources* synthesizes scientific knowledge about the impact of different land uses on soils in a manner that resource managers can use it. The book offers contribution to the challenge of food production and soil management as population continues to grow in parts of the world already experiencing food insecurity and shrinking arable land. Improved management on existing arable lands is imperative to guarantee food security for the increasing population.

Food importation is important to augment production in Africa, Asia, and Latin America. Countries in these regions are consequently among the largest net importers of nitrogen, phosphorus, and potassium as well as of virtual water in traded agricultural commodities. Nevertheless, soil-fertility decline and water scarcity persist in many countries in the regions. *Land Use and Soil Resources* offers an explanation on the driving factors of nutrient and water flows across world regions, and the need to factor environmental costs into nutrient and water management.

Irrigation is crucial for crop production in many areas of the world characterized by hydrologic scarcity and variability, but poor irrigation practices often saturate land with salts and render croplands barren in the long run. Salinization and waterlogging constitute a threat to the sustainability of irrigation projects in both developed and developing countries. *Land Use and Soil Resources* combines agronomic and environmental facts in a coherent manner to highlight the conditions for the sustainability of irrigation.

The systemic links between cities and rural areas has always posed a formidable challenge to humankind vis-à-vis producing enough crops to feed the populace, and encroachment of cities on agricultural lands and sensitive ecosystems, amongst other problems. As cities develop as centers of nonagricultural production, they also introduce pollutants into the environment. Soil pollution in most cities is at levels warranting instant and urgent action.

Assessment and management of soil quality for land-use planning is increasingly important due to increasing competition for land among many land uses and the transition from subsistence to market-based farming in many countries. The major challenges include predicting land-use suitability and assessing land-use impacts on soil quality to sustain land productivity. This book presents methods for soil-quality assessment using land-evaluation principles and geospatial information technology.

The rate at which soil organic carbon is lost through cultivation and other disturbances undermines the role of soils in buffering climate change. Besides, soil erosion by water associated with early agriculture is currently the most destructive form of soil degradation with profound effects on rural livelihood and environmental sustainability. *Land Use and Soil Resources* documents the strategies to stem further soil carbon losses. It also highlights the successes and challenges of soil and water conservation measures. Soil management strategies require broader sustainable development policy frameworks for success. In the twenty-first century, soils will become more important as an economic and social resource. Soil is vital for human survival on Earth, but paradoxically our cavalier attitude to this natural resource makes its ecosystems one of the most degraded. The task of disseminating knowledge about soils is extremely urgent. The challenges of soil management vis-à-vis human well-being are presented in a scientifically coherent manner in this book. I count it a great privilege to introduce *Land Use and Soil Resources* at this crucial moment of human history.

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Under-Secretary-General of the United Nations

# Contents

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**Eric Craswell** specialized in soil microbiology and soil fertility at the University of Queensland and was awarded his Ph.D. in 1973. He worked on nitrogen cycling and the efficiency of fertilizers for cereal crops at centers in Queensland, Alabama, and the Philippines. After an extended period in research management in the field of land and water resources, he developed an interest in nutrient and water cycling at the global scale and recently served as Executive Officer of the Global Water System project based at ZEF in Bonn.

**Bidjokazo Fofana** is Senior Agronomist at the Africa Division of IFDC. He holds a Ph.D. in Weed Science and Agronomy from Justus-Liebig University of Giessen. He coordinates development projects with a focus on natural resource management. His research aims to derive methods for improved land management, to optimize inorganic fertilizer-use efficiency through integrated use with organic matter, and to improve crop yield and animal production.

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**Hanspeter Liniger** is the Coordinator of the global WOCAT (World Overview of Conservation Approaches and Technologies) network for documenting, evaluating, and disseminating sustainable land management practices worldwide. During his 10 years in Kenya he has been focusing on research in improving rainfed agriculture through water conservation as well as in assessing the impact of land use on soil productivity and river flows. He is also involved in teaching and supervising students from Europe as well as developing and transition countries in the field of soil and water conservation.

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**Diego de la Rosa** is a Professor of Soil Science at the Spanish Research Council (CSIC), Sevilla, Spain. His research focuses on agroecological approaches for the assessment of soil systems, making application of information technology for developing land-use and management-decision support tools. With special reference to the Mediterranean region, he has conducted numerous studies in the area of agricultural land evaluation and degradation modeling, which have been reported in more than 150 publications. Since 1990, his investigation results are being included into the MicroLEIS system (http://www.microleis.com).

**Pete Smith** is Professor of Soils and Global Change in the School of Biological Sciences at the University of Aberdeen, Scotland, UK. His research interests include the impacts of global change, for example, land-use and climate change, on soils, and the use of soils, especially in agricultural systems, to mitigate climate change. He is a modeler and investigates global change–soil interactions at scales ranging from sites, through continents, to the globe. He is especially interested in soil carbon and greenhouse gas fluxes from soils and from agriculture.

**Ramon Sobral** is Soil Survey and Land Evaluation Researcher at Argentina National Institute of Agriculture Research (INTA), Buenos Aires, Argentina. He is devoted to soil classification and land interpretations for rural development and land-use planning. During the 1990s, he designed the Productivity Index applied to the Atlas of Soils of Argentina. He also developed indicators of soil quality and soil health for the Argentine Benchmark Soil Series project.

**Lulseged Tamene** is Postdoctoral Fellow at the University of Bonn, Center for Development Research. His M.Sc. is on GIS/Remote Sensing Applications for resources management in developing countries and holds a Ph.D. in Ecology and Land Management. His research interests are modeling erosion and sedimentation processes, analyzing land-use/cover changes and their implications on land and water resources, and assessing land management options for sustainable use of water resources. Specifically he is interested in GIS, Cellular Automata, and Multiagent-based models for integrated assessment of water- and soil-degradation processes and the major drivers.

# List of Figures

# List of Tables

# Chapter 1
# Impact of Land Use on Soil Resources

**Ademola K. Braimoh and Paul L.G. Vlek**

The land system is a coupled human–environment system comprising land use, land cover, and terrestrial ecosystems (Global Land Project, 2005). Land use connects humans to the biophysical environment. Conversely, the characteristics and changes in the biophysical environment influence our land-use decision-making. Thus, there is a continuum of states resulting from the interactions between natural (biophysical) and human (social) subsystems of land (Fig. 1.1). Though not always, the dynamics of this continuum generally moves toward increasing human dominance and impact. Thus, mitigating adverse environmental changes requires an improved knowledge of human impact on natural processes of the terrestrial biosphere.

Soil is a basic resource for land use. It is the foundation of all civilizations (Hillel, 1992), serves as a major link between climate and biogeochemical systems (Yaalon, 2000), supports biodiversity, and plays an important role in the ability of ecosystems to provide diverse services necessary for human well-being (Young & Crawford, 2004). Thus, soils must not be neglected in any development endeavor either at local, regional, or global level.

Good soils are not evenly distributed around the world. Depending on parent material, climate, relief, vegetation, and time that determine soil formation, soils have inherent constraints that limit their productivity for various uses. Most soil constraints are not mutually exclusive. For instance, highly acidic soils with aluminum toxicity also have high phosphorus-fixation capacity. The inherent constraints of soils for agricultural production vary widely across regions. For example, erosion hazard, defined as very steep slopes (>30%) or moderately high slope (8–30%) accompanied by a sharp textural contrast within the soil profile, varies from 10% for soils of North Africa and Near East to 20% for soils of Europe. On the other hand, shallowness, the occurrence of rocks close to the soil surface, varies from 11 percent for soils of South and Central America to 23% for soils of North Africa and Near East (FAO, 2000).

Human impact is an additional challenge to the inherent constraints of soils to support life on earth. Soil degradation is largely an anthropogenic process driven by socioeconomic and institutional factors. At the global level, five major human causative factors of soil degradation are overgrazing, deforestation, agricultural mismanagement, fuelwood consumption, and urbanization (UNEP, 2002). Soil degradation often occurs so creepingly to the extent that land managers hardly

A.K. Braimoh and P.L.G. Vlek (eds.), *Land Use and Soil Resources*.

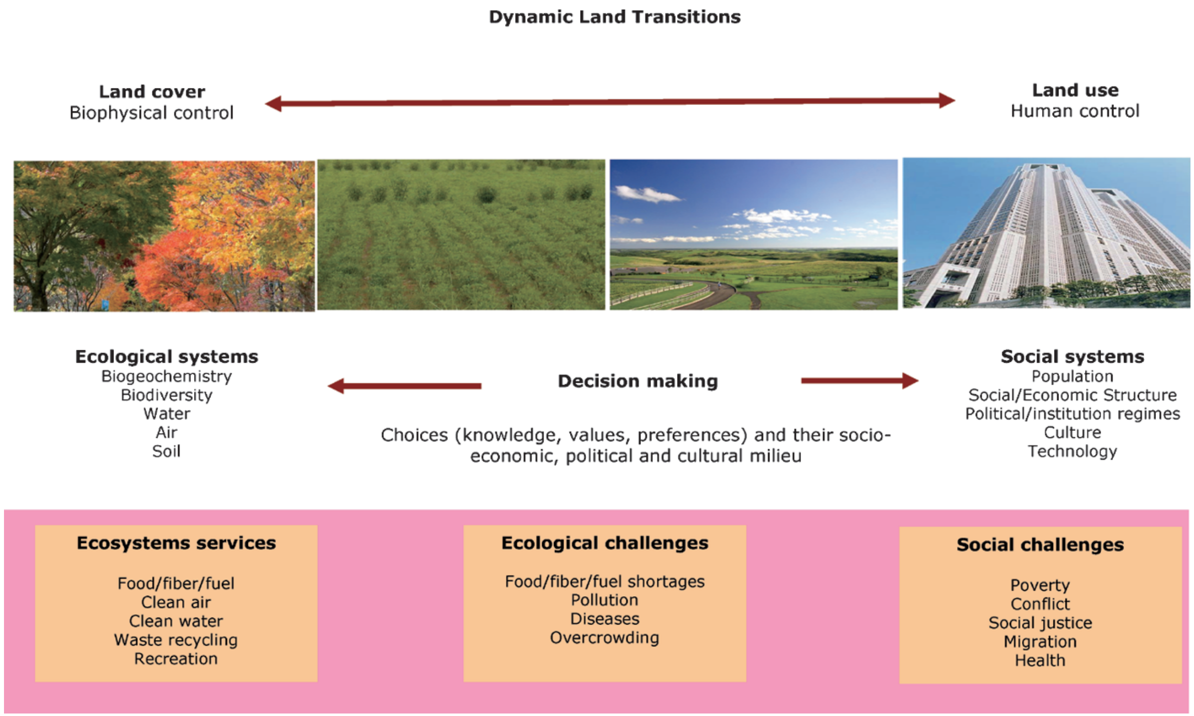


**Fig. 1.1** The continuum of states resulting from the interactions between natural and social dynamics. (Adapted from Global Land Project, 2005). Human decisions lead to different states along the continuum from wilderness to mega-cities. Different system characteristics are observed depending on whether biophysical or human control is more dominant. Different ecological and social challenges also result from human interference

contemplate initiating timely ameliorative or counterbalance measures (Vlek, 2005). It is often associated with food insecurity, decline in living standard, social upheavals, and the collapse of civilizations (Weiss et al., 1993; Wood, Sebastian, & Scherr, 2000).

The past few years have witnessed considerable interest in land-use research as a result of the realization of the influence of land-use and land-cover changes on Earth System functioning. Land use still faces large-scale changes and modifications in the near future due to population growth, political and socioeconomic changes related to globalization, and changes in land-related policies. Like the inherent biophysical constraints, human-induced changes on soil ecosystems are highly complex, vary across the world, and are profoundly impacting ecosystem services and human well-being. Though not all human impacts are negative, the environmental crises associated with adverse land-use changes have created a compelling need for a unifying volume that addresses the multifaceted impacts of land use on soils.

This book synthesizes information on the impact of various uses on soils. It is written with scientific clarity to inform policies for sustainable soil management. In Chapter 2, Smith writes on soil organic carbon (SOC) dynamics and management. SOC dynamics, the link between climate and biogeochemical systems, is a major pathway to understanding and predicting human impacts on the Earth (Yaalon, 2000). SOC losses arise from converting grasslands, forests, or other native ecosystems to croplands, or by draining or cultivating organic soils. On the other hand, positive impacts on SOC arise from restoring grasslands, forests, or native vegetation on former croplands, or by restoring organic soils to their native condition. With growing demand for food, more land is required to produce crops, implying greater potentials for SOC losses. Globally, the carbon sink capacity of agricultural and degraded soils is about 50–60% of historical carbon loss (Lal, 2004). While the rate of soil carbon sequestration depends on soil properties, climate, and farming practices, Smith argues for a broader sustainable management framework for the adoption of successful soil carbon management in developing countries. This includes policies to encourage fair trade, reduced subsidies for agriculture in developed countries, and less onerous interest on loans and foreign debts.

Recent estimates indicate that 854 million people are undernourished worldwide, with the highest proportion (about 61%) residing in Asia and the Pacific (FAO, 2003). Sub-Saharan Africa where 10% of the world's human population resides has the highest prevalence of undernourished people of 33%. Food production in many developing countries is hampered by decreasing per capita cropland, soil nutrient depletion, lack of access to intensification inputs, and lack of enabling policy environments that favor smallholders. In Chapter 3, Ramankutty, Foley, and Olejniczak review the major changes in global distribution of croplands during the twentieth century. Between 1900 and 1990, per capita cropland area decreased from 0.75 ha to 0.35 ha—less than the minimum 0.5 ha required to provide an adequate diet (Lal, 1989). Population growth was not met by a corresponding increase in cropland expansion first because increases in food production were achieved by agricultural intensification, and also because cropland expansion did not always occur in the regions with the highest population growth. Thus, food security by nations with insufficient agricultural production was achieved primarily through food aid and trade. As cropland and settlement expansion has claimed prime agricultural land, there is increasing reliance on technology for improved agricultural productivity. Even though food production is generally adequate at the global level, the global food production system is becoming increasingly vulnerable owing to the dependence on technology to increase productivity.

Since the transition from hunting and foraging to agriculture about 10,000 years ago, human dependence and impact on soils have become more apparent, with soil erosion standing out as the most destructive form of soil degradation. Three epochs of soil erosion can be identified since cultivation began in the Fertile Crescent in the Middle East (McNeill & Winiwarter, 2004). The first epoch occurred in the second millennium BC during the expansion of early river basin civilizations, when farmers cleared forested slopes for agriculture. In the next 3,000 years, conversion of forests to farmlands also occurred in Africa, Eurasia and the Americas. The second epoch occurred during the sixteenth to nineteenth century when the introduction of agricultural machinery (plowshares) in Eurasia, North America, and South America accelerated soil erosion on farmers' fields. The third epoch occurred after 1945 when rapid population growth amongst other factors encouraged migration into tropical rainforests. On the average, the soils of the world have lost 25.3 million tons of humus per year since 10,000 years ago. Over the last 300 years the average loss was 300 million tons per year. The last 50 years in particular have brought human-induced soil resources degradation to exceptionally high levels. On the average, 760 million tons of humus has been lost per year in the last half-century (Rozanov et al., 1990). Ethiopia in East Africa is among the countries with the highest soil erosion rates. Its highlands lose over 1.5 billion tons of topsoil per year, leading to a reduction of about 1.5 million tons of grain in the country's annual harvest (Taddese, 2001). While there may be some uncertainties in these statistics, the magnitude of soil erosion problem is largely indubitable.

It is noteworthy that from the 1930s, modern soil conservation endeavors (mostly sponsored by governments) has broadened significantly (McNeill & Winiwarter, 2004), utilizing several techniques, including contour plowing, use of cover crops, and conservation tillage. In Chapter 4, Hurni et al. highlight the development of agriculture since 1950, and elaborate on progress in soil and water conservation techniques. They reveal that social factors (land tenure security, market access, and increased level of participation in decision-making) are necessarily involved in soil water conservation. While measures developed for modern agricultural systems have begun to show positive impacts, external support in the form of investment in sustainable land-management technologies is still required for small-scale farming. In an empirical study reported in Chapter 5, Tamene and Vlek applied soil erosion models to identify high-risk areas to target management intervention in Ethiopia. The model generally predicted higher erosion than deposition, implying that soil loss is higher than the amount that can be redistributed within the catchments, thereby increasing the potential for sediment export. The study further indicates that a land-use planning approach could help reduce erosion problems in Ethiopia, and other parts of the world with similar environmental conditions.

Degradation of soils and the depletion of water resources that caused the collapse of irrigation-based societies about 6,000 years ago are threatening the viability of irrigation at present. The fact that irrigation is vital for increased productivity is well appreciated by farmers, governments, and international donors. However, the expansion of irrigation, which had been a principal focus of agricultural development for the past few years, has lately been offset by the abandonment of older irrigated areas due to depletion of groundwater reserves, waterlogging and salination, or diversion of water supplies to alternative uses. Chapter 6 by Vlek, Hillel, and Braimoh focuses on the prerequisites of sustainable irrigation. The authors explain the process of waterlogging and salt buildup and factors that accentuate the problems. Case studies on how irrigation problems manifest in different parts of the world were also reviewed. The case studies generally indicate the importance of early warning systems to detect the onset of problems in irrigated agriculture. The prospects of climate change further calls for adroit management of irrigation as well as proactive environmental policies. The continuous diminution of good-quality water for irrigation calls for stepping up research to produce crop varieties that require less water and nutrients and have increased salt tolerance. There is also the need to develop economic incentives that encourage water conservation.

The impact of globalization on nutrient and water flows is the focus of Chapter 7 written by Grote, Craswell, and Vlek. The differences between the nutrient and water balance in nutrient- and water-deficit and surplus countries largely reflect the large disparities in resources and agricultural policies between less developed and industrialized countries, respectively. The international net flows of nitrogen, phosphorus, potassium (NPK) nutrients amounts to about 5 Tg (1 Tg = $10^{12}$ g) in 1997 and are projected to increase to about 9 Tg in 2020. This represents a major human-induced perturbation of global nutrient cycles. The major net importers of NPK and virtual water in traded agricultural commodities are West Asia/North Africa and sub-Saharan Africa. Countries with a net loss of NPK and virtual water in agricultural commodities are the major food exporting countries—the USA, Australia, Canada, and Latin America. Agricultural trade liberalization and the reduction of subsidies could reduce excessive nutrient and water use in nutrient- and water-surplus countries and possibly make inputs more affordable to farmers in nutrient- and water-deficient countries. Institutional strengthening and infrastructure development are also required in nutrient- and water-deficient countries. Grote, Craswell, and Vlek also advocate factoring environmental costs into nutrient and water management.

Despite the fact that sub-Saharan Africa is a major net importer of nutrients, the problem of soil-nutrient depletion still persists in the region. Soil-nutrient depletion is one of the major causes of food crises in sub-Saharan Africa. Opinions are however diverse as to the causes of the depletion in the world's most ancient landmass. In Chapter 8, Breman, Fofana, and Mando write on strategies for ameliorating nutrient deficiencies in soils of sub-Saharan Africa. They state that farmers in sub-Saharan Africa deplete soils primarily because the soils are poor by nature. The extremely poor resource base, unfavorable value–cost ratio, and inadequate socioeconomic and policy environments caused the green revolution to bypass Africa. Breman, Fofana, and Mando further explain how the redistribution of organic matter and the nutrients it contains can help in transitioning agriculture in sub-Saharan Africa from extensive to intensive phase.

The concept of soil quality experienced the most rapid adoption in the 1990s as a consequence of the effects of land use on the dynamic aspects of soil quality indicators (Karlen, 2004). Soil quality is a notion that is much broader, but includes the capacity of the soil to supply nutrients, maintain suitable biotic habitat, and resist degradation. Soil quality is the key to agricultural productivity; especially in low-input production systems where productivity-enhancing technologies are largely out of reach of the farmers. Soil quality is not often considered a policy objective by policymakers unless soil degradation threatens other development objectives (Scherr, 1999). The decline in long-term productivity currently constitutes a threat to livelihood in many developing countries, necessitating the development of indicators for soil quality management. Methods to assess soil quality are discussed by de la Rosa and Sobral in Chapter 9. Acknowledging that the task of assessing soil quality is complicated, the authors nonetheless argue for an approach based on knowledge derived from agroecological land evaluation. They also make a case for the incorporation of spatial information technology in soil quality prediction. General trends in soil quality management strategies that can be adapted to different farming situations are discussed.

Urban sprawl is a ubiquitous phenomenon in developed and developing countries. Globally, urban land-use activities potentially remove about 7% (2.4 million $km^2$) of all cultivated systems from agricultural production, of which a proportion is high-quality farmland (McGranahan et al., 2005). As the world continues to urbanize, we have lost contact with soils and the services they provide to sustain life. In Chapter 10, Marcotullio, Braimoh, and Onishi provide a review of the multiscale impact of cities and urban processes on soils. Though urbanization is not accompanied by economic growth in developing countries, soil pollutant contamination in their cities continues to increase to levels warranting immediate action. The authors argue for a global assessment of urban soils to identify the patterns and processes of anthropogenic impacts. This should help in developing appropriate intervention measures.

**Acknowledgments** Most of the chapters in this book were presented at the LUCC's[1] Technical Session "Impact of Land-use Change on Soil Resources" at the 6th International Human Dimensions Program on Global Environmental Change (IHDP) Open Meeting in Bonn from 6 to 9 October 2005. We are grateful for the financial assistance provided by the IHDP, the United Nations University Institute of Advanced Studies, and the Japan Ministry of Science and Technology (MEXT) through the Special Funds for Promoting Science and Technology. We thank all authors for their thoughtful contributions, despite their busy schedules. We also thank Chris Barrow, Donald Davidson, Xixi Lu, Anita Veihe, Willy Verheye and Barbara Wick for their constructive reviews.

[1] Land Use and Land Cover Change (LUCC) was a joint project of the IHDP and IGBP. LUCC and Global Change and Terrestrial Ecosystems (GCTE) have been succeeded by the Global Land Project (www.globallandproject.org).

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# Chapter 2
# Soil Organic Carbon Dynamics and Land-Use Change

**Pete Smith**

**Abstract** Soils contain more than twice the amount of carbon found in the atmosphere. Historically, soils have lost 40–90 Pg C globally through cultivation and disturbance. Current rates of carbon loss due to land-use change are about 1.6 ± 0.8 Pg C $y^{-1}$, mainly in the tropics. The most effective mechanism for soil carbon management would be to halt land-use conversion, but with a growing population in the developing world, and changing diets, more land is likely to be required for agriculture.

Maximizing the productivity of existing agricultural land and applying best management practices to that land would slow the loss of, or is some cases restore, soil carbon. However, there are many barriers to implementing best management practices, the most significant of which in developing countries are driven by poverty and in some areas exacerbated by a growing population. Management practices that also improve food security and profitability are most likely to be adopted. Soil carbon management needs to be considered within a broader framework of sustainable development. Policies to encourage fair trade, reduced subsidies for agriculture in developed countries, and less onerous interest on loans and foreign debt would encourage sustainable development, which in turn would encourage the adoption of successful soil carbon management in developing countries.

**Keywords** Soil organic carbon (SOC), land-use change, sequestration, barriers, sustainable development, climate mitigation

## 2.1 Introduction

### *2.1.1 Soils and the Global Carbon Cycle*

Globally, soils contain about 1,500 Pg (1 Pg = 1 Gt = $10^{15}$ g) of organic carbon (Batjes, 1996), about three times the amount of carbon in vegetation and twice the amount in the atmosphere (IPCC, 2000a).

A.K. Braimoh and P.L.G. Vlek (eds.), *Land Use and Soil Resources*.