1 Land-use Change Impacts on Soil Processes in Tropical and Savannah Ecosystems: An Introduction

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1.1 Introduction

> For most of history, few things have mattered more to human communities than their relations with soil.
> (McNeill and Winiwarter, 2004, p. 1627)

Soils are the thinnest, outermost layer of the Earth's land surface: a complex, heterogeneous combination of weathered parent material, living and dead organic matter, water and gases upon which humans are wholly dependent. Soils take thousands of years to fully develop; yet poor management can lead to rapid and ultimately detrimental changes in their physical, chemical and biological characteristics. The disparity between the time taken to form and the speed with which soils can degrade means they are inherently fragile and thus require prudent management. There is, however, widespread evidence to suggest that careful and sustainable soil management is not the norm, and that the global soil resource is being depleted, threatening the numerous ecosystem services they provide (Banwart, 2011; Richter *et al.*, 2011; UNCCD, 2012; Koch *et al.*, 2013). In compiling and editing this book we have brought together a collection of case studies from around the globe that illustrate the impact of a range of land-use changes on the physical, chemical and biological characteristics of soils and provide a snapshot of the challenges we face in ensuring sustainable soil management in tropical and savannah environments.

1.2 The Importance of Soil to Human Well-being

There are numerous ways in which soils support human well-being.

First, the sustained fertility of soil is essential for food, fibre, animal feed, timber and, increasingly, biofuel production. With the world's population projected to increase to 9 billion people by 2050, the sustainable and efficient use of soils will be central to global food security (Stocking, 2003; Godfray *et al.*, 2010) and the diversification of energy sources through biomass production (Tilman *et al.*, 2009). The demands we place on soils are likely to increase in the future, thus ensuring soils are managed sustainably and are not degraded further will become ever more important.

Second, soils are integral to the water cycle (Falkenmark and Rockström, 1996), making clean water available to humans and helping to regulate stream and river flows. Degraded and

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polluted soils within a catchment will typically result in degraded and polluted stream water. Eroded and compacted soils are more likely to lead to overland flow generation, leading to *in situ* reductions in soil moisture and greater instances of crop drought as well as increased problems linked to flooding and sediment deposition. Effective management of soils therefore underlies effective catchment management.

Third, the organic carbon (C) stored in soils is estimated to be around 1500 Pg to a depth of 1 m globally (Post *et al.*, 1982; Eswaran *et al.*, 1993; Batjes, 1996) (a Petagram is equivalent to 10^{15} g or 1 billion tonnes). This is twice the mass of C in the atmosphere as CO_2 and three times the C in aboveground vegetation. Soil respiration (the flux of plant- and microbially generated CO_2 from soils to the atmosphere) is the second largest terrestrial C flux (Bond-Lamberty and Thomson, 2010). Land-use changes, particularly forest clearance and grazing intensification can significantly increase soil respiration C fluxes markedly with likely positive feedback to future climate warming (Grace *et al.*, 2006; Thomas, 2012). There is, however, great potential for increasing the soil C stock through adoption of land management practices that increase soil organic matter (SOM) content, the win–win scenario of increased C storage and soil fertility advocated by Lal (2004) and others. Careful consideration is, however, needed to account for the complete C balance to ensure that well-meaning land management interventions do not lead to unintentional consequences for the fluxes of other greenhouse gases (Powlson *et al.*, 2011). A clearer understanding, and quantification, of the amount of C stored in soils under different land uses is therefore essential for an improved understanding of the global C cycle and how this will be altered in the near future by human activities.

Finally, soils are host to an enormous reservoir of microbial biodiversity; thousands of species can be found in just a gram of soil, most of which we know very little about and which are overlooked by many scientists. However, understanding the diversity and functioning of soil microbial communities (archaea, bacteria and fungi in particular) is of major importance due to their key roles in regulating the biogeochemical cycles of C, nitrogen and other elements (Falkowski *et al.*, 2008; Singh *et al.*, 2010). In addition, the potential for utilizing microorganisms in the search for the next generation of antibiotics and other pharmaceuticals is only just being realized as limitations associated with the inability to culture most microbes are being overcome through rapid advances in molecular techniques (Daniel, 2004; Singh and Macdonald, 2010; Lewis, 2012).

In order to manage soils sustainably and to ensure we continue to benefit from the essential range of ecosystem services they provide, we need a much better understanding and awareness of when and how changes in soil characteristics become long-term degradation. A particular challenge is to predict the soil response to land-use changes that may be non-linear or characterized by thresholds (Nikolaidis, 2011). This is a priority in tropical and savannah environments with high population densities because: (i) soils typically contain highly weathered clay minerals with limited capacity to form complexes with organic matter (Feller and Beare, 1997; Zech *et al.*, 1997; Rasche and Cadisch, 2013); (ii) persistently high soil temperatures and moisture facilitate rapid oxidation of SOM (Joergensen, 2010; Hayakawa *et al.*, 2014); and (iii) high rainfall intensities equate to high potential energy and erosion potential as loss of vegetation cover and aggregate stability can result in very large increases in soil erosion through overland flow and landslides (Lal, 1990; Sidle *et al.*, 2006).

A loss of soil 'quality' often leads to reduced yields and accelerated erosion. In some cases, particularly in drier areas affected by dust storms, this can have immediate and adverse impacts on human health (Griffin *et al.*, 2001). For example, cases of valley fever, or *Coccidioidomycosis*, in the human population are prevalent in agricultural areas experiencing wind erosion. Cases of valley fever have increased in the south-west USA over the last decade (Centers for Disease Control and Prevention, 2013) and may be associated with a deterioration of soils and an increase in dust storm events.

It is encouraging to see that there is an increasing number of international and national organizations, policies, agreements and initiatives to protect and raise awareness of our soil resource. Examples include the International Soil Reference and Information Centre (ISRIC), the United Nations Convention to Combat Desertification (UNCCD), the Food and Agriculture Organization of the United Nations (UN-FAO) Global Soil Partnership and World Soils Week among others. Although 2015 is the International Year of Soils, it is dispiriting to report that the European Union

(EU) Soil Framework Directive has recently been withdrawn, despite the estimated annual cost of soil degradation across the EU of €38 billion per year (European Commission, 2006, in Hartemink and McBratney, 2008). There are clearly still many challenges ahead.

1.3 Land-use Change and Soil Properties

Changing land use, particularly the removal of forest cover for agriculture and the intensification of grazing, has a major and widespread impact on soils (Ellis and Ramankutty, 2008; Don *et al*., 2011). Over half of the world's soils are now cultivated, grazed, subject to logging disturbance or have been built upon (Richter, 2007; Ellis, 2011). This has resulted in major changes to soil properties as well as the soil-related resources available to us (Yaalon, 2007). The major land-use changes affecting soils in the tropics are complex and numerous and it is misleading to generalize too much; however, the following are all notable drivers of change in various parts of the tropics.

The expansion of agriculture into areas of native vegetation across tropical regions is widespread (Gibbs *et al*., 2010). Agricultural expansion may be small scale (agroforestry or swidden agriculture) but large-scale expansion of monoculture crops is likely to have a more pervasive effect on soil processes and functions due to the much larger disturbance to the soil through ploughing and addition of nutrients and other chemicals. Conversion to agriculture is arguably the most prevalent land-use transition in tropical regions leading to a number of alterations to soil including: (i) loss of SOM and C; (ii) periodic but rapid additions of fertilizers and pesticides; (iii) changes to soil hydrology, both directly through irrigation and indirectly through changes to evapotranspiration rates; and (iv) impacts upon soil organisms that will feed back to influence soil properties and functioning.

In sub-tropical and dry sub-humid savannahs, pastoralism is the dominant agricultural land use. In many areas, a reduction in the area of communal grazing land available to those without land tenure due to privatization is leading to increased animal stocking densities (Thomas, 2012). This leads to changes in the natural vegetation cover, particularly in the balance between trees, shrubs and grasses that, in turn, affects the fire return period (Grace *et al*., 2006; Eldridge *et al*., 2011). Soils are affected indirectly by all these changes, but they are also affected directly by the trampling action of livestock (Thomas, 2012).

The number of people living in urban areas is now more than that in rural areas, with the rate of increase being most rapid in tropical countries (Seto *et al*., 2011). This is important as urbanization has an obvious and dramatic effect on soils (Marcotullio *et al*., 2008), although it has received far less attention when compared to the role that agriculture and forestry can have on soils and soil productivity. Renewed interest in urban agriculture in tropical countries (Hamilton *et al*., 2013; Orsini *et al*., 2013) has increased the importance of improving our understanding of soils in urban environments and the potential for urban-based agriculture to address food needs. With this, however, comes a new set of sustainability related challenges such as urban planning policy, the utilization of waste products for fertilizers and the potential for soil contamination. This is a particularly important research area for contemporary soil science.

Soils are also commonly affected by chemical and biological contaminants from a variety of sources, including organic manures (van der Perk, 2013). These are a threat to soil productivity and health, particularly as pollutants may be subsequently ingested if food grown on contaminated land is consumed. Deep weathering of soils, typical of much of the tropics, can often exacerbate heavy metal additions through mining and cause widespread pollution. For example, mercury is used in gold mining to form a mercury–gold amalgam and help in the recovery of gold. Many areas of the tropics have land used for artisanal small-scale gold mining that releases around 1000 t of mercury a year to the environment (Telmer and Veiga, 2009) where it leads to pollution of watercourses, soils, sediments and higher trophic levels.

Changes to soil properties and processes are not necessarily wholly undesirable, and a certain amount of change should be viewed as an unavoidable consequence of utilizing soils for the wider human good. Indeed, there are examples of soil properties improving as a consequence of land-use changes, such as the *terra preta do índio* (or Amazonian dark earths) created by pre-Colombian inhabitants of South America prior to the arrival of Europeans (Glaser *et al.*, 2001; Marris, 2006). These are some of the most fertile tropical soils and the conditions that led to their creation are still being elucidated; indeed, much of the focus on biochar (e.g. Sohi *et al.*, 2010) in current research stems from the discovery of the inclusion of charred remains in *terra preta* soil. On the Indonesian island of Java, there has been an island-wide increase in soil C since the 1970s following a prior decline from the 1930s onwards (Minasny *et al.*, 2011). This has been attributed to increased application of crop residues and animal manure to improve soil fertility following government intervention. Other examples of restoration of soil processes following disturbance include the re-growth of plantations on old pastures or recovery of secondary forests on old shifting cultivation sites that can both lead to recovery of SOM and a subsequent increase in soil fertility (e.g. Don *et al.*, 2011). In addition, a number of agricultural management practices such as reduction of tillage, the use of cover crops and the use of organic amendments can all induce C storage in soils (Lal, 2004).

1.4 Themes and Scope of this Book

This book is not a comprehensive account of all the drivers of soil change in the tropics, nor does it cover all areas of the tropics. It does, however, take a broad view of the tropics, with the inclusion of studies from South Africa and the dry sub-humid tropics of the Kalahari as well as the humid tropics. Tropics are drawn from a wide geographical area including South and Central America, South-east Asia, India and Africa, and the chapters have been contributed by authors from all of these areas as well as Europe, North America, Australasia and Japan. It thus provides a snapshot of a range of factors affecting soils across the globe. From this, we shed light on emerging topics that can be can be grouped into the following themes.

1.4.1 The effects of land-use change on soil microbial populations

Advances in molecular and biochemical techniques now mean that the enumeration of soil microbial biomass, diversity and functionality is much more straightforward than it was even a few years ago. This has allowed the extent to which clearing natural vegetation for crops alters the soil microbial populations and the functions they perform to be elucidated from many sites. Studies from the Andaman Islands of India (Dinesh *et al.*, Chapter 2), Malaysia (D'Angelo *et al.*, Chapter 3; Brearley, Chapter 4) and the Amazon (Mendes *et al.*, Chapter 5) all report consistent findings on the impact of the clearance of natural vegetation cover for agriculture. Between them, the studies show a reduction in SOM, microbial biomass or activity and changes to microbial community composition. These changes then have clear knock-on effects on other key soil processes and functions such as nitrogen cycling, moisture retention, erodibility and acidification (Fujii *et al.*, Chapter 6). The message is clear that in nearly all circumstances, clearance of natural vegetation for agriculture will lead to detrimental changes to soil properties.

1.4.2 Urban soils, agriculture and soil contamination

Two chapters report on the neglected topic of urban soils and agriculture in Kenya, South Africa, Zimbabwe (Chipungu *et al.*, Chapter 7) and Malawi (Mkwambisi *et al.*, Chapter 8). Together, both studies show that, irrespective of the country or city, there are similar challenges and opportunities to improving access to land for crops in urban areas. In nearly all cases, soils are on marginal land and farming is undertaken on an informal basis without the permission of local authorities. Although the utilization of waste from a variety of sources can help improve soil fertility, urban farmers regularly run the risk of soil contamination. The theme of contamination is also explored by Grimaldi *et al.* (Chapter 9), who demonstrate the clear impact gold mining in French Guiana can have on mercury stocks and fluxes in soils.

1.4.3 Land-use effects on soil carbon and soil organic matter

The preservation of SOM is integral to many soil conservation strategies as well as to global efforts to increase terrestrial C sequestration. Studies from a broad range of environments demonstrate how land-use change affects soil C stocks and the rate at which organic C is respired. Corre *et al*. (Chapter 10) show how soil C is unevenly distributed around catchments in Ecuador and how land-use changes can lead to large losses of C through erosional processes. Following on, Thomas *et al*. (Chapter 11) reveal how sensitive the C stock in the Kalahari is to grazing intensity, while Ng Cheong and Umrit (Chapter 12) show how clearance of natural vegetation in Mauritius leads to a loss of the original soil organic C and replacement with that derived from sugar cane cropping. In contrast, Powers *et al*. (Chapter 13) show how soil C stocks can be restored during the process of secondary succession in dry tropical forests of Costa Rica, but Schwendenman and Kaiser (Chapter 14) demonstrate that afforestation with teak may not lead to an increase in soil C stocks in Panama, at least over the timeframe of their study.

In the concluding chapter, we briefly summarize key points from the book, bring together a number of the chapter authors to consider areas that are in need of further research and then conclude with suggestions for a sustainable way forward. This is clearly important given the essential role played by soils in maintaining human civilizations (Hillel, 1992; McNeill and Winiwarter, 2004; Montgomery, 2007) and understanding, balancing and mitigating potential conflicts between the multiple demands placed on soils by humans is paramount to the sustainable utilization of this key resource now and into the future.

References

Banwart, S. (2011) Save our soils. *Nature* 474, 151–152.

Batjes, N.H. (1996) Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science* 47, 151–163.

Bond-Lamberty, B. and Thomson, A. (2010) Temperature-associated increases in the global soil respiration record. *Nature* 464, 579–582.

Centers for Disease Control and Prevention (2013) Increase in reported Coccidioidomycosis – United States, 1998–2011. *Morbidity and Mortality Weekly Report (MMWR)* 62, 217–221.

Daniel, R. (2004) The soil metagenome – a rich resource for the diversity of novel natural products. *Current Opinion in Biotechnology* 15, 199–204.

Don, A., Schumacher, J. and Freibauer, A. (2011) Impact of tropical land-use change on soil organic carbon stocks – a meta-analysis. *Global Change Biology* 17, 1658–1670.

Eldridge, D.J., Bowker, M.A., Maestre, F.T., Roger, E., Reynolds, J.F. and Whitford, W.G. (2011) Impacts of shrub encroachment on ecosystem structure and functioning: Towards a global synthesis. *Ecology Letters* 14, 709–722.

Ellis, E.C. (2011) Anthropogenic transformation of the terrestrial biosphere. *Philosophical Transactions of the Royal Society Series A – Mathematical, Physical and Engineering Sciences* 369, 1010–1035.

Ellis, E.C. and Ramankutty, N. (2008) Putting people in the map: Anthropogenic biomes of the world. *Frontiers in Ecology and the Environment* 6, 439–447.

Eswaran, H., Van Den Berg, E. and Reich, P. (1993) Organic carbon in soils of the world. *Soil Science Society of America Journal* 57, 192–194.

Falkenmark, M. and Rockström, J. (1996) The new blue and green water paradigm: Breaking new ground for water resource planning and management. *Journal of Water Resources Planning and Management* 132, 129–132.

Falkowski, P.G., Fenchel, T. and Delong, E.F. (2008) The microbial engines that drive Earth's biogeochemical cycles. *Science* 320, 1034–1039.

Feller, C. and Beare, M.H. (1997) Physical control of soil organic matter dynamics in the tropics. *Geoderma* 79, 69–116.

Gibbs, H.K., Ruesch, A.S., Achard, F., Clayton, M.K., Holmgren, P., Ramankutty, N. and Foley, J.A. (2010) Tropical forests were the primary source of new agricultural land in the 1980s and 1990s. *Proceedings of the National Academy of Sciences of the USA* 107, 16732–16737.

Glaser, B., Haumaier, L., Guggenberger, G. and Zech, W. (2001) The 'Terra Preta' phenomenon: A model for sustainable agriculture in the humid tropics. *Naturwissenschaften* 88, 37–41.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M. and Toulmin, C. (2010) Food security: The challenge of feeding 9 billion people. *Science* 327, 812–818.

Grace, J., San José, J.J., Meir, P., Miranda, H.S. and Montes, R.A. (2006) Productivity and carbon fluxes of tropical savannas. *Journal of Biogeography* 33, 387–400.
Griffin, D.W., Kellog, C.A. and Shinn. E.A. (2001) Dust in the wind: Long range transport of dust in the atmosphere and its implications for global public and ecosystem health. *Global Change and Human Health* 2, 20–33.
Hamilton, A.J., Burry, K., Mok, H.-F., Barker, S.F., Grove, J.R. and Williamson, V.G. (2014) Give peas a chance? Urban agriculture in developing countries. A review. *Agronomy for Sustainable Development* 34, 45–73.
Hartemink, A.E. and McBratney, A.B. (2008) A soil science renaissance. *Geoderma* 148, 123–129.
Hayakawa, C., Funakawa, S., Fujii, K., Kadono, A. and Kosaki, T. (2014) Effects of climatic and soil properties on cellulose decomposition rates in temperate and tropical forests. *Biology and Fertility of* Soils 50, 633–643.
Hillel, D. (1992) *Out of the Earth*. Aurum Press, London.
Joergensen, R.G. (2010) Organic matter and micro-organisms in tropical soils. In: Dion, P. (ed.) *Soil Biology and Agriculture in the Tropics, Soil Biology* 21, Springer-Verlag, Berlin, pp. 17–44.
Koch, A., McBratney, A.B., Adams, M., Field, D., Hill, R., Lal, R. *et al*. (2013) Soil security: Solving the global soil crisis. *Global Policy Journal* 4, 434–441.
Lal, R. (1990) *Soil Erosion in the Tropics: Principles and Management*. McGraw-Hill, New York.
Lal, R. (2004) Soil carbon sequestration impacts on global climate change and food security. *Science* 304, 1623–1627.
Lewis, K. (2012) Recover the lost art of drug discovery. *Nature* 485, 439–440.
McNeill, J.R. and Winiwarter, V. (2004) Breaking the sod: Humankind, history, and soil. *Science* 304, 1627–1629.
Marcotullio, P.J., Braimoh, A.K. and Onishi, T. (2008) The impact of urbanization on soils. In: Braimoh, A.K. and Vlek, P.L.G. (eds) *Land Use and Soil Resources*. Springer-Verlag, Heidelberg, Germany, pp. 201–250.
Marris, E. (2006) Black is the new green. *Nature* 442, 624–626.
Minasny, B., Sulaeman, Y. and McBratney, A.B. (2011) Is soil carbon disappearing? The dynamics of soil carbon in Java. *Global Change Biology* 17, 1917–1924.
Montgomery, D.R. (2007) *Dirt: The Erosion of Civilizations*. University of California Press, Berkeley, California.
Nikolaidis, N.P. (2011) Human impacts on soils: Tipping points and knowledge gaps. *Applied Geochemistry* 26, S230–S233.
Orsini, F., Kahane, R., Nono-Womdim, R. and Gianquinto, G. (2013) Urban agriculture in the developing world: A review. *Agronomy for Sustainable Development* 33, 695–720.
Post, W.M., Emanuel, W.R., Zinke, P.J. and Stangenberger, A.G. (1982) Soil carbon pools and world life zones. *Nature* 298, 156–159.
Powlson, D.S., Whitmore, A.P. and Goulding, K.W.T. (2011) Soil carbon sequestration to mitigate climate change: A critical re-examination to identify the true and the false. *European Journal of Soil Science* 62, 42–55.
Rasche, F. and Cadisch, G. (2013) The molecular microbial perspective of organic matter turnover and nutrient cycling in tropical agroecosystems – What do we know? *Biology and Fertility of Soils* 49, 251–262.
Richter, D. deB. (2007) Humanity's transformation of Earth's soil: Pedology's new frontier. *Soil Science* 172, 957–967.
Richter, D. deB., Bacon, A.R., Mobley, M.L., Richardson, C.J., Andrews, S.S., West, L. *et al*. (2011) Human-soil relations are changing rapidly: Proposals from SSSA's cross-divisional soil change working group. *Soil Science Society of America Journal* 75, 2079–2084.
Seto, K.C., Güneralp, B. and Hutyra, L.R. (2012) Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences of the USA* 109, 16083–16088.
Sidle, R.C., Ziegler, A.D., Negishi, J.N., Nik, A.R., Siew, R. and Turkelboom, F. (2006) Erosion processes in steep terrain – truths, myths, and uncertainties related to forest management in Southeast Asia. *Forest Ecology and Management* 224, 199–225.
Singh, B.K. and Macdonald, C.A. (2010) Drug discovery from uncultivable microorganisms. *Drug Discovery Today* 15, 792–799.
Singh, B.K., Bardgett, R.D., Smith, P. and Reay, D. (2010) Microorganisms and climate change: Feedbacks and mitigation options. *Nature Reviews Microbiology* 8, 779–790.
Sohi, S.P., Krull, E., Lopez-Capel, E. and Bol, R. (2010) A review of biochar and its use and function in soil. *Advances in Agronomy* 105, 47–82.
Stocking, M.A. (2003) Tropical soils and food security: The next 50 years. *Science* 302, 1356–1359.
Telmer, K. and Veiga, M.M. (2009) World emissions of mercury from artisanal and small scale gold mining. In: Pirrone, N. and Mason, R. (eds) *Mercury Fate and Transport in the Global Atmosphere Emissions, Measurements and Models*. Springer-Verlag, Heidelberg, Germany, pp. 131–172.
Thomas, A.D. (2012) Impact of grazing intensity on seasonal variations of soil organic carbon and soil CO_2 efflux in two semi-arid grasslands in southern Botswana. *Philosophical Transactions of the Royal Society Series B – Biological Sciences B* 367, 3076–3086.

Tilman, D., Socolow, R., Foley, J.A., Hill, J., Larson, E., Lynd, L. *et al.* (2009) Beneficial biofuels – the food, energy, and environment trilemma. *Science* 325, 270–271.

United Nations Convention to Combat Desertification (UNCCD) (2012) *Zero Net Land Degradation*, UNCCD Secretariat Policy Brief. Bonn, Germany.

Van der Perk, M. (2013) *Soil and Water Contamination* (2nd edition). CRC Press, Boca Raton, Florida.

Yaalon, D.H. (2007) Human-induced ecosystem and landscape processes always involve soil change. *BioScience* 57, 918–919.

Zech, W., Senesi, N., Guggenberger, G., Kaiser, K., Lehmann, J., Miano, et al. (1997) Factors controlling humification and mineralization of soil organic matter in the tropics. *Geoderma* 79, 117–161.