Sustainable Land Management for Environmental Benefits and Food Security

A synthesis report for the GEF

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Preface

This paper brings together the latest knowledge about sustainable land management and its potential to deliver global environmental benefits and improved livelihoods. It will strengthen the scientific and technical understanding of sustainable land management and its contributions to environmental objectives, both global and local. The GEF's Scientific and Technical Advisory Panel (STAP) commissioned the study to support targeted efforts in the management of land degradation and to raise awareness of this vital issue, as the GEF considers its focus for the next phase (GEF7: 2018-2022).

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Cover photo: Green terrace rice paddy at Mu Cang Chai, country. Source: Draftangle.

Important note

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Executive summary

Around 54% of the Earth's land surface area, 2 billion hectares (ha), is degraded to some degree (UN FAO 2011). On the African continent alone, degradation is estimated to affect 124 million ha. Soils are becoming less productive due to salinization, waterlogging, pollution, acidification, mineral and nutrient depletion. Malnutrition affects 815m people, and world food production must double over the coming half century to meet the needs of 9-10 billion people. The sustainable management of the global land resource is an issue at the very heart of the human future and that of all life on Earth.

The aim of Sustainable Land Management (SLM) is to maintain land resources and their associated ecosystem functions while, at the same time, sustaining production of goods and services, especially safe and healthy food. Well-structured and resourced SLM programs have the potential to provide global environmental benefits by combating land degradation and by arresting and reversing the decline in biodiversity and land-based ecosystem services. Effective and widespread adoption of SLM will also deliver large social and economic benefits through productivity gains and the enhanced resilience of agroecosystems. These are essential to address two of the greatest challenges facing the world today – food security and climate change.

This report synthesises current scientific knowledge about SLM and its contribution to combating land degradation, enhancing food security and addressing climate change adaptation and mitigation. It presents principles for SLM, guidance for identifying suitable SLM practices, and a framework for prioritising SLM interventions, including a strategy for selecting indicators appropriate to the context, for monitoring outcomes of SLM investments. The report is intended to inform design and implementation of SLM programs, including supporting planning for land degradation neutrality (LDN), Target 15.3 in the Sustainable Development Goals.

Forms of land degradation include nutrient decline, wind and water erosion, loss of soil biodiversity, soil sealing (due to expanding industrial and urban uses), contamination, salinization, compaction and acidification. Impacts extend beyond soil health to processes such as pollution of aquifers and freshwater resources, water depletion, deforestation and biodiversity loss. Understanding these processes and their impacts on ecosystem services informs development of good practices for SLM, and identification of indicators for monitoring SLM, targeted to local or regional circumstances.

SLM practices aim to:

- maintain or improve soil health and the productivity of the land resource base
- sustain ecosystem functions
- utilise and complement natural processes for nutrient management, pest management
- minimise greenhouse gas emissions
- minimise emissions of pollutants to air, water and soil
- enhance biodiversity on-site, including agro-diversity, and off-site
- use resources (nutrients, water, fuel, land, labour) efficiently
- avoid excessive use of pesticides.

Good practice for SLM is derived from these broad objectives, interpreted in the local context, with edaphic, climatic, cultural and social and economic characteristics taken into account. Examples of applicable SLM strategies include: (1) cover crops, stubble retention and organic amendments to build soil organic matter and increase soil moisture and nutrient storage and improve soil structure; (2) integrated soil fertility management using locally-appropriate combinations of organic and inorganic sources of nutrients; (3) better crop selection targeting locally-adapted varieties combined with creation of favourable growing conditions at the micro-climatic level; (4) contour planting to promote infiltration and minimise run-off and erosion; and (5) reduced tillage to manage surface crusting and soil compaction, creating better seedbed conditions and enhancing root depth. These SLM practices reduce the risk of land degradation, and can contribute to rehabilitation or restoration of degraded areas, and thus to the achievement of land degradation neutrality.

SLM can deliver multiple environmental and sustainable development benefits. Benefits are enhanced by attention to management of competing objectives at the landscape or catchment scale, sustaining livelihoods, especially for vulnerable communities, involving land users and other stakeholders to apply local knowledge and applying adaptive management.

Sustainable intensification of agriculture – in which yields are increased without adverse environmental impact and without the cultivation of more land – will contribute to food security by addressing the “yield gap” (the difference between actual yield and maximum attainable yield). Importantly, sustainable intensification does not imply uniform practices across agroecosystems; it should be applied within an integrated land management strategy that prioritises land use according to capability, and includes “land sparing” for conservation of high-value ecosystems. Closing the yield gap can occur, in part, by rehabilitating degraded areas to increase productive capacity. Furthermore, SLM practices, which focus on enhancing soil health, will simultaneously enhance nutritive value of food. Improved yields and crop diversity for smallholder farmers provide the basis for greater self-sufficiency in local food production.

Better understanding of the drivers of land degradation and the barriers to adoption of particular SLM practices will support efforts to develop good practice for the highly diverse agroecosystems of the world. Adoption will be enhanced by education and extension programs that demonstrate application, provide training, and take into account relevant socioeconomic constraints. For example, barriers for smallholders may include lack of capital, lack of knowledge or confidence to make a change, and lack of sufficient labour to implement a change. Hence, SLM practices need to be developed in collaboration with land users, using local knowledge of the environmental, economic and social conditions to minimise resistance to their adoption or reversion to previous practices once incentives are removed.

Clearly defined, biophysical and socioeconomic indicators, and suitable metrics to quantify them, are required to assess effectiveness of SLM interventions, and to identify opportunities for the expansion of SLM practices into new areas. Due to the diversity of processes, symptoms and drivers, and their interactions, no specific set of indicators and metrics is universally applicable; indictors should be chosen to reflect the key variables in each situation. This report provides guidance for monitoring SLM across diverse conditions. We present a strategy for identifying suitable indictors and metrics appropriate to the relevant scale and priorities. This guidance could be used as a basis for the evaluation of investment in SLM.

Monitoring the effectiveness of programs for the adoption of SLM is challenging because SLM may deliver benefits slowly, over several decades, particularly where programs target the recovery of degraded lands. Process indicators can be used to monitor levels of activity, and are particularly important where measurable outcomes are slow to appear.

Summary and recommendations

Sustainable land management is critical to the global response to climate change, land degradation and threats to biodiversity, food security and the ecosystem services vital to human and planetary well-being. The global environmental benefits from SLM include:

- improved provision of agroecosystem and forest ecosystem services, including food and fibre production
- climate change mitigation through reduced greenhouse gas emissions and increased carbon sequestration in landscapes managed for production
- increased resilience of agroecosystems and forest ecosystems to climate change and other anthropogenic and natural stressors
- conservation of, and sustainable use of, biodiversity in natural and production landscapes
- reduced pollution of the aquatic environment and enhanced buffering of flood damage
- reduced rates of extinction and depletion of animal and plant life.

The following strategy is recommended for prioritizing SLM investment:

1. *Encourage early Intervention:* Early adoption of SLM practices can prevent or arrest land degradation at least cost. Addressing land degradation effectively demands immediate action based on existing knowledge, and a willingness to trial and improve "best-bet" systems using adaptive management. Apply the LDN response hierarchy of Avoid > Reduce > Reverse land degradation, in prioritising SLM interventions.
2. *Utilise land potential assessment:* Land use planning and management decisions should seek to use land within its capability, according to its potential, to minimise risk of land degradation.
3. *Utilise Yield Gap Analysis*: Yield gap analysis can indicate the adequacy of current land management practices and the condition of the land. In planning interventions to reverse degradation, target investment towards areas where yield of crops and pasture are markedly below the yield potential. Closing the yield gap on existing managed lands can contribute to conserving natural landscapes for biodiversity and other ecosystem services, as well as meeting current and future food demands.
4. *Promote appropriate SLM practices*: promote SLM practices that 1) suit the local biophysical and socio-economic context; 2) are informed by expert and local knowledge, including field trials; 3) are applied in an integrated landscape management approach, targeting suitable areas for sustainable intensification and others for "land sparing"; 4) enhance resilience of the land resource base and nutritive value of food produced.
5. *Implement enabling policy* to facilitate development, promotion and implementation of SLM practices, through codification. Relevant aspects include land tenure mechanisms, mechanisms to provide finance, market structures for inputs including fertilisers and seeds, market structures for outputs such as grain and animal products, infrastructure, technical support institutions including government and non-government organisations, energy policy, and environmental laws.
6. *Build capacity*: SLM requires commitment and investment in research, innovation, governance and implementation programs on a global scale. It also demands investment in capacity building at local level, to identify and develop and scale-up locally-applicable SLM practices.

7. *Apply suitable indicators to monitor effectiveness of SLM:* Scientifically-sound locally-relevant SLM indicators and metrics are required to measure baselines (benchmarking current condition) and monitor change. Indicators should be selected to reflect soil health and land condition, including identified site-specific constraints and land degradation risks, and to detect off-site impacts. A long-term commitment to monitoring is needed to detect slow recovery or slow decline in land condition.
8. *Apply adaptive management:* Modify SLM recommendations where new knowledge and learning from monitoring indicate adverse impacts or opportunities for enhanced outcomes.

Figure 1 Terraced slopes, Duoro Valley, Portugal. Photo: M. Hewes

1. Introduction

1.1. Context

Every year, the Earth loses more than 25-40 billion tonnes of topsoil, due mainly to human activity (FAO and ITPS, 2015). Scientists estimate that we have lost one third of our available soil since 1970 (Cameron *et al.* 2015). Around the world, fertile land is turning to desert at rates 30-35 times greater than in pre-industrial times (UN 2015). Around 54% of the Earth's land surface area, 2 billion hectares (ha), is degraded to some degree (UN FAO 2011). On the African continent alone, degradation is estimated to affect 124 million ha. Soils are becoming less productive due to salinization, waterlogging, pollution, acidification, mineral and nutrient depletion. Many of the approximately 815 million people who are chronically hungry today live in regions of sub-Saharan Africa and southern Asia subject to factors that increase the risk of land degradation: high climate variability, water scarcity, steep slopes and shallow, fragile and nutrient-poor soils. These issues are coupled with the perceived need to double world food production over the coming half century to meet the needs of 9-10 billion people. As around 95 per cent of the world food supply, the planet's terrestrial biodiversity, and the services provided by the environment to humanity, depend on the soil, the sustainable management of the global land resource base is an issue at the very heart of the human future and that of all life on Earth.

Pressure on the land resource is increasing at all scales from local to global due to human factors, notably: (1) growing demand for food in terms of both quantity (kilojoules of energy) and quality (proportion of animal protein in the diet) for an expanding and wealthier world population; (2) competition for productive land for biofuel, urban expansion and other non-food uses; (3) unsustainable land use practices that result in ongoing land degradation and which diminish soil health, indicated by lower nutrient status and organic content; (4) global agribusiness systems that drive down prices for farmers, pressuring them to farm intensively and unsustainably; and (5) the mounting impacts of anthropogenic climate change, which is projected to exacerbate variations in year-to-year yields and income from agriculture, threatening the resilience of agroecosystems and the stability of food production systems worldwide. Pressures also arise from natural factors such as natural climate variability, extreme weather events and wildfire; these add to the challenge of matching management practices to environmental conditions for optimal yields and for sustainable use of the land resource.

Land degradation may result from a range of natural and management pressures on land resources, and their interaction. In Australia, for example, rangeland degradation results from the coincidence of prolonged drought with high grazing pressure from both domestic stock and native animals. The ability to reduce stock numbers to match feed availability during drought may be affected by economic and logistical circumstances (e.g. labour and distances). Similarly, extended dry periods have been a factor in land degradation in sub-Saharan Africa. But, in this case, as in other developing countries, the direct impact on human populations suffering under-nutrition and with little or no capacity to rehabilitate land is often much greater. Thus, while the combination of human and natural pressures on land can limit land-holder capacity to implement good practices, land management, policy and socioeconomic constraints can also hinder the adoption of SLM practices.

Recognising the urgent need for effective policy response to land degradation, the UNCCD proposed the concept of Land Degradation Neutrality (LDN), which has now been adopted as Target 15.3 of the Sustainable Development Goals (SDGs). LDN is defined as "a state whereby the amount and quality of land resources necessary to support ecosystem functions and services and enhance food security remain stable or increase within specified temporal and spatial scales and ecosystems", and its goal is to maintain or enhance land-based natural capital, and its associated ecosystem services such as provision of food and regulation of water and climate, while enhancing the resilience of the communities that depend on the land. The Scientific Conceptual Framework for Land Degradation Neutrality (Orr et al, 2017; Cowie *et al.*, 2018) identifies that implementation of SLM is critical to achieving LDN.

Indeed, SLM is vital for achieving a range of SDGs. As noted by Smith *et al.* (2018) and Akhtar-Schuster *et al.* (2017), healthy land and soil are particularly relevant to:

- SGD 1, No Poverty, as a large proportion of impoverished populations in developing countries rely on productive land for their livelihoods;
- SDG 2, Zero Hunger, which depends on healthy soil to enable production of safe and nutritious food;
- SDG 13, Climate Action, in which soil carbon sequestration offers significant potential for climate change mitigation and makes ecosystems more resilient to future climate change; as well as
- SDG 15, Life on Land, that relies on land-based natural capital and the ecosystem services that flow from healthy land and soil.

The GEF recognises that a comprehensive landscape approach to SLM is needed to address the multi-faceted nature of land degradation across the wide range of agroecological and climatic zones in arid, semi-arid, sub-humid and humid areas of the world (GEF, 2014). The GEF's investments to combat land degradation focus on regions where agricultural and rangeland management practices underpin the livelihoods of poor rural farmers and pastoralists. The GEF prioritises projects for enhancing production of food crops and livestock through efficient use of land, soil, water and vegetation in agroecosystems. Thus, the GEF is well-placed to facilitate coordinated investment in SLM for global environmental benefits and to add significant value to national programs that pursue Land Degradation Neutrality and address food security and climate change challenges.

1.2. Objectives and scope of this study

This report examines sustainable land management (SLM) and its potential as an integrative strategy to address multiple environmental and sustainable development objectives. It highlights the linkages between SLM and soil health, land degradation, food security, climate change mitigation and adaptation.

It is intended to provide information and guidance on fostering SLM, to a wide range of stakeholders involved in agriculture, environmental management and sustainable development. It aims to support investment in SLM by the GEF, particularly investments in pursuit of Land Degradation Neutrality.

After providing definitions and context, this report:

- explores the anthropogenic and natural drivers of land degradation, and the potential environmental and socioeconomic benefits of SLM;
- examines the role of SLM in addressing the critical challenge of global food security
- describes the key processes of land degradation and their impacts, as the basis for developing good practice guidance on SLM that is scientifically sound and robust;
- proposes principles for SLM that promote soil health, productivity and ecosystem services;
- presents a framework for identifying SLM practices suited to the context and objectives;
- provides guidance on identifying indicators for evaluation of a site in terms of land potential and soil condition, and indicators for monitoring outcomes of SLM investments;
- discusses the barriers to adoption of good practice for SLM; and
- provides recommendations for developing and implementing SLM programs in ways that optimise global environmental benefits.

SLM is largely, though not exclusively, concerned with agricultural systems. Food and fibre production occupy more land than any other use, so are associated with the greatest land degradation in terms of area affected. However urban development and mining can also be responsible for severe land, water and ecosystem degradation. Effective SLM programs must therefore consider the biophysical, economic and social constraints for a whole region or community, for all land uses.

The large number of interacting biophysical and socioeconomic issues make the development of effective SLM programs highly complex. Climate change, resource scarcity and population growth contribute significantly to uncertainty over the potential effectiveness of system responses to SLM interventions. In reviewing these challenges, this paper draws on a wide range of published papers, program and project reports, and other information. However, SLM is an area of broad impact and continuing development, and it is not possible to comprehensively cover all aspects of the topic in equal detail.

Recommendations are provided to guide GEF investment in support of SLM, and planning of SLM programs. Users are encouraged to review and refine SLM plans as new data and experience in practical implementation of SLM interventions become available over time.

1.3. Sustainable land management – key terms and concepts

The terminology of SLM used in this paper aims to be consistent with the current international technical literature. However, many terms are defined and used differently by different groups, which reflects, in part, the way they have evolved and have been applied in various disciplines. Definitions of selected key terms relating to land and its management are provided in Box 1 to guide consistent interpretation of the paper. The intent is not to provide a comprehensive syntax of land management terms but, rather, to explain how those terms are used in this paper, so the reader can more readily understand SLM and the intent of SLM practices discussed here.

Historically, “land management” has been used narrowly to mean “soil management”. However, it has also referred more broadly to the management of ecosystem features, including soils, rocks and other solid geological features, rivers, vegetation, fauna and human infrastructure (FAO, 2007; Lal, 2010a; Koch *et al*., 2013). The evolution of approaches to land management, illustrated in

Figure 2, provides an understanding of the current position:

A. Early interest in environmental impacts stressed approaches based on land evaluation (FAO, 1976; Stocking and McCormack, 1986; McCormack, 1987) and land capability (Klingebiel and Montgomery, 1961; Dent and Young, 1981; OEH, 2012) that focused on managing soil, particularly in agricultural lands. Through this perspective, SLM is the inverse of management that results in degradation of land, including reduction in soil health (Beinroth, *et al.,* 1994). The link between SLM, land degradation and soil health is important in efforts to develop solutions to the complex issues of land degradation (See Section 4).
B. A broader approach to management of natural resources (land, water and air) followed. In this approach land is defined comprehensively to include the biosphere, soil, hydrology (surface water and groundwater reserves), geology, human settlements and associated infrastructure (United Nations, 1995). The environmental resources that were considered varied between studies, depending on the specific objectives of the study, but generally align with the concept of land potential.
C. More recent approaches to land management encompass the three pillars of sustainability – environmental, economic and social (World Bank, 1998, 2008; FAO, 2007; Liniger *et al*., 2011; Hatfield and Moran, 2013). This holistic perspective is now accepted as a more appropriate perspective (FAO, 2007), but it is also the most complex and requires more time and resources (IEO, 2017). Approach C is consistent with the current pursuit of Land Degradation Neutrality (LDN), which aims to sustain the land -based natural capital, and the ecosystem services that it delivers, in order to provide food security and enhance human-wellbeing (see section 2.2).

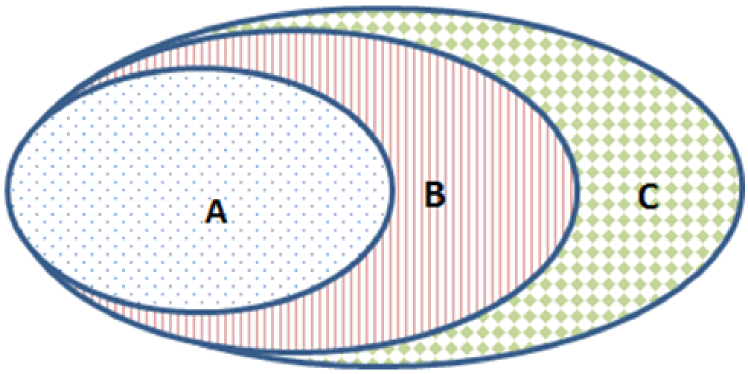

Figure 2 Approaches to the assessment of land management.
Key: A: Land evaluation/land capability approach focussed on soil management (Klingebiel and Montgomery, 1961; FAO, 1976; OEH, 2012); B: Land potential approach considering environmental resources of soil, landscape, biodiversity, water and air (United Nations, 1995; UNEP, 2016); C: Social-ecological system approach including environmental, economic and sociological aspects (FAO, 2007; World Bank, 2008; Liniger et al., 2011).

Hence, land management has evolved to include the concept of "sustainability". The Brundtland Commission (1987) defined sustainable development as "development that meets the needs of the present, without compromising the ability of future generations to meet their own needs". While this original definition remains the most cited, sustainability is in reality a complex concept that has been subject to various interpretations. The British Standards Institute (BSI), *BS 8900-2 Guidance for managing sustainable development* defines sustainability as "an enduring, balanced approach to economic activity, environmental responsibility and social progress" (BSI, 2013). More recently sustainability has been linked to the concept of a water-energy-food-nexus (Wilchens 2017; Hatfield *et al.* 2017). Processes influencing the sustainability of agricultural production and of natural resources are dynamic, complex, and uncertain so that, particularly when applied to land management, sustainability depends on the context (D'elia and Likens, 2012).

This report uses the World Bank definition of sustainable land management: "a knowledge-based procedure that helps integrate land, water, biodiversity and environmental management to meet rising food and fibre demands, while sustaining ecosystem services and livelihoods". SLM encompasses the management of land resources (soils, water, plants and animals) for food and fibre production and other ecosystem services, while protecting the long-term productive potential and ecological value of these resources. This broad definition integrates all three pillars of sustainability – environmental, economic and social – and highlights the complexities of implementing SLM across biogeographical and governance boundaries. While targeting productive lands, SLM is expected to benefit "natural" ecosystems through inter-dependent elements such as hydrology, biodiversity and other ecosystem processes that lead to off-site impacts of agroecosystems (Box 2). Thus, the focus of this report is agricultural systems, in which there is substantial scope for interventions, and where the need for action is critical to meet land degradation neutrality and food security targets.

Due to the strong links between SLM and soil health, land degradation, food security, climate change mitigation and adaptation, SLM is an integrative strategy to address multiple environmental and human development objectives. This report concentrates largely on the environmental pillar of SLM, particularly aspects relating to soil health (Approach A in

Figure 2) due to its importance in agro-ecosystems and for global food security. It also considers the economic and social constraints to implementing SLM, and discusses the challenges associated with effective planning, promotion and adoption of land management activities that are understood as sustainable in the more contemporary Approach C (FAO, 2007; Liniger *et al.,* 2011; White, 2013).

Soil health is a key concept in understanding and managing the processes of land degradation and restoration, and for evaluating effectiveness of SLM interventions. It refers to the capacity of the soil to deliver ecosystem services, including economic and environmental goods and services, as well as the soil condition. Understanding which soil properties constitute soil health, and how land management practices affect those properties, is fundamental to identifying effective SLM practices.

Another key concept underpinning SLM is the that of land potential (UNEP, 2016; Orr *et al.* 2017) also known as land capability in some regions (OEH 2012; Gray *et al.* 2015; Murphy 2016). Land potential reflects two fundamental, independent aspects: the capacity to provide ecosystem services including food, water and fibre, and the resilience of the land to the impacts of management practices and its susceptibility to degradation, including resilience to climate change (FAO 1976, 2007; Dent and Young 1981; OEH 2012; Gray *et al.* 2015; Orr *et al.* 2017). It is possible for a soil to have a low capacity to provide ecosystem services, but a low susceptibility to land degradation. Alternatively, a soil may have a high capacity to provide ecosystem services and a high susceptibility to land degradation. There is not a simple relationship between capacity to provide ecosystem services and soil properties linked to soil degradation (Palm *et al.* 2007).

Land degradation neutrality, defined as a state whereby the amount and quality of land resources necessary to support ecosystem functions and services and enhance food security remain stable or increase within specified temporal and spatial scales and ecosystems, is the new paradigm in land degradation policy, adopted by the UNCCD (UNCCD, 2016), and also as Sustainable Development Goal Target 15.3. LDN strives to maintain or enhance the land resource base and the ecosystem services that flow from it. LDN encourages a dual-pronged effort in sustainable land management to reduce the risk of land degradation, combined with effort in land restoration and rehabilitation to counteract the impacts of land degradation. Thus, SLM is fundamental to achieving land degradation neutrality.

1.4. Sustainable land management – understanding the need

The need for SLM is defined by the extent or risk of land degradation. Land degradation is defined as any deterioration of the natural potential of land that affects ecosystem integrity by reducing either its sustainable productivity or its native biological richness and maintenance of resilience (GEF, 2005). The Millennium Ecosystem Assessment (MA) emphasised the loss of ecosystem goods and services across all terrestrial biomes as a result of pressures from land-use change and exploitation of resources (See also Chapter 4).

There is considerable uncertainty in estimating the area of degraded land. Land conditions vary so widely, particularly in climates with seasonal dry periods and frequent droughts, that distinguishing land degradation from normal dynamics in land cover and productivity is challenging. Studies vary in their estimates of the extent of degradation, due to differences in definitions and methods. Despite this uncertainty, the enormity of the problem is clear. According to Bruinsma (2009), over half of agricultural land is classed as moderately or severely degraded, i.e. half of the global area of 4.9 billion ha, which is comprised of 1.5 billion ha of cropland and 3.4 billion ha of grazing land. Moreover, the area of arable land alone classed as degraded is estimated to be increasing by 5-6 million ha each year (Hamdy and Aly, 2014). The pressures leading to land degradation are detailed in Chapter 2.

Land degradation affects ecosystems in all agro-climatic zones. In the drylands, an estimated 12 million ha of formerly productive land becomes unproductive each year through drought and unsustainable management practices (UNCCD, 2011); this represents a loss equivalent to 20 million tonnes of grain every year. However, about 78% of all land assessed as degrading is found in non-dryland areas (UNCCD, 2011); these lands produce much of the world's food. There is wide variation in estimates of the rate of productivity losses due to land degradation. This variation arises from differences in baseline assumptions, indicators of degradation and modelling approaches, and how productivity loss is defined (Wiebe, 2003). Net productivity loss is commonly defined as the sum of yield losses and cost increases. Crosson (1995a, 1997) estimated cumulative productivity losses for cropland and pasture ranging from 0.1 to 0.2 percent per year. Wiebe (2003) summarised estimates of productivity loss in agricultural land in the United States, finding reported values from as little as 0.04% productivity loss (taking into account yield loss and cost increases) per year across most crops (Alt *et al.* 1989) to 8% per year decline in maize yields (Pimentel *et al.* 1995). Wiebe (2003) concluded that land degradation impacts on productivity are sensitive to location-specific biophysical and economic factors and are, therefore, difficult to predict at regional and global scales. Further uncertainty arises from the dearth of long-term experiments from which impacts of SLM practices could be unequivocally quantified, and the differences in focus of the various assessment methods. Soil scientists using biophysical methods may estimate the impact of soil erosion on crop yields in experiments that change topsoil depth with

Box 1. Key definitions relating to SLM, soil, land and ecosystems

Desertification: Deterioration of land in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities (UNCCD, 2011, Article 1a).

Ecosystem: A dynamic complex of plant, animal and microorganism communities and the non-living environment interacting as a functional unit. Examples include natural forests, landscapes with mixed patterns of human use and ecosystems intensively managed and modified by humans, such as agricultural land and urban areas.

Ecosystem services: Benefits obtained from ecosystems, including:

- provisioning services such as food, water, timber and fibre
- regulating services that affect the climate, floods, disease, waste, air and water quality
- cultural services that provide recreational, aesthetic and spiritual benefits
- support services, e.g. soil formation, photosynthesis, nutrient cycling (MA, 2005; Niemeijer and Moran, 2006) (World Bank, 2008).

Land: The terrestrial system that comprises the natural resources (soil, near surface air, vegetation and other biota, and water), the ecological processes, topography, and human settlements and infrastructure that operate within that system (adapted from FAO, 2007 and UNCCD, 1994; see also Lal, 2010a; Koch *et al*., 2013).

Land degradation: Reduction or loss of the biological or economic productivity and complexity of rain-fed or irrigated cropland, or range, pasture, forest and woodlands (GEF, 2013d).

Land degradation neutrality: a state whereby the amount and quality of land resources necessary to support ecosystem functions and services and enhance food security remain stable or increase within specified temporal and spatial scales and ecosystems (UNCCD, 2016; Cowie et al. 2018)

Land potential: The inherent, long-term potential of the land to sustainably generate ecosystem services, which reflects the capacity and resilience of the land-based natural capital, in the face of ongoing environmental change.

Land rehabilitation: Actions undertaken with the aim of reinstating ecosystem functionality, where the focus is on provision of goods and services, rather than re-establishing the pre-existing ecological structure and function. (Orr et al., 2017)

Land restoration: The process of assisting the recovery of an ecosystem that has been degraded. Restoration seeks to re-establish the pre-existing ecological structure and function, including biotic integrity. (Orr et al., 2017)

Land sparing: the intensification of production to maximise agricultural yield within a fixed area and dedicating other land to biodiversity conservation (Hulme et al., 2013).

Land sharing: (also called 'wildlife-friendly farming'): using low intensity, low-input agriculture, so that agriculture and biodiversity conservation co-exist on the same land (Balmford et al., 2005).

Land Type: Class of land with respect to land potential, which is distinguished by the combination of edaphic, geomorphological, topographic, hydrological, biological and climatic features that support the actual or historic vegetation structure and species composition on that land. (Orr et al., 2017)

Soil health: Continued capacity of a soil to function as a vital living system (within ecosystem and land-use boundaries) to sustain biological productivity, maintain quality of air and water, and promote plant, animal and human health (Doran et al., 1996). Soil quality is often used synonymously with soil health.

Soil natural capital: The stock of natural assets yielding a flow of either natural resources or ecosystem services. Value can be assigned to the soil natural capital by quantifying the ecosystem services it provides (Dominati et al., 2010).

Soil security: The maintenance and improvement of the world's soil resources so they can continue to provide food, fibre and fresh water, make major contributions to energy and climate sustainability, and help maintain biodiversity and the overall protection of ecosystem goods and services (Koch et al., 2013; McBratney et al. 2017).

Sustainable land management: A knowledge-based procedure that helps integrate land, water, biodiversity and environmental management (including input and output externalities) to meet rising food and fibre demands, while sustaining ecosystem services and livelihoods (World Bank, 2008).

Sustainable intensification: Increasing food production or yields on existing farmland without adverse environmental impact and without the cultivation of more land (Global Soil Partnership, 2014).

Box 2. Key features of sustainable and unsustainable land management

Benefits of Sustainable land management*:* investment in SLM to control and prevent land degradation in productive landscapes is an essential and cost-effective way to deliver multiple global environmental benefits (GEF). SLM innovations that address productivity needs in crop, livestock, and forest landscapes also contribute to: biodiversity conservation by reducing the conversion of natural ecosystems and safeguarding agro-biodiversity; reduced risks of pollution and degradation of water resources, to ensure sustainable flows for consumptive uses; reduced deforestation and emission of greenhouse gases in production systems; and increased sustainability and resilience of agroecosystem services (GEF, 2013b).

SLM aims to:

- preserve and enhance the productive capabilities of cropland and grazing land
- sustain productive forest areas and, potentially, commercial and non-commercial forest reserves
- maintain the integrity of watersheds for water supply and hydropower-generation needs and wetland conservation
- maintain the ability of aquifers to serve the needs of farming and other productive activities (World Bank, 2008, p. 5).

SLM practices improve soil health and enhance productivity by building soil organic matter, improving soil structure, reducing erosion, increasing water infiltration, increasing water-use efficiency, replenishing soil nutrients and increasing the efficiency of nutrient uptake.
Examples of SLM practices include:

- managing grazing pressure to maintain groundcover
- integrating nitrogen-fixing legumes into crop and livestock systems to improve fertility
- adopting reduced tillage, retaining residues, using cover crops or integrating a pasture phase into cropping systems to improve soil organic matter stocks
- using mineral fertilisers conservatively and in combination with manure, crop residues, compost and other soil amendments
- enhancing agro-diversity through intercropping and agroforestry.

Unsustainable land management*:* Unsustainable management practices are considered the main drivers of land degradation, in particular desertification and deforestation, causing reduced agricultural productivity (GEF, 2013b). The impacts of these practices include loss of soil, changes in natural habitats and ecosystems, reduced ecosystem services (loss of water infiltration, loss of agro-biodiversity, loss of wild biodiversity), as well as decreases in land productivity leading to poor harvests and food shortages. Climate change is now exacerbating these problems.
Examples of unsustainable land management practices include:

- continuous cropping, with frequent tillage, no fallow and low species diversity
- regularly burning crop residues
- excessive irrigation and fertiliser application
- continuous high intensity grazing leading to loss of ground cover
- frequent, widespread rangeland burning.

other factors held constant. In contrast, economists seek to include behavioural responses of farmers and other decision makers in econometric analyses that estimate the productivity consequences of erosion, and may include multiple factors such as topsoil depth and fertiliser application. In addition,

biophysical data tend to be site-specific, whereas economists often use aggregated data, e.g. for fertiliser use. Both the biophysical and econometric approaches are costly to undertake. As a result, derived data are limited to small sample size, introducing additional uncertainty into any broader inferences from the analyses.

Despite the uncertainty over the rate of productivity loss, it is clear that, if the rate of gain in crop yields in future is lower than the rate of growth in food demand, as is projected, even small degradation-induced losses of productivity will be a significant cause for concern.

While land degradation has clear impacts on land productivity at a local level, the interconnectivity between ecosystems across scales means that downstream impacts on the biosphere can also be significant. Hence, land degradation – especially desertification and deforestation – is now widely recognised as a threat to the global environmental commons. The potential impacts – which include loss of biodiversity, effects on climate, adverse effects on water quality and long-term impacts on productivity of agricultural lands, managed forests and natural ecosystems and on human health – threaten the well-being and livelihoods of people, particularly the poor and vulnerable (UNCCD 2011). The Food and Agriculture Organization of the United Nations has reported that one out of every three people is affected by land degradation (FAO, 2011).

Box 3. Global land degradation – estimates of extent and impact

- About 24% of total global land area has been affected by land degradation, including over half of the total farmed area.
- Globally, 1.5 billion people and 42% of the very poor are directly affected by land degradation.
- Each year, an estimated 25-40 billion tons of fertile soil are lost globally (FAO & ITPS 2015).
- In the drylands, due to drought and desertification, 12 million ha of land are transformed into new man-made deserts each year. That is an area with potential to produce 20 million tons of grain every year.
- In the last two decades, significant land recovery and improvement have occurred in the drylands. For instance, many regions have already adopted farmer-managed natural regeneration and agroforestry techniques, such as planting of “fertiliser trees” on farmlands and grazing lands. Such techniques have contributed to improving over 6 million ha across Africa, but more than 2 billion ha of land worldwide is suitable for rehabilitation through forest and landscape restoration (UNCCD, 2011).
- In all, 67% of Africa’s land is affected by land degradation; 4-7% of land in sub-Saharan Africa is severely degraded.
- The cumulative loss of productivity is 25% of cropland and 6.6% of pasture land.
- Half of soil degradation is attributed to overgrazing (FAO, 2011).

Soil status and condition vary across a range of scales. However, the diversity of estimates in published studies and general paucity of information especially on pressures on land at a local scale does not permit more than qualitative assessment of impacts on regional communities. One of the better-documented regions is Sub-Saharan Africa where loss of arable land per capita is particularly extreme (Figure 3). Land degradation has been estimated to affect 124 million ha, with an extreme, irreversible effect on 5 million ha (Jones *et al*., 2013). Africa’s population has increased by 300% since the 1960s, whereas the area of agricultural land has increased only marginally. As a result, the number of people to be fed from each hectare of land in Africa has increased from 1.91 to 4.55. Because the majority of African countries are not in a strong economic position to import food, pressure has increased on land resources to meet local nutrition needs. In an alternative assessment of the area of degraded lands (Pagiola 1999 quoting Olderman *et al.* 1990), Asia has more degraded lands than Africa, an estimated 700 Mha compared to 500 Mha for all of Africa. There has been little change in the total area of cultivated land in Asia since 1990, and small increases are anticipated in future (Dixon *et al.*, 2001; UNEP 2014), although there is a degree of uncertainty in both historic trends and projected future changes in net cultivated area. Asia has large areas of arid lands that are vulnerable to desertification including parts of Afghanistan, China, India and Pakistan (Eswaran *et al.* 2001). Although the number of people to be fed per hectare has increased, there has been an intensification of agriculture and an increase in yields to meet the increased demand (UNEP 2014). Potentially this intensification of agriculture increases the risk of degradation if land management practices are not sustainable.

The major forms of degradation recorded in Africa include nutrient decline, desertification, wind and water erosion, loss of soil biodiversity, loss of agricultural land to urbanization, industrialization (soil sealing), soil contamination, salinization, soil compaction and landslides (Jones *et al.,* 2013). Some forms of land degradation such as decline in soil nutrient status can be corrected with inputs, but may be more difficult to correct under conditions where agriculture is dominated by low-input practices (Ngoze *et al*., 2008; Liniger *et al.*, 2011; Winterbottom *et al*., 2013; Harris and Orr, 2014). Appendix 1 provides more detail on land degradation issues in different regions.

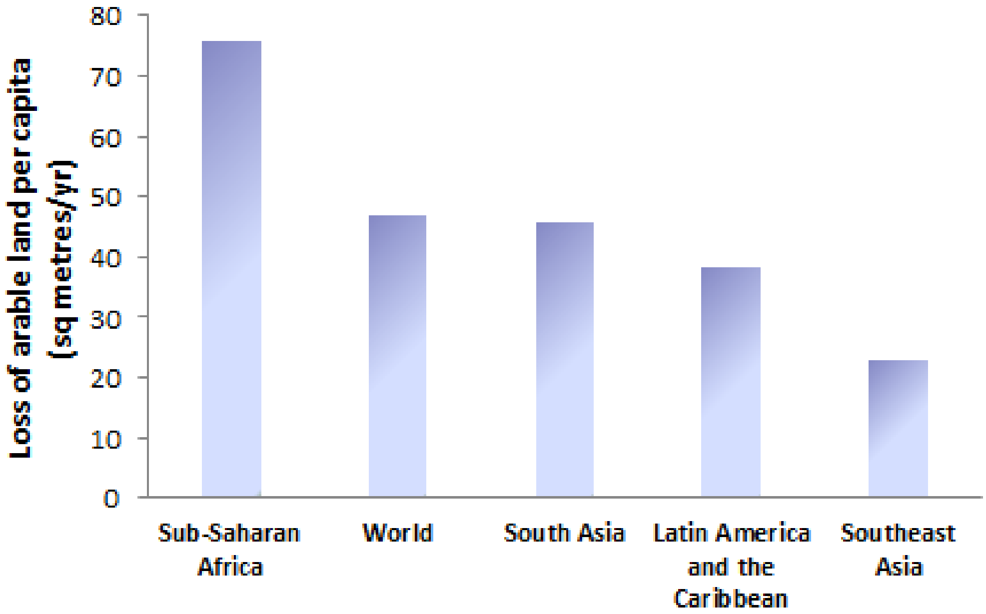

Figure 3 Regional distribution of degradation of arable land. The figure highlights the importance of the issue for many of the world's most poor and vulnerable peoples. Source: UNCCD, 2011.

1.5. Sustainable land management – understanding the challenges

Land degradation reduces food yield potential, biodiversity and ecosystem services. While the severity of the impact of land degradation varies between countries and regions (Kassam *et al*., 2013), the wide distribution of land with reduced productivity due to land degradation accentuates the challenge of food security globally. It has been estimated that global food production will need to more than double by 2050 as the population increases to more than 9 billion people (Beddington *et al.,* 2011). Expanding agriculture into new lands to replace areas with lost or reduced productive capacity is not a desirable solution, due to the impacts on climate and biodiversity. The challenge is, therefore, to produce more food from the same or less land in a way that does not diminish the potential for future production or harm the natural environment. The potential for sustainable intensification of agricultural production on existing agricultural land is discussed in the context of global food security in Chapter 3. SLM practices could contribute to reversing degradation and restoring productivity on a significant proportion of the 2 billion ha degraded land that is suitable for rehabilitation (UNCCD, 2011).

The challenge of achieving food security is exacerbated by uncertainty over the land area affected by degradation, the impacts on agroecosystems and people, and the potential for restoration. Greater knowledge of the quantitative impacts of land degradation would assist in planning and prioritizing interventions and the development of appropriate policy responses.

Despite uncertainty in quantifying land degradation and its impacts, statistics from UNCCD (2011) (Figure 3) illustrate the large challenge for SLM programs designed to combat land degradation. Food and fibre production are the focus for SLM investment, but environmental concerns extend beyond agriculture and forestry. Natural landscapes and waterways, which also provide ecosystem services on which human populations depend, are also vulnerable to the negative consequences of unsustainable management (UNCCD, 2011). Thus, SLM also seeks to minimise negative off-site impacts.

A challenge for effective implementation of SLM programs is understanding the barriers to adoption of good practice. These barriers may arise from biophysical, social, economic or cultural constraints to changing land management. Biophysical constraints have a range of sources, including climatic and soil limitations and the challenge of defining good practice with the flexibility that allows for the variable interaction of land use and management with natural resource factors. Socioeconomic constraints at household level may include financial circumstances, skills, security of land tenure and marketing arrangements. The capacity to introduce incentives to promote adoption may be limited by institutional factors and political structures, while social instability and conflict also affect the potential for effective action as explained in the next chapter. These factors may interact to influence the extent of adoption of SLM practices, and so influence the duration and severity of ongoing land degradation and the effectiveness of responses.

2. Context for implementing sustainable land management

2.1. The land resource – drivers, pressures and opportunities

The Food and Agriculture Organization of the United Nations (FAO, 2008) estimated that in 2005-2007, of the total global land area, 1.530 billion ha was arable land, 4.055 billion ha was forest and 3.374 billion ha was meadows and pastures, i.e. approximately 38% of land was suitable for crop or grazing and 31% was forested (Figure 4).

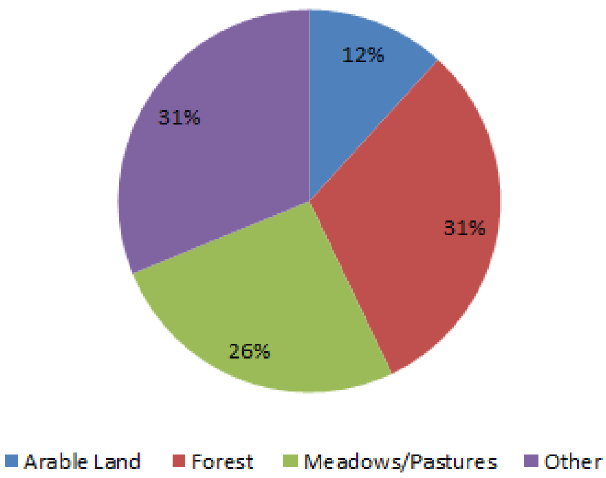

Figure 4 Global land use. Source: FAO, 2008.

Factors that individually and in combination exert increasing pressure on the land resource include:

- demand for food from a growing population
- demand for higher quality, higher protein diets preferred by the expanding "middle-class", especially in developing and newly-industrialised countries
- impacts of anthropogenic climate change on agroecosystem health and productivity
- increased urbanization and its spread onto high quality agricultural lands
- high energy prices affecting the cost of farm inputs such as fertilisers and demand for land for bioenergy
- water scarcity that can limit productivity of crops under irrigation, result in lower organic matter input to soils and increase the risk of over-grazing in grasslands
- competition for finite land resources between production of food, animal feed, bioenergy and materials
- competition for finite water supplies with megacities and the energy and mining sectors.

Pressures on land resources contribute to degradation in a range of ways, on-site (e.g. soil erosion or declining soil nutrient levels), downstream or off-site (e.g. pollution of water bodies through sediment and nutrient flows) and socially (e.g. under-nutrition and poverty). Externalities flowing from economic factors such as market or trade restrictions and government stability or policy development (including mining development and international land investments) are also felt locally and at broader scales. Some pressures and their relevance to SLM are introduced below and key issues expanded in later chapters.

2.1.1. Food demand

Human-induced changes in the potential productivity of land are a threat to the capacity of the planet to support a growing population (Foley *et al.,* 2005). The magnitude of, and mechanisms for, the impact of land degradation on global food security are complex, and spatially and temporally variable.

Of the 14 billion ha of ice-free land on the Earth, 11% is used for crop cultivation and 25% for pasture to directly or indirectly feed the approximately 7.5 billion people living on the planet today (FAO, 2011). The cropland alone produces approximately 2 billion tonnes of grain each year for human food and animal feed, providing around two-thirds of total direct and indirect protein intake (Tubiello *et al.,* 2007), while using approximately 70% of the water resources withdrawn from aquifers, rivers and lakes (World Bank, Undated; OECD, 2017).

The United Nations Population Division (UNPD) projects that global population will reach 8.6 billion in 2030, 9.8 billion in 2050 and 11.2 billion in 2100, (UNDES, 2017). This helps define the additional pressure on finite land resources. However, response to this pressure must consider variations in population growth between countries and the future distribution of people relative to productive land. Most of the projected population growth will be in the urban areas of developing countries. For example, Niger's population is predicted to rise from the 12 million recorded in 2000 to 120 million in 2100 (Searchinger *et al.,* 2013). Migrations are significant, but difficult to predict. For example, with Niger predicted to be adversely affected by climate change, emigration to Europe and elsewhere in Africa will likely to be higher than global averages. The refugee crisis that has seen millions of people flee Syria including over a million seeking asylum in Europe, is partially attributed to climate-change induced drought in 2007-2010, that devastated food production and livelihoods, and led to mass migration out of rural areas (Kelley *et al.* 2015). Such population shifts will have major consequences for land management in regions seeing sharp decreases and increases in population.

The economic and demographic profiles of populations in different regions will change. As a result, pressures on land resources will also be affected by the changing composition of diets, as well as the total demand for food. Growing affluence, notably in Asia, is pushing more of the population into the global "middle class" – those with a daily consumption between US $10 and $100. Of the 5 billion new members of the middle class expected by 2030, two-thirds are expected to live in Asia. Increased demand for more resource-intensive foods such as vegetable oils and protein, especially animal protein, is already evident in the region (Foresight, 2011).

On the other hand, unequal access to nutrition across the globe will likely continue, adding even greater pressure on the limited productive land area in some regions. In 2017, there were approximately 815 million undernourished people in the world (FAO, 2017), predominantly in Africa and South Asia, and 4 billion faced water scarcity (Mekonnen and Hoekstra 2016). This is despite the world producing more than enough food for the total global population if it was distributed equally and without waste. Food shortages can occur rapidly in regions where production varies widely due to seasonal fluctuations and weather extremes, which have direct and indirect impacts on crops and pastures. Other factors such as pests and disease of plants and livestock, politics, conflict and market forces also affect access to nutrition (Sanchez and Swaminathan, 2005; Jones *et al*., 2013). Climate variability and extremes along with water scarcity, steep slopes and shallow, fragile and nutrient-poor soils may further exacerbate under-nutrition indirectly by increasing the risk of land degradation (World Bank, 2003; Overseas Development Group, 2006). Decreasing the number of food-insecure people is one of the major humanitarian challenges facing the world today, and one that is inexorably linked to success in developing and implementing SLM. This is recognised in Sustainable Development Goal 2: End hunger, achieve food security and improved nutrition, and promote sustainable agriculture. The need is most urgent where under-nourishment is more prevalent, but SLM response must be global, to meet the SDG targets. However, undernutrition is just one form of malnutrition that affects the sustainability of land management for food production. Malnutrition may reflect acute or chronic deficiencies in macronutrients (carbohydrates, fats and proteins) or micronutrients (vitamins and minerals) or excessive intake of food, out of balance with energy expenditure, leading to increased body weight and fat accumulation. Obesity may be accompanied by deficiencies in micronutrients when the diet is not balanced but dominated by high energy, low nutrition foods (FAO, IFAD, UNICEF, WFP and WHO 2017). In this context, the SDGs are relevant, especially ending all forms of malnutrition (Target 2.2). It has been estimated that, in aggregate, the world's food system currently [in 2016] generates enough food energy for all people (Fischer and Garnett 2016). However, not all have adequate and affordable nutrition, and addressing environmental problems associated with current and future food production, particularly degradation of agricultural land and vulnerability to climate change, will need to involve the entire food system including consumption and waste. Building the capacity of farmers to invest in technologies which improve efficiency, and fostering sustainable land management, will increase their resilience to a cycle of land degradation, poverty and decreased food security (Overseas Development Group, 2006).

Meeting global demand for food in 2030 has been estimated to require 50% more food, 50% more energy and 30% more fresh water than in 2010 (Beddington *et al.,* 2011). Feeding the 9-10 billion population anticipated by the mid-century will place enormous pressure on the world's finite natural resources unless there is a significant shift towards higher efficiency or a marked reduction in food waste. The demand for food will need to be met with little additional land coming into production. The connection between agricultural and natural ecosystems through processes such as hydrology, pollination and species movement means that food security depends on sustainable management of the broader landscape. However, the ecosystem services provided by both natural ecosystems and those managed for food and fibre are already under threat from over-exploitation. As below, major modifications to the environment, including urbanization, infrastructure development and overexploitation for food systems, are critical drivers of land degradation. Urbanisation is also expected to increase pressure on water supplies. Thus, increased water-use efficiency for agriculture will be critical (Marston *et al.,* 2015), particularly in areas where access to clean drinking water is insufficient to meet human needs. Without SLM, land and water resource degradation will increasingly threaten food security in all nations, including many that today have adequate nutrition.

2.1.2. Climate change

Anthropogenic climate change is projected to have widespread severe impacts on agroecosystems (IPCC, 2014). The science showing that the Earth has warmed over the past 200 years is now settled (e.g. Solomon *et al.*, 2007; IPCC, 2013). Global mean temperature has risen by slightly more than 0.8°C since the 1850s, a warming trend consistent across independent temperature records taken over land and sea and in ocean surface water (Ciais *et al*., 2013; Tans and Keeling, 2013). In addition to a hotter world, changes in rainfall patterns and in the frequency and severity of extreme weather events are predicted (Solomon *et al.,* 2007).

Agriculture is highly sensitive to weather and to changes in climate (Wheeler and von Braun, 2013; Ray *et al.,* 2015); thus, human-induced climate change is expected to directly influence crop production for food, feed and fodder. Climate change is also predicted to affect livestock health through heat stress, reduced access to drinking water and changes in pasture quantity and quality; it will also likely alter the pattern and balance of trade of food and food products. Sea level rise is expected to inundate and salinise key low-lying farming regions such as fertile river deltas. Natural ecosystems are also expected to be affected by higher temperatures, impacts on water availability and sea level rises. Some regions may experience increasing aridity, more erratic and unpredictable rainfall and increased severity of extreme events (Bega *et al*., 2002; Heller and Zavaleta, 2009). Important projected impacts of climate on agricultural production also include changes in the range of pests and diseases (affecting crops and livestock and also human health and well-being), and reduction in nutritional value of food (FAO & ITPS 2015; Myers *et al.*, 2017). There will be increased likelihood of extreme weather events (drought, floods, frosts, storms) that not only directly impact agricultural production, but also increase damage to physical infrastructure.

Impacts are likely to be exacerbated by the dynamic interactions between environmental variables and between environmental and socioeconomic vulnerability. For example, drought and heat stress are tightly coupled; increased rates of evapotranspiration can add to the effects of reduced seasonal rainfall or constraints on irrigation due to reduced available water storage in dams (Sage, 2013). The risk of land degradation is exacerbated when drivers act in combination. For example, a variable climate and overgrazing or over-cultivation can combine to increase the risk of degradation (McKeon *et al.*, 2004, Figure 5).

The impacts of climate change on agroecosystems will very likely be more challenging in developing countries where bioclimatic conditions are often already marginal for food production and where low socioeconomic circumstances limit the capacity for adaptive responses by communities and land managers (Howden *et al*., 2007; Parry, 2009). The variable impacts of climate change at the community level and lack of data at an appropriate scale to develop response strategies for vulnerable communities have been illustrated by Bambrick *et al*. (2015). This study collected data at local scales directly from households and communities in Ethiopia. It showed that impacts of climate and perceptions of the risk of events such as floods and rising temperature differed over distances as small as 1 km, highlighting the need for small-scale community-level research. Larger-scale research and modelling can overlook local risks for food, water, sanitation and health in poor and vulnerable communities.

SLM projects have great potential to contribute to climate change mitigation and adaptation. Mitigation strategies include carbon sequestration in vegetation and soils (e.g. through planting trees in riparian zones or as shelter belts, converting to reduced or no-till crop production and retaining crop stubble, maintaining ground cover in grazing lands, and rehabilitating degraded land). More efficient use of fertilisers can reduce greenhouse gas emissions such as nitrous oxide from soil, while improved feed quality can reduce enteric methane. The global theoretical potential sink through soil carbon management is estimated to be 0.9 to 1.3 Gt C per year with possibly as much as three-quarters of this potential on cropping lands (Lal, 2004; Smith *et al.*, 2008; Paustian *et al.*, 2016; Minasny *et al.*, 2017). This high theoretical potential is unlikely to be achieved. A more realistic estimate of the economic potential for global soil organic carbon sequestration at reasonable carbon prices is likely to be markedly lower, perhaps in the order of 0.4 – 0.7 Gt C per year (Smith *et al.*, 2008; Smith, 2016).

Quantification of mitigation can be included in design of SLM projects through baseline benchmarking and periodic monitoring. Potentially, it may enable greater financial returns to the farmer by earning "carbon credits" under appropriate policy frameworks. Building soil organic matter to sequester carbon also contributes to climate change adaptation, through enhanced infiltration and higher water- and nutrient-holding capacity. It should be noted that carbon sequestration rate will slow to zero as a new steady state is reached, usually after 20-100 years. Carbon sequestered in soil is vulnerable to loss, so the SLM practices must be maintained to ensure "permanence" of the sequestration. Maintenance of SLM practices has value for soil health and productivity even when there is no net gain in soil organic carbon, as the turnover in carbon pools can mobilise nutrients and improve soil condition and plant growth.

Figure 5 Impacts of land management and tillage. Left: Impacts of land management (stocking rate) on land condition across a fenceline in north-east Australia; the paddock on the right has been degraded due to grazing during drought while the paddock on the left has good ground cover due to removal of livestock. Right: Impact of tillage on soils resulting in loss of vegetative cover, surface erosion and loss of soil organic matter. Photos: (L) B. Henry; (R) B. Murphy.

In summary, changes in the potential productivity of land due to climate change are likely to increase further the pressure on land resources. This is especially likely in more arid regions such as sub-Saharan Africa, which are already vulnerable to over-cultivation and over-grazing (IPCC 2007, 2014).

2.1.3. Urbanization

Globally, the rate of urbanization has been decreasing in recent years. However, consistent with patterns of population growth in already densely populated regions, the absolute urban population is still increasing, and current trends for mechanisation and automation in agriculture and mining are likely to stimulate further increase. In 2008, for the first time, more than half of the world population lived in urban areas. By 2045, urban populations are expected to exceed 6 billion (World Bank, 2018), nearly two thirds of the global population. Higher density living decreases the impact of rising population on the rate of conversion of agroecosystems to urban land use. However, where expansion of cities does occur, the growth is likely to encroach on high quality productive lands. It is estimated that urban expansion will result in a loss of 1.8 to 2.4% of croplands by 2030 and much of this (80%) will be in Asia and Africa (d'Amour *et al.* 2017). Of major concern, the cropland expected to be lost to urbanisation is 1.77 times more productive than the global average (d'Amour *et al.* 2017). Rosegrant *et al*. (2002) estimated that urban expansion in developing countries decreases cropland by 0.5 million ha/year). Furthermore, urban and peri-urban expansion and rising land values of adjacent lands can diminish the viability of local agricultural production (Naab *et al.,* 2013).

Jones *et al.* (2013) identified “soil sealing” as a specific form of land degradation related to urbanization. Covering soil surfaces with buildings, roads and other infrastructure reduces the area available for essential functions such as food production, filtering and storing rainwater, and providing habitat for plants, animals and soil organisms. As most urban areas are located on soils that are relatively fertile, urban expansion often consumes some of the most productive land remaining, and frequently land with good access to water. Urbanization may also substantially degrade water quality, especially where wastewater treatment is absent. The resulting degradation of inland and coastal waters impairs water supplies, depletes oxygen and kills fish, increases blooms of cyanobacteria (including toxic varieties) and contributes to waterborne disease (Pimm and Raven, 2000).

Urbanization is likely to be a major problem for regional food security in future, due to the cumulative localised effects of loss and degradation of productive lands through soil sealing, and regional impacts on water scarcity and water quality for food production. The higher demand for food from diminished area of productive land increases pressure on land resources.

2.1.4. Energy demand

Globally, the agriculture sector is highly dependent on nitrogenous fertilisers to support productivity (Tilman *et al*., 2011; Nkonya *et al*., 2013; Challinor *et al.,* 2014). Global oil prices significantly affect affordability of chemical fertilisers, particularly urea and other nitrogen sources whose manufacture is energy-intensive (Wood and Cowie, 2004). The recent massive expansion in shale oil production, particularly in the US, amongst other factors, has led to a substantial reduction in oil price (Liu and Li, 2018), and potential for further expansion of shale oil and other unconventional sources has led to uncertainty over future production and prices, although the price is expected to increase in the long term (Lee and Huh, 2017).

Climate change and renewable energy policies are also expected to impact future development of the oil industry, as pressure mounts to “decarbonise” human activities. A major impact of climate policies is likely to be expansion of bioenergy, which is expected to play a significant role in climate change mitigation, as part of the low carbon renewable energy mix required to reduce GHG emissions (IPCC, 2014). The use of arable land for energy crops has the potential to force food production onto more nutrient-poor, low production lands; at the same time, use of cereals in the production of bioenergy could compete with production for food and animal feed, placing additional pressure on yields on current agriculture land. The increased demand for biofuels also directly impacts the availability of nutrients for growing food crops by increasing prices and removing organic matter that would otherwise have helped keep soil fertile through return of crop residues. Hence, increased demand for fertilisers for energy crops could push up prices of fertilisers required for sustainable land use for food crops.

Policies for promotion of bioenergy are increasingly focussed on non-food biomass sources such as forestry and agricultural residues, to reduce competition with food production. More than 1.5 billion tonnes of dry crop (grain plus sugar cane) residues have been estimated to be available for lignocellulosic biofuel production without new land being required (Kim and Dale, 2004). However, much larger quantities of biomass are anticipated to be mobilised for bioenergy: bioenergy linked to carbon capture and storage (BECCS) has been identified as a technology that could, if able to be implemented at commercial scales, deliver the substantial negative emissions expected to be required to meet global climate targets (IPCC, 2014). Removal of residues for bioenergy will increase nutrient export and diminish organic matter input to the soil, potentially reducing soil health. Expansion of biomass production for BECCS would have major implications for land resources, and supplies of nutrients and water (Smith *et al.*, 2015).

On the other hand, there are opportunities to produce biomass for bioenergy in conjunction with ongoing agricultural and forestry activities, by utilising residues, for example. Some options could contribute to SLM: energy crops could be integrated strategically into agricultural landscapes to manage salinity (Davis et al, 2013) or water pollution (Brandes *et al.*, 2018). Furthermore, biomass crops can be grown on contaminated land unsuitable for food or fodder production, contributing to phytoremediation (Pandey *et al.*, 2016), or on marginal or degraded lands where conventional agricultural enterprises are not viable, thus reversing land degradation on these sites, and potentially contributing to land degradation neutrality.

2.1.5. Agricultural demand for water

Agriculture, particularly irrigated crop and pasture systems, places high demands on global freshwater supplies. Global water withdrawals are estimated at approximately 10% of the total global renewable resource, approximately 3,900 km^3 per year. Consumptive water use is estimated to be 1,800 to 2,300 km^3 per year (Gleick, 2003); of this total, food and fibre production have been estimated to be responsible for approximately 85%.

Consumptive water use directly affects freshwater supplies through withdrawals, losses and diversions. This reduces the flow in rivers, especially in more arid regions. The consequent increase in aridity and/or decline in water quality through processes such as salinization directly contributes to land degradation. In addition, the extraction of groundwater reserves has been assessed as unsustainable in the longer term almost universally; water tables have already declined in many regions (Foley *et al.,* 2005). NASA, for example, rates one third of the Earth's major groundwater basins as 'in distress' (NASA 2015) Land use also affects water supplies; it changes the surface water balance and partitioning of precipitation into evapotranspiration, runoff and groundwater flow. Surface runoff and river discharge generally increase when natural vegetation is cleared (Costa *et al*., 2003). Land use can adversely affect water quality: erosion of degraded lands, increased nutrients and agricultural chemicals in run-off and leachate can increase sediment load and cause eutrophication. These impacts on water availability and quality are complex, and are an important consideration in the development of practical land management programs for long-term sustainable production and ecosystem health.

2.1.6. Competition for land

There are natural constraints on the availability of land suitable for growing crops. These include aridity, low nutrient status and erosion hazard (which is related to slope, rainfall erosivity and soil erodibility). With about 1.5 billion ha under cultivation (Table 1), there is at most about another 1.5 billion ha of potentially arable land (Bruinsma, 2009), mostly in sub-Saharan Africa and South America. An increase of 75 million ha, i.e. about a 5%, is predicted to occur by 2050 (FAO, 2009). In 2008, cropland comprised about 10% (around 1,500 Mha) of the world land area, whereas agricultural area in total makes up around 33% (around 4,900 Mha) (UNEP 2014). From 1961 to 2007 total cropland area increased by some 11%, or approximately 150 Mha globally, with large regional differences (UNEP 2014 Figure 2.2). The share of irrigated land has increased, and there has been a steady decline in the area of cultivated land per person, falling from about 0.44ha per person in 1961 to 0.23 ha per person in 2008 (Table 1; FAO, 2011)

Table 1 Changes in land use 1961 to 2009 Source: FAO, 2011

	1961	1980	1990	2000	2008/2009
Cultivated land (Mha)	1368	-	-	-	1527
Rainfed (Mha)	1229	-	-	-	1226
Irrigated (Mha)	139	-	-	-	301
Cropland per person (ha)	0.45	0.32	0.29	0.25	0.23

Competition for arable land is set to increase as a result of pressures including: (a) urbanization as populations increase and productive land is converted to urban and recreational uses (See Section 2.1.3); (b) climate change mitigation policies and carbon markets that introduce demand for land for carbon sequestration in biomass and soils to gain “carbon credits”; (c) plantings for energy crops (See Section 2.1.4); and (d) other non-agricultural uses, including development for mineral resources and protection for recreational use and conservation reserves. The outcome of this competition will need to be intensification of production on agricultural lands (more product from each hectare of land) to continue to meet growing food demand (Tilman *et al.*, 2011).

Competition for land has led to the concepts of “land sharing” and “land sparing”, to integrate agricultural production and biodiversity conservation, as well as sustainable intensification, as mechanisms to manage competing priorities. These are discussed in Sections 3.3.1 and 3.3.2.

2.1.7. Biodiversity loss

Biodiversity refers to the variety of living organisms, at the genetic, species and ecosystem level. Biodiversity is a multivariate concept that includes both production, natural and feral/exotic species living above-ground and those belowground (See for example OECD, 2002). Globally, biodiversity and bio-productivity are being lost at a rapid rate, despite increasing knowledge of the threats, and increasing efforts in conservation. Agriculture is the main contributor to biodiversity loss, through deforestation for expansion of agricultural land, modification of grassland for grazing, drainage and impacts of agricultural chemicals and fertilisers on farmland and on natural systems.

Land degradation affects biodiversity through loss of suitable habitat for individual or multiple species. Soil biodiversity is impacted by land degradation processes that reduce chemical and physical fertility, which in turn further reduces soil health.

The activities of organisms in natural ecosystems and production systems can deliver services that are environmentally, socially and economically important. These services include nitrogen fixation, production of food and fibre, nutrient cycling, water purification, erosion control, contaminated site remediation, pollination, pest and disease control, and cultural or spiritual values associated with ecosystems. There is increased scientific understanding about how biodiversity regulates the delivery of ecosystem services (FAO 2015), although our limited understanding of soil biological processes represents an important gap in SLM knowledge. It has been estimated that 1g soil may contain up to 1 billion bacteria, 200 m fungal hyphae, and a wide range of soil macrofauna such as mites, nematodes and earthworms, and reductions in the abundance and presence of soil organisms leads to the decline of multiple ecosystem functions, including plant diversity, carbon storage and nutrient cycling and retention (Wagg *et al.*, 2013). Indeed, below-ground biodiversity is a key resource for maintaining the functioning of ecosystems (Wagg et al, 2013).

Quantification of biodiversity and the impacts of land degradation on biodiversity may use a range of indicators such as species richness (the number of species), evenness (the relative abundance of different species), community composition (groups of species present), functional group richness (the number of groups of species performing different ecosystem functions), genetic similarity and community similarity (FAO 2015). Biodiversity metrics include the IUCN Red List of Threatened Species, diversity indices and area of key habitat; soil biodiversity measures include and ratios, enzyme activity, microbial biomass, and ratio of fungi to bacterial species.

Sustainable land management practices and strategies can enhance biodiversity and bioproductivity on-farm, and reduce off-site impacts on natural ecosystems, as discussed in Section 3.2.

2.2. The policy environment

Sustainable land management underpins the goal of sustainable development supported by governments around the world and by all organizations concerned about future food security (e.g. IFPRI, 2013). The increasing pressure on the world's land resources for greater productivity places demands on policy developers to create a policy and regulatory environment that supports all three pillars of sustainability – environmental, economic and social. Development of evidence-based policy that recognises the fundamental rights of all people to sufficient nutrition to lead a healthy life and the right to earn a fair income, while also protecting the environment and its finite resources, requires input from the research community. To be effective, research and policy development should be undertaken through participatory approaches that engage landholders and incorporate local knowledge.

Policies that raise agricultural productivity, deliver co-benefits for sustainable natural resource management, and contribute to hunger reduction – especially those targeting smallholders and rural communities – will underpin effective SLM programs. Combining these policies with social measures that increase incomes for poor families magnifies the benefit and provides further positive development by enhancing markets, employment opportunities and economic growth (FAO, IFAD and WFP, 2013). Initiatives such as The Economics of Ecosystems and Biodiversity (TEEB) aim to help decision makers demonstrate and quantify the financial value of ecosystem services and biodiversity. The benefits, however, are dispersed across widely differing cultural and socioeconomic interests. This limits the influence of conservation objectives on global policies for SLM.

While financial incentives are limited, policies can motivate actions and investment to address environmental degradation. At the same time, policies that ignore the risks of land and resource degradation or that introduce barriers to SLM through regulatory or financial instruments will increase the threats to, and hamper recovery of, ecosystem services. The risks are substantial where short-term economic benefits are at odds with longer-term sustainability and goals for human well-being. Payments for ecosystem services have been implemented in few situations and their effectiveness has yet to be fully assessed.

According to Tilman *et al.* (2002), for society to maximise the net benefits of land management as required for increased agricultural production to meet future food needs, there must be a fuller accounting of both costs and benefits of alternative management practices. They propose that this accounting should be the basis of policy, ethics and actions. However, developing sound policy for SLM can be difficult due to the common lack of clear linear relationships between improved practices, resource outcomes and value, and the absence of agreed metrics to monitor policy impact.

Since the 1970s, SLM and food security have been the target of several domestic and international policy initiatives. These initiatives, launched in response to failed harvests, high grain prices and years of famine in sub-Saharan Africa, caught the attention of the United Nations. Attention was raised further following the 1992 Earth Summit in Rio de Janeiro. In 1994, the United Nations Convention to Combat Desertification (UNCCD), as well as the United Nations Framework Convention on Climate Change (UNFCCC) and the United Nations Convention on Biological Diversity (UNCBD) were initiated. The UNCCD specifically recognised "the complex interactions among physical, biological, political, social, cultural and economic factors" that result in desertification and lost productivity. Sustainable land management and conservation of natural resources were subsequently identified as fundamental to the pledge of 185 countries at the World Food Summit in Rome in 1996 to halve the number of hungry people in the world by 2015.

The UNCCD is the only legally binding instrument dedicated to land (see section 6.1) and is a major avenue for investment in programs to combat land degradation and desertification. The GEF, as a financial mechanism for the UNCCD, has adopted a broad, comprehensive landscape approach to SLM to combat land degradation (see section 6.2). A key target region for GEF programs is sub-Saharan Africa (Figure 3). The extent and impacts of land degradation (see Section 1.4) make clear the urgency of arresting the spread of desertification and beginning to restore areas suffering loss of productivity and ecosystem health.

Land degradation neutrality (LDN) was introduced by the UNCCD at Rio +20, and adopted at UNCCD COP12 (UNCCD, 2015). LDN is defined as "a state whereby the amount and quality of land resources necessary to support ecosystem functions and services and enhance food security remain stable or increase within specified temporal and spatial scales and ecosystems". Pursuit of LDN requires effort to avoid further net loss of the land-based natural capital relative to a reference state, or baseline. LDN encourages a dual-pronged effort involving sustainable land management to reduce the risk of land degradation, combined with efforts in land restoration and rehabilitation, to maintain or enhance land-based natural capital, and its associated ecosystem services (Orr et al, 2017; Cowie *et al.*, 2018). Planning for LDN involves projecting the likely cumulative impacts of land use and land management decisions, then counterbalancing anticipated losses with measures to achieve equivalent gains, within individual land types (where land type is defined by land potential). Achieving LDN therefore requires integrated landscape management that seeks to optimise land use to meet multiple objectives (ecosystem health, food security, human well-being). The response hierarchy of Avoid > Reduce > Reverse land degradation articulates the priorities in planning LDN interventions. There is enormous potential to learn from past land management practices that did not take sufficient account of sustainability principles, to inform development and implementation of SLM programs to improve productivity, and restore degraded lands, in pursuit of LDN.

LDN has been considered more of an aspirational goal than a practical goal (Grainger, 2014). Difficulties in implementing LDN identified by Grainger (2014) include:

- Doubts about the meaning of “zero land degradation” because using land for production will almost always degrade soil compared to its unmanaged natural condition; furthermore, despite some degree of degradation, the land can still be highly productive.
- The absence of baseline estimates of soil degradation in many areas.
- Lack of knowledge of land degradation rates in many areas.
- The need to develop national and international monitoring systems.
- The need to develop land-use planning programs.

The “Scientific Conceptual Framework for Land Degradation Neutrality” (Orr et al, 2017; Cowie *et al.*, 2018) addresses these technical and scientific constraints. The conceptual framework has been developed to provide a scientifically sound basis for planning, implementing and monitoring LDN. The LDN Target Setting program of the UNCCD’s Global Mechanism is assisting countries in devising plans for pursuing LDN.

In response to a recognised need for more consolidated political support to strengthen the international focus on land and soil, the Global Soil Partnership for Food Security and Climate Change Mitigation and Adaptation (GSP) was launched by FAO in 2011. The GSP brings together international, regional and national organizations that are working in the area of soil protection and sustainable management, and aims to implement the provisions of the 1982 World Soil Charter, and to raise awareness of the importance of soils for food security and climate change adaptation and mitigation. The GSP has developed a plan of action to promote sustainable management of soil resources (Global Soil Partnership, 2014) and guidelines on sustainable soil management (FAO, 2017).

The 2030 agenda for sustainable development, adopted by the United Nations in 2015, comprises 17 Sustainable Development Goals (SDGs). Sustainable management of land resources underpins the goals related to hunger, climate change and environment. Goal 2 seeks to “End hunger, achieve food security and improved nutrition and promote sustainable agriculture”. It includes the target: “By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality” (Target 2.4), to be assessed by the indicator “Proportion of agricultural area under productive and sustainable agriculture”. LDN is an explicit goal: “By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world”, Target 15.3)

The importance of the land to climate change mitigation and adaptation has increasingly been recognised by the UNFCCC. The Paris Agreement, which aims at limiting the increase in global temperature to well below 2 degrees, points to the need for balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases. The “4 per 1000” initiative launched by France at UNFCCC COP21 aims to encourage action to increase soil carbon sequestration, to enhance food security, climate change mitigation and resilience to climate change (Minasny *et al.*, 2017). The UNFCCC’s “Koronivia joint work on agriculture” brings together the two subsidiary bodies of the convention to address issues related to agriculture, including increasing soil carbon, soil health and soil fertility. This initiative could facilitate transformation to low-carbon agricultural systems that are resilient to climate change.

There are common or complementary goals and approaches amongst the policy instruments and initiatives that address the land. Pursuit of SLM can simultaneously address multiple environmental and sustainable development objectives. Collaboration across the conventions and coordination of efforts could maximise the synergies, reducing costs and enhancing effectiveness of interventions on the land (Cowie et al, 2007). New initiatives, especially LDN and 4 per 1000 are expected to stimulate investment in SLM.

2.3. Threats to food security

Land is a finite resource. Three major pressures impact the capacity the land resource to provide food: declining productivity due to land degradation, competing uses of farming lands and climate change impacts.

Where land degradation occurs, reduced soil health depletes the resource base for food production at both local and global scales. Estimates of the magnitude of the impact are highly uncertain due to large variation from site to site (see Section 1.4). Some studies suggest annual average losses in cropland yield productivity may be quite small, averaging only 0.2 to 0.4% a year (FAO 2002), while in some areas, reduced productivity has been estimated at up to 50% (UNCCD, 2011). Degradation in arid and semi-arid regions, defined as desertification, is considered a threat to 33% of the global land surface and to affect 50% of the people who live in Africa. Desertification is also a risk for significant areas of Asia, especially Afghanistan and Pakistan, and parts of China, Myanmar, Nepal, Mongolia, India, Papua New Guinea, Sri Lanka and Thailand. Specific land degradation processes that threaten agricultural productivity include nutrient depletion, erosion of top soils (Mbagwu *et al*., 1984, Lal, 1987; Stocking, 2003), acidification and salinization. A 2015 report (Nkonya *et al.* 2015) estimated the loss of production of three globally important and representative crops, maize, rice and wheat, due to decline in soil fertility to be in the order of USD 15 billion per year. This is roughly equivalent to 1.4% of the global crop output value. In addition, the cost of loss of milk and meat due to degradation of grazing land was estimated to be about USD 6.8 billion or 1% of the global value of livestock production.

An increasing driver of loss of productive land for food is competition for biofuel production, which is in demand for energy security and climate change mitigation (CAST, 2013). The United Kingdom House of Commons Select Committee on International Development concluded that biofuel production is a threat to food security (HOC, 2013) because it: (a) competes with food production for land and other farming inputs; and (b) accelerates food price rises. Several developed countries, including the United Kingdom, European Union and Australia, now have mandated renewable fuel targets that will drive further conversion of land to biofuel production. For example, the United Kingdom requires 5% biofuels in road transport fuels; to partly address this pressure, the HOC recommended an emphasis on pasture-fed cattle so that grains can be available for human food and biofuel where possible. The committee also proposed reduction of food waste as an essential contribution to food security by relieving the pressure on land and nutrient resources for crop production. The European Union has capped incentives for biofuels based on food crops, and enhanced incentives for lignocellulosic and waste feedstocks, and provides a bonus for biofuels grown on degraded land.

The projected negative impacts of climate change (IPCC, 2014) threaten global food security, as production will increasingly struggle to meet demand to 2050 and beyond. The IPCC Fifth Assessment Report Working Group II, released March 2014, concluded that without strategies to alleviate the impacts, climate change would lead to the equivalent of an average reduction in yield of 2% per decade over the coming decades. This additional stress due to higher temperatures, changes in rainfall patterns and increase in extreme weather events will accelerate tensions in the supply/demand relationship.

Growth in yields of staple crops such as wheat and rice is already insufficient to meet increasing world demand, exacerbated by increasing diversion of crops to animal feed, particularly in Asia. There will be additional pressures on grain supplies and, hence, on arable land. Livestock, primarily pigs and chickens, already consume 36% of total energy produced globally in farm systems. In some countries, e.g. the United States and Brazil, increasing use of grain as feed for ruminants is exacerbating this pressure. Modelling studies suggest that crop-level adaptation (e.g. planting date, fertiliser, irrigation, cultivar selection) may be able to increase yields of wheat and maize by 7% to 15% under realistic projected climate change scenarios (Challinor *et al*., 2014). This potential benefit highlights the need for investment in adaptation strategies for agriculture for sustainable production of food. However, there remains uncertainty about the most effective strategies for different locations and circumstances, and especially to cope with the projected increase in climate extremes. By examining historical data, Troy *et al.* (2015) found that the relationship between crop yields and climate is non-linear, particularly where extremes of temperature and rainfall occur. For example, yields of rain-fed soy crops declined linearly as daily maximum temperatures increased (or rainfall decreased) until a threshold was reached after which yields dropped dramatically. Where available, irrigation was shown to be an effective adaptation mechanism, shifting this critical threshold and alleviating the yield decline. This study demonstrates that the impacts of climate on food security are complex: simplistic adaptation strategies will not be effective in all situations.

In addition to the downward trends in yield, acute shortages or “food crises” are possible in a future where changing climate is projected to decrease resilience of some agroecosystems and accelerate degradation in vulnerable lands, thus increasing the likelihood of crop failures. The risk will be exacerbated as globalization increases interdependencies across national borders and further increases competition for land, particularly arable land. Conflict between countries is a large and unpredictable additional stress on the availability of high quality land for food production and access by those in need. Both productivity and ecosystem services will be under greater pressure from the impacts of these stressors on communities and agroecosystems, making SLM even more challenging in the future.

In response to concerns over future food security and environmental impacts of current food production systems, there is increasing research effort focused on development of unconventional food production systems, including cultured meat, foods based on algae, insects and mycoprotein, and novel production systems such as vertical and roof-top farming. Proponents suggest that these approaches could relieve pressure on land resources, however, there are many challenges to overcome before such systems could be deployed at large scale. Furthermore, the study by Smetana *et al.* (2015) raises questions over the sustainability of some alternative protein options.

Garnett (2013) proposed three broad approaches to food security: (a) enhanced efficiency; (b) demand restraint; and (c) food system transformation. No consensus exists on a single preferred approach to future food system sustainability. Indeed, a combination of options is likely to be required. But greater efficiency, including nutrient use efficiency, is perhaps the dominant approach to increasing productivity, while minimizing adverse impacts on the environment. Other contributions will likely come from reducing waste and changing demands. These include demands related to over-consumption and, for some people, dietary choices e.g. decreasing red meat consumption. The remainder of this review focuses on SLM, which sits within approach (a).

3. Sustainable land management strategies for food security, biodiversity conservation and climate change mitigation

3.1. Sustainable intensification

There are limited prospects for expanding cropland area to meet the growth in demand for food and feed, due to competition with other land uses, and the risk of adverse impacts on climate and biodiversity from the conversion of forest, grassland and wetland to cropping (Stern, 2007). Sustainable intensification is thus seen as an important strategy to meet demand. Sustainable intensification refers to increasing production while improving the efficiency of resource use through the application of sound agroecology principles. The objective is to use renewable land resources (soils, water, plants and animals) for production and other ecosystem services, while protecting the long-term productive potential of these resources (Stocking, 2008). Sustainable intensification has gained support as a logical response to deliver food security for a growing population through more efficient use of existing land resources (Foresight 2011; Tilman *et al.,* 2011).

Intensification of agriculture means a larger proportion of the growing demand for food can be met by existing agricultural land. Importantly, sustainable intensification does not necessarily mean increasing yields across all current production areas. Rather, it means increasing yields where compatible with sustainability, e.g. through improved integration of cropping and livestock activities to maximise nutrient cycling or diversification to high value crops or trees for new markets. Intensification in some areas may accompany lower crop yields in other areas or returning some land to conservation reserves to reduce degradation caused by continued production on fragile soils (Garnett *et al.,* 2013). In this flexible approach, sustainable intensification is compatible with other food production strategies such as “land-sparing”, described in the next section; it will be most effective as part of a multi-pronged strategy for achieving food security (Garnett *et al*., 2013).

However, intensification also increases the risk of land degradation and biodiversity loss, so particular attention must be paid to managing these risks (Tscharntke *et al*., 2012).

3.2. Land sharing and land sparing

Land use for agricultural production always modifies the resource from its natural state and alters the original biodiversity to some degree. A proposed approach to sustainable management, “wildlife-friendly farming”, integrates agriculture and conservation on farms in a way that enhances ecosystem functionality. The goal is to increase biological diversity and reduce the threat of species loss by “land sharing”; that is, using low intensity, low-input agriculture, so that agriculture and biodiversity conservation co-exist on the same land (Balmford *et al*., 2005). Actions to achieve more wildlife-friendly farming include reducing inputs of chemicals such as pesticides and fertilisers, and retaining extensive areas of low-impact farming or grazing within the farm landscape (Balmford *et al*., 2005). However, a lower input approach will commonly decrease yield per unit area, and therefore total production, unless a greater area is farmed; agriculture will thus occur over a wider area if the same production level is to be maintained, potentially resulting in landscapes that contain little untouched land (Butsic and Kuemmerle, 2015).

In developed countries, including some regions of the European Union, the loss of production and income due to land-sharing management is compensated by government payments for the ecosystem services value of these biodiversity-friendly practices (e.g. European Environment Agency, 2002). In the low-intensity low-input systems that still characterise production in many developing countries, there is evidence that loss of species is much less (around 50% of species relative to natural habitats) than in intensive production which usually supports far fewer species, particularly of macrofauna (Benton *et al.,* 2003; Donald, 2004; Naidoo, 2004; Balmford *et al.,* 2005; Scholes and Biggs, 2005).

An alternative approach to wildlife-friendly farming is "land sparing". This approach concentrates high-input, high-yielding agriculture on a smaller area of land, thereby sparing other land for biodiversity conservation (Phalan *et al.*, 2011; Butsic and Kuemmerle, 2015). Land sparing may be achieved by not converting natural land to agriculture, or by restoring some managed land to natural habitat (Green *et al.,* 2005, Matson and Vitousek, 2006; Fischer *et al.*, 2008; Phalan *et al.*, 2011; Scariot, 2013). The scale of past land sparing can only be estimated indirectly (Balmford *et al*., 2005). There is evidence, however, that without yield increases over the previous 40 years, India would have required twice the land area under cropping in 2005, and China and the United States would require three times the area (Balmford *et al.* 2005).

Intensification, to allow land sparing, increases the potential for adverse environmental impacts on- and off-site, for example through increased use of agrichemicals and fertilisers (Balmford *et al*., 2005). For example, excessive rates of nitrogen can result in eutrophication, pollution of groundwater and emissions of ammonia and the powerful greenhouse gas nitrous oxide (Spiertz, 2008). Thus, intensification undertaken for land sparing must apply sustainable intensification approaches including high efficiency of resource use, to minimise environmental risks, as discussed in section 3.1.

The potential contribution of land sparing to meeting future food security needs, while conserving biodiversity, depends on the extent to which crop yields can be increased on existing land to reduce pressure for conversion of new land to agricultural production. Balmford *et al.* (2005) examined the cropland area needed for 2050 food production under a land-sparing approach, and assessed the sensitivity to plausible variations in yield. The area for a suite of 23 important food crops would need to increase by 23% in developing countries under intermediate scenarios. Yield had as strong an influence on the projected increase in land requirement as population growth and per capita consumption, while the level of projected food imports had a dominant influence. In contrast, the comparative analysis for developed countries showed cropland to meet 2050 food requirements could decrease by 4%. In this case the change was less sensitive to assumptions about population, diet, yield and trade. These results suggest that the future role of land sparing will depend on a range of factors but in developing countries is highly dependent on the potential to increase crop yields.

This analysis of the role of yield in the potential for land sparing creates an important incentive for investment in closing the yield gap in developing countries (see Section 3.3), to meet both productivity and biodiversity conservation objectives. Sustainable land management to increase yield on existing productive lands contributes significantly to meeting future food demand and allows for the allocation of land for conservation purposes.

Land sharing and land sparing are sometimes seen as representing alternative trade-offs to balance the need for increased food production with the need for biodiversity conservation (Green *et al.,* 2005; Renwick and Schellhorn 2016). Both strategies have relevance in different situations for developing SLM practices and combating land degradation; which is more practical and, indeed, more sustainable, will depend on the particular location, climate, socioeconomic situation and policy environment (Fischer *et al.,* 2008; Ramankutty and Rhemtulla, 2013). In many landscapes a combination of land sharing and land sparing will prove the optimal strategy for achieving a balance between production and biodiversity conservation (Butsic and Kuemmerle, 2015; Renwick and Schellhorn 2016).

3.3. Closing the yield gap

Potential productivity at any location is determined by natural bio-geophysical factors (e.g. climate, soil type, topography and landforms). The "yield gap" describes the difference between this potential, i.e. the maximum attainable yield for a location, and the actual yield (Bruinsma, 2009), and can be as high as 80% in some locations. For example, while the yields for maize are 40 to 60% of locally attainable yields for maize in a wide range of countries in Africa where maize is a major crop, in poorer fields, yields may be only 10 to 20% of attainable yields (Tittonell and Giller 2013; FAO 2011b). A yield gap is often not the result of land degradation; thus, the gap may be bridged by adopting well-adapted plant varieties and agronomic practices with small changes in management such as changing sowing dates, improved sowing practices and better weed control or use of fertiliser (Bruinsma, 2009; van Wart *et al.,* 2013; Lal, 2013; Yengoh and Ardo, 2014).

Areas that have high potential productivity but achieve low yields at the farm scale, have potential for large yield increases through improved land management. Assessing the yield gap provides information on the performance of agriculture and the potential for growth in food production for different regions and crops. There is a growing consensus that "closing the yield gap" on lands currently producing below their potential could make a substantial contribution to achieving world food security (Foley *et al.* 2011; Tilman *et al.,* 2011). Importantly, targeting under-performing lands will also benefit many of the more food-insecure communities.

High priority should be given to areas of high yield gap to firstly identify the reasons and, where possible, close the yield gap. Reasons for lands producing below their potential vary, but include poor agronomic practices and socioeconomic factors affecting access to technologies such as irrigation and chemical fertiliser. Yengoh and Argo (2014) investigated reasons for poor yields in Cameroon, and concluded that most food crops were being grown in suitable regions, and that the yield gap was largely due to agronomic practices, such as variety selections, nutrient management, soil management and weed control, and policy limitations, including constraints on the allocation of land to agricultural production, and limited government support for extension services for small-holder farmers (Garcia-Ponce *et al.* 2012; Thiele 2002), that inhibit the dissemination of advice and agronomic knowledge to land managers, as well as their access to seed, fertiliser and finance. Thus, yield gap analysis provides a way to identify areas where improved yields are achievable, and also helps to understand the critical crop, soil and management factors that are limiting current yields (Bruinsma, 2009; van Ittersum *et* *al.,* 2013; Yengoh and Ardo, 2014). This understanding provides potential for improving yields and contributing to sustainable intensification of food production.

3.4. Rehabilitation of degraded land

Although presenting significant challenges, rehabilitation can return degraded land to a productive state, thereby contributing to food security, and supporting "land sparing". Rehabilitation practices seek to address the decline in soil health due to nutrient depletion (Kanmegne *et al.,* 2006) and the loss of soil organic matter (Lal *et al.,* 2007). Increasing the soil organic carbon pool within the root zone by 1 tonne of carbon per hectare per year or by 0.07 g/100g/yr in the surface 10 cm, has been estimated to increase food production in developing countries by 30 to 50 Mt per year; this includes 24 to 40 Mt per year of cereals and legumes, and 6 to 10 Mt per year of roots and tubers (Lal *et al.* 2007). Sustainable land management practices have potential to stimulate the rehabilitation of degraded soils, restore nutrient levels and rebuild soil organic matter; this, in turn, will arrest degrading processes such as erosion, due to better soil structure and vegetation cover.

Soil organic matter also represents an important link between SLM, climate change mitigation and climate change adaptation (see Section 2.1.2). While the benefits are recognised, there are financial, institutional, educational and social barriers to building soil carbon (Smith, 2008; Govers *et al.,* 2013; Lal 2016). This is especially the case in the warm, arid to semi-arid regions of the world where the yield gap is often greatest. Here there are often economic and agronomic barriers to increasing soil carbon and organic losses commonly exceed inputs. Losses through decomposition and erosion are often high and inputs of plant residues may be constrained by issues including unwillingness to divert residues from alternative uses such as feeding livestock. Economic or labour constraints may limit capacity to apply the nutrients necessary to increase the amount of biomass produced.

Biological systems commonly have a degree of natural resilience to mild and moderate disturbance. Thus, recovery from some level of degradation is possible without major disruption to livelihoods, given suitable climate and application of sustainable land management practices. However, degradation beyond a threshold will result in long-term loss of productivity, and restoration of ecological function can be slow, impractical or prohibitively expensive. The absolute threshold beyond which rehabilitation is impractical varies with landscape and regional climate characteristics. Sensitivity to long-term degradation depends on the natural resilience of landscapes and human pressures on them for production. As land is subjected to multiple pressures from unsustainable practices such as over-cultivation or over-grazing, which can deplete nutrients and soil carbon (See Box 3), it becomes more vulnerable to severe degradation. The potential for climate change to exacerbate the vulnerability of agroecosystems to land management pressures is increasingly recognised as an additional constraint to rehabilitating degraded land through SLM.

The Land Degradation Neutrality initiative (see section 2.2) will provide an added incentive, and funding, for rehabilitation of degraded land, thereby contributing to addressing the food security challenge.

3.5. An integrated land management approach to food security

Godfray *et al.* (2010) emphasised the importance of integrating the social, economic and environmental pillars of sustainability to meet the challenge of global food security. They argued that achieving food security for a growing world population will require a revolution in the social and natural sciences concerned with food production, including breaking down barriers between these disciplines to optimise productivity across a more “complex landscape of production, environmental and social justice outcomes”.

The GEF’s holistic approach towards environmentally sustainable development aims to meet the rise in food demand without compromising natural capital and ecosystem services. If all the world’s people are to become truly food secure, a concerted effort will be required to address the yield gap. This gap is particularly severe for smallholder farmers, who make up a large proportion of the farming population in many developing countries (e.g. 70% in Cameroon; Yengoh and Ardo, 2014). Garnett *et al.* (2013) emphasise the need to improve self-sufficiency in food production (local action) and also to make more progress in efficiency through sustainable intensification (global objectives). Hence, in addition to focusing on productivity, the economic and policy barriers that limit access to nutrition for all people will need to be addressed.

As the primary managers of large areas of the global land surface, farmers play a major role in determining the ecological condition of landscapes, as well as the sustainability of local, and ultimately global, food production. However, other factors which are beyond their control – such as climate – moderate the effectiveness of agricultural practices in ensuring sustainable land management.

In sub-Saharan Africa, seasonal variability and weather extremes are among the greatest threats to food production and food security (Gregory *et al.*, 2005). Many communities in this region have limited capacity to cope with, and adapt to, the impacts of variations in climate that occur on a range of timeframes. Extended periods of drought can be particularly challenging for land managers and, indeed, to their survival. Hence, identifying good agricultural practices that efficiently use natural resources, maintain ecosystem services and reliably increase food and fibre yields and improve the resilience of these agroecosystems is critical, but challenging.

Recognising the potential for both synergies and trade-offs is also critical where agricultural production is already challenged by climatic and land condition. For example, agricultural systems managed more intensively for higher yields often require high external inputs. However, these systems can also have low resource-use efficiency and contribute negative environmental impacts, such as through off-site impacts of N fertiliser (Spiertz, 2008). Resource-use efficiency is, therefore, a fundamental goal for both sustainable land management, to reduce environmental impacts, and to realise potential yields for food security.

In most food production systems, vulnerability to degradation will very likely increase as a result of climate change; climate scientists predict that the adoption of improved management practices will be lower in those regions already under pressure from food insecurity, climate variability and poverty, particularly in the tropics (IPCC, 2007, Chapter 5). The frequency and severity of extreme events such as droughts, floods and hurricanes are forecast to increase with global warming, and weather patterns are set to become less predictable. Food supplies are likely to become less reliable and prices are likely to increase. These changes will have the greatest negative impact on smallholder farmers, pastoralists and the poor, particularly in regions already suffering land degradation and desertification.

Sustainable land management, including integrated management of water and nutrients, with social and financial incentive programs and policy support, will be critical to ongoing food security. Past success in reducing under-nutrition has been variable; progress towards hunger alleviation through redressing soil and landscape degradation and increasing productivity occurred earlier in East and West Africa than in northern Africa (FAO, IFAD and WFP, 2013). Factors contributing to slow progress include food price inflation and political instability as well as lack of natural resources, especially good-quality cropland and renewable water resources. Global food security requires collective action to provide ongoing access to arable land and grasslands in good condition, adequate water resources, and knowledge and tools to promote the adoption of good practice for sustainable management.

3.6. The many benefits of SLM - summary

When implemented effectively, SLM has the capacity to achieve a wide range of environmental, economic and social objectives. These include improving food and fibre production on existing farmland without adverse environmental impacts, and the maintenance of productivity into the future. Beyond food production, SLM can improve water access and quality, reduce greenhouse gas emissions, conserve biodiversity, enhance resilience to climate change, improve human health, and energy security. Thus, SLM can improve the well-being and livelihoods of people.

Cowie *et al.* (2007) highlighted how SLM practices can contribute to meeting the major environmental objectives of mitigating and adapting to climate change, combating land degradation and desertification, and conserving biodiversity (Table 2).

Table 2. Environmental impacts of some sustainable land management practices.
+ and - indicate the direction and magnitude of the potential impact.

Practice	Climate change	Biodiversity	Desertification
Crop residue retention	++ increased soil organic carbon	++ increased soil biodiversity	+ improved soil fertility ++ reduced soil erosion + increased water retention
Fertilization	++ to + increased biomass - increased nitrous oxide emissions	0 to – off-site effects on aquatic species	+++ increased land cover - acidification
Organic amendments (manure, compost, mulch, biosolids)	+ to +++ increased soil organic carbon	+ to – increased biodiversity or decrease if amendments contaminated	+++ improved soil fertility + reduced erosion ++ increased water retention

Source: Based on Cowie *et al*., 2007.

Liniger *et al.* (2011) describe a range of land management practices that are sustainable under different soil, land, climate and socioeconomic conditions, and enhance ecosystem services at different scales – from the field to watershed/catchment/landscape level, to national and global levels.

The connections between SLM, soil health to ecosystem services have been reviewed by Hatfield *et al.* (2017) and Adhikari and Hartemink (2016). A strong link is proposed between particular soil properties and the capacity of the soil to provide specific environmental services. SLM aims to maintain or improve soil health so that land can provide the ecosystem functions required to deliver ecosystem services to support human well-being. The links between SLM and soil health are expanded in Chapters 4 and 5.

Indirectly, the flow-on contributions of SLM can improve livelihoods to alleviate poverty and improve the resilience of functional ecosystems into the future (Searchinger *et al.*, 2013). Socioeconomic objectives for SLM (adapted from World Bank, 2008; Sanginga and Woomer, 2009) are that it:

- fosters an enabling environment for broad-based and sustainable rural growth
- promotes agricultural productivity and competitiveness
- encourages non-farm economic growth which will relieve pressure on over-exploitation of land resources for food or income, especially in poor seasons when land is vulnerable to degradation.
- improves social well-being, manages and mitigates risk and reduces vulnerability
- enhances the sustainability of natural resource management
- reduces poverty and hunger
- articulates good practice in agricultural policy and investments
- utilises and builds local knowledge of agroecosystems
- supports gender equity and empowerment of women
- combats diseases and improves health
- develops global partnerships.

While these benefits do not apply to every SLM intervention, this list serves to direct planning for investment to consider the social and economic dimensions in addition to environmental goals of sustainability. In summary, SLM programs must meet multiple goals. Widespread adoption of good SLM practices enhances the potential to maximise productivity, enhance food security, sustain livelihoods and deliver ecosystem services now and in the future. It also helps to prevent and/or reverse land degradation through integrated management of crops and trees, livestock, soil, water, nutrients, disease and pests. Through enhanced soil organic matter, improved nutrient-use efficiency and strategic use of pesticides it contributes to climate change mitigation and adaptation, and to the conservation of biodiversity. However, there remain many barriers to achieving these goals. Approaches to facilitate the adoption of SLM are discussed in Chapter 5.

Figure 6 Low impact, extensive grazing provides sustainable production and maintenance of ecosystem services. Photo: B. Henry.

4. Sustainable land management to combat land degradation and enhance soil health

4.1. Relationship between SLM and land degradation

SLM, soil health and land degradation are intimately linked. SLM practices minimise the risk of land degradation (see 4.2) and maintain soil health. Furthermore, they can reverse the impacts of land degradation, potentially restoring the productivity of degraded land (Bell, 2002; Liniger *et al.,* 2011; Read *et al.,* 2012; Winterbottom *et al.,* 2013). The development of effective SLM practices, that maintain soil health and combat land degradation, requires an understanding both of land degradation processes and of the interacting influence of the biophysical variables (soil, climate, land form, water resources and agroecosystem features) that determine land potential.

Without SLM, decline in soil health resulting from degradation processes can lead to loss of productivity, which in turn further exacerbates degradation: as plant growth is restricted, organic inputs decline and the risk of erosion increases, causing a downward trend in land condition that can lead to a tipping point, beyond which recovery is very difficult. An example of such a threshold is seen in the semi-arid rangelands: when high grazing pressure and drought coincide, ground cover declines, which reduces capacity to intercept rainfall, so infiltration decreases, leading to a transition to a lower productivity state (Fernandez et al, 2002). In the eastern Australian rangelands, 50% ground cover has been identified as a critical threshold for water erosion (Eldridge, 2001; Tighe *et al.*, 2012).

The extent to which the productivity of degraded lands can be restored is debatable, and the long-term impacts of some land degradation processes on the productive potential of soils are unknown (Wiebe, 2002). The effects of degradation processes such as loss of topsoil, soil acidification, salinization and accumulation of toxicities in certain soil types can have longer-term impacts, but nutrient decline may be reversible in relatively short periods. In practice, the loss of nutrients may not be easy to correct under conditions where agriculture is dominated by low-input practices (Ngoze *et al.*, 2008, Liniger *et al.*, 2011; Winterbottom *et al.*, 2013; Harris and Orr, 2014). Further, the supply of global environmental public goods such as climate regulation, biodiversity and avoided degradation of land is traditionally not valued in economic terms (Niemeijer and Moran, 2006).
In areas with well-functioning markets and well-defined property rights, landholders have an incentive to protect the long-term productive potential of their soil and land (Wiebe, 2002).

4.2. Forms and processes of land degradation

Traditionally, land degradation studies have concentrated on soil degradation processes (Eswaren *et al.,* 2001; see Chapter 1). In the context of this review "land" refers to the terrestrial system that comprises the natural resources (soil, climate, vegetation and other biota, topography, geology, air, water resources), the ecological processes, and human settlements and infrastructure that operate within the system (adapted from FAO, 2007 and UNCCD, 1994). This is consistent with the more recent understanding that land management includes off-site and related impacts such as flood events, pollution of aquifers and freshwater resources, loss of biodiversity, water scarcity and food insecurity (FAO, 2011). Jones *et al.* (2013) discuss land degradation in the African continent and Table 3 summarises the major forms and processes of land degradation worldwide. Appendix 1 provides a more detailed description based on a survey by FAO (2011). Importantly, some degradation processes also have off-site impacts on water, air, vegetation, landforms and possibly human infrastructure and health, in addition to on-site impacts. The linkages between the drivers of land degradation, degradation processes and impacts on soil processes are summarised in Table 4.

It is theoretically possible to estimate a "soil loss tolerance" factor, relevant to the principle that the rate of use of renewable resources should not exceed the rate of regeneration (Vivien 2008), based on knowledge of the threshold for soil erosion beyond which crop productivity will be impacted under the given soil depth, prior erosion and other factors determining productivity, and the rate of soil formation which, in turn, is complex (Schmidt *et al.*, 1982; Stockmann *et al.,* 2014). In practice, soil may be considered to be essentially a non-renewable resource (Eswaran *et al.*, 2001) because soil forms so slowly that agriculturally useful soil that is lost will not be replaced in a time frame that is practical for food provision, and perhaps not for several generations.

With respect to land resource degradation as opposed to soil loss, negative impacts may possibly be overcome through substitution of human capital and technology, e.g. through fertilisers, soil ameliorants, deep ripping and earthworks. A critical point is that there is a cost associated with input of resources. In many areas affected by land degradation, capital and technology may be limited or not available (FAO, 2007; Koch *et al*., 2013).

Figure 7 Severe gully erosion on a soil with a highly sodic subsoil in the central tablelands of NSW. Salinity outbreaks can exacerbate risk of gully erosion. Photo: B. Murphy.

Figure 8 Gully erosion in north-eastern Australian rangelands as a result of fragile soils, seasonal drought and grazing. Photo: B. Henry

4.3. Soil health and land potential

Soil health determines the capacity of the soil to provide ecosystem services. The role of soils in providing ecosystem services has been summarised using the terminology of the Millennium Ecosystem Assessment (MA 2005) by Dominati *et al.* (2010). They identified that the role of soils in providing ecosystem services includes:

- Productivity: soil nutrient cycles provide nutrients to plants contributing to plant growth
- Filter and reservoir: soils fix and store solutes passing through the soil, purify and store water, provide water for plant growth and mitigate the occurrence of floods
- Structural: soils provide physical support to plants, animals and human infrastructure such as buildings and roads
- Biodiversity conservation: soils are a reservoir of biodiversity providing habitat for thousands of species, including those important for pest and disease control and management of wastes
- Resource: soils provide raw materials such as sand, peat and clay.

In this report, we define soil health as *the capacity of a soil to function, within land use and ecosystem boundaries, to sustain biological productivity, maintain environmental health and promote plant, animal and human health* (Doran *et al.* 1996; Doran and Ziess, 2000; Wilson *et al.* 2008; McBratney *et al.* ,2014). The health of a soil can be inferred by measuring specific soil properties (see below) and by observing other site indicators (e.g. erosion, waterlogging, poor plant growth) and plant symptoms of nutrient deficiency and toxicity. Terms used in the literature to describe the health of the soil include soil quality (Hartemink, 1998; Gregorich, 2002; Karlen *et al.*, 2003), soil condition, natural soil capital (Dominati *et al.*, 2010) and soil security (McBratney *et al.* 2014, 2017). While some authors distinguish between these terms, they are largely synonymous. The term "soil security" encompasses the socioeconomic aspects of sustainability, in its dimensions of capital, connectivity and codification, in addition to the biophysical dimensions of capability and condition. For this report, we use the term soil health, as it is preferred in several publications on sustainability (Dumanski and Pieri, 2000; World Bank, 2008; Liniger *et al.*, 2011).

Table 3 Land degradation processes that can be addressed by sustainable land management practices.

Land degradation process	Description of process	Extent
Nutrient decline Jones *et al.* 2013; Hartemink 2006; Nkonya *et al.* 2013	Many agricultural systems export more nutrients than they return to the soil, giving a net loss of nutrients. Biological fixation of N is important to mitigate this loss.	Large areas of agriculture throughout the world suffer a deficit of nutrients over time. Large areas of Africa are affected by insufficient use of fertilisers.
Deforestation FRA 2010	Clearing of existing forests, necessary for biodiversity conservation, protection of soil and water resources, timber production and social/education functions.	Large areas in Africa, Asia and South America.
Desertification Jones *et al.* 2013; Tueller 2002	Loss of ground cover and increased erosion that occurs when there is a reduction or loss of the biological or economic productivity of soils in arid, semi-arid or dry sub-humid areas.	About 40% of the land surface of Africa is under threat. Also, parts of Asia, Australia, North America and South America.
Soil organic matter decline Govers *et al.* 2013	Reduced organic matter concentration in soils causing decline in soil condition and soil health, loss of soil organic carbon.	Widespread loss of soil organic matter under agriculture. Some recovery of soil organic matter levels with conservation farming.
Water erosion Jones *et al.* 2013 Lal 1990; 2001; Batjes 1996	Loss of soil material from the soil profile on-site and potential pollution of water bodies off-site.	Widespread: affects land that is cultivated and left fallow, and where overgrazing occurs. Areas with low ground cover are susceptible.
Wind erosion Jones *et al.* 2013 ODG 2006 Leys 2002	Loss of soil material and associated carbon and nutrients from soil profile. Dust storms can cause visibility and health problems.	Largely in drier, more arid areas with low rainfall and low ground cover.
Soil acidification Craswell 2001 Sanchez *et al.* 2003 Dent and Pons 1995	a. Acidification of the surface soil under agriculture is caused by removal of bases and leaching of nitrates. Soil pH falls below 5.5 (water) and aluminium can become toxic as Al^{3+}. b. Acid sulfate soils in many poorly drained and often coastal environments can produce acidity when drained.	Acidification under agriculture is largely confined to specific soil types with naturally low pH or low buffering capacity to acidification. Acid sulfate soils are a specific soil type that occurs in poorly drained conditions, often in coastal environments.
Soil sealing Jones *et al.* 2013 D'Amour *et al.* 2017	Loss of agricultural land under urbanization and infrastructure development.	Many human settlements were initially established on some of the most fertile agricultural land, and urban expansion occupies more fertile land.
Soil salinization Gupta and Abrol 1990 Sanchez *et al.* 2003 Rengasamy 2006	Accumulation of salts in the soil to toxic levels due to changes in soil hydrology through irrigation or clearing. Increased levels of sodicity are a common associated problem.	Common on sub-humid to arid areas and large flat alluvial areas with significant stores of sale.
Toxicity and heavy metal pollution Dondeyne *et al.* 2009 Naidu *et al.* 1996 Van-Camp *et al.* 2004	Soil contamination with toxic materials, often in association with mining and industrial land uses.	Usually associated with old mining sites and urban sites. Common in small sites in South America and Africa and other locations.

Table 4 Land and soil degradation drivers, processes and impacts Source: Adapted from Palm et al. 2007; Dominati et al. 2010; Lal and Stewart 1990

Driver (Cause of degradation)	**Degradation process** (not aligned across rows within causes)	**Impact on soil processes** (not aligned across rows within causes)
Biomass burning, removal of organic residues	* Loss of vegetation cover * Exposure of surface to water and wind erosion * Loss of soil organic matter * Breakdown of soil structure, aggregation and porosity * Crusting and surface sealing * Removal of soil organic carbon/soil organic matter	* Reduction in infiltration capacity * Changes in soil water retention * Increased runoff rate and amount * Accelerated erosion by water and wind – depends on rainfall erosivity, slope and soil erodibility *Increased bulk density and reduced porosity * Reduction in N and nutrient mineralization from soil organic matter * Reduction in activity of soil biota
Excess tillage, excessive traffic by machinery and animals causing compaction, overgrazing	* Reduction in aggregate stability * Increased bulk density and reduced porosity * Compaction of soils * Loss of vegetation, reduced vegetation cover * Exposure of loosely tilled soil to erosion pressures * Removal soil organic carbon/soil organic matter	* Accelerated erosion by water and wind - depends on rainfall erosivity, slope and soil erodibility * Increased bulk density and reduced porosity * Waterlogging and anaerobic conditions * Reduction in N and nutrient mineralization from soil organic matter * Reduction in activity of soil biota
Insufficient fertiliser, no legumes in rotation	* Nutrient depletion	* Decreased amounts of available macronutrients including N, P, S, K * Poor growth leads to decreased soil organic matter
Excessive use of fertilisers	* Acidification following leaching after excessive addition of N * Eutrophication of waterways and water resources following leaching of excess nutrients or inclusion of nutrients in sediments.	* Acidification of soils and Al and or Mn toxicity following nitrate leaching or removal of N in produce. * Leaching of nutrients and pollution of waterways and water sources with excessive nutrients. * Emission of N_2O into the atmosphere * build-up of some heavy metals such as Cd with excessive use of some [poor quality fertilisers
Little or no organic inputs into the soil	* Decline of soil organic carbon * Decline in diversity and abundance of soil biota	* Shift in species composition and diversity of favourable soil organisms
Irrigation with poor quality water, inadequate drainage	* Salinization * Build-up of exchangeable sodium.	* Accumulation of soluble salts in soils and increasing levels of electrical conductivity * Accumulation of exchangeable sodium in soils to critical levels that affect soil properties * Increasing pH in soils high in carbonates in association with increasing levels of exchangeable sodium (alkalinization).
Application of industrial, mining, urban wastes, some pesticides and herbicides	* Toxification, contamination with heavy metals, pollution	* Excessive build-up of some compounds and elements _eg Al, Mn, Fe, heavy metals (Pb, Hg, Cu) * Increase in soil pathogens

Soil health has two dimensions: soil capability (determined by the inherent, largely stable properties, that determine the natural limitations that influence potential productivity), and soil condition (determined by variables that reflect the soil status, and thus the current productivity). Soil health is only one contributor to the capacity of land to sustainably generate ecosystem services (Herrick *et al.* 2013b, 2016; UNEP, 2016). This capacity, the land potential, is dependent on the natural capital of the land, which is determined by the properties of the soil that constitute soil capability, and the geomorphological, biological, hydrological and climatic features of the site (Orr *et al.* 2017). The relationship between land capability and soil health is illustrated in Figure 9. Land capability (as defined by OEH, 2012, see also Dent and Young 1981; Emery 1986; Gray *et al.* 2015) is a similar concept to land potential; here, we use the term land potential. Land potential has two aspects: (1) the natural capital, determined by soil capability and site features, that interact to determine the quantity and nature of ecosystem services provided (FAO 1976, 2007; Dominati *et al.* 2010); and 2) resilience, which determines the susceptibility to degradation, and therefore the ability to absorb disturbances without degradation or change to the functionality of the system (OEH 2012; Dent and Young 1981; Gray *et al.* 2015;). These two aspects are independent: a soil with a low capacity to provide ecosystem services, may have a high or low resilience; similarly, a soil with a high capacity to provide ecosystem services may have a high or low resilience. The land's natural capital governs productive potential, and, therefore, the delivery of provisioning services, including food production. The land's resilience determines the probability of maintaining food production under the impact of shocks and trends such as drought, population increases or market collapse, and the land management changes that result from these drivers. If land is used beyond its capability, land degradation is likely to occur (Gray *et al.* 2015). Land suitability (FAO, 1976, 2007) is a related concept that describes how appropriate a specific land use is for a specific site, based on likely yields, inputs and risks.

Understanding which soil properties constitute soil capability and soil condition, and how land management practices affect those properties, provides a pathway for identifying soil constraints and risks, choosing suitable SLM practices, and selecting indicators to evaluate the outcomes of SLM interventions. Inherent features such as climate, landform, soil depth and texture and mineralogy determine the capacity of a soil to provide ecosystems services, and the risk of land degradation, so are useful indictors of land potential and soil capability. The major properties that determine land potential and soil capability are listed in Table 5. Climate and landscape features influence the productivity of a site and have a large effect on the drivers of land degradation, as well as the resilience of soils. Monitoring soil condition is a key element in detecting land degradation, identifying where current practices are unsustainable and evaluating the effectiveness of SLM interventions (Shepherd *et al.*, 2008; Lal 2013). Suitable indicators for monitoring soil condition depend on the specific features of the site and the ecosystem services that are the target of SLM practices. The soil processes and properties that support particular ecosystem services, and drivers that impact on these functions, are listed in Table 6. There are many interactions between properties, functions and ecosystem services. For example, the ecosystem service of regulating water flows in the landscape is dependent on soil hydraulic properties, the capacity of the soil to support transpiring vegetation and ground cover. Therefore, there are many properties that influence each soil function, as shown in Table 6. Properties that can be suitable indicators of soil condition are listed in the final column of Table 6. These are properties that reflect degradation status, and are responsive to SLM practices. There are many interactions between properties, functions and ecosystem services. For example, the ecosystem service of regulating water flows in the landscape is dependent on soil hydraulic properties, the capacity of the soil to support transpiring vegetation and ground cover. Therefore, there are many properties that influence each soil function, as shown in Table 6. Properties that can be suitable indicators of soil condition are listed in the final column of Table 6. These are properties that reflect degradation status, and are responsive to SLM practices.

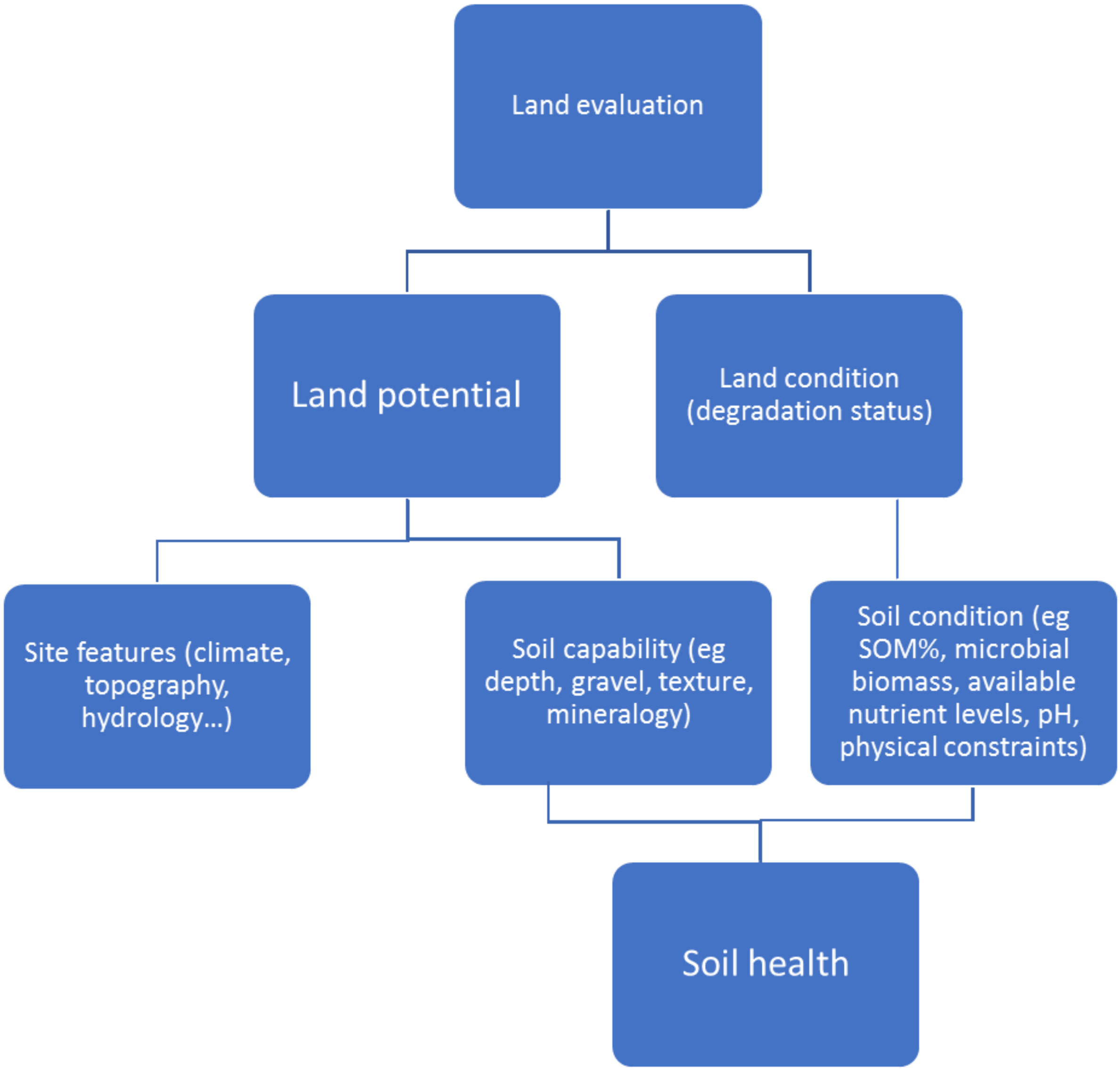

Figure 9 Relationship between land potential and soil health, and the factors that determine these key aspects

Selection of properties to indicate soil condition, land degradation and the response to SLM should be based on the ecosystem services of most importance in the context (soil, landscape and land use) (Carter, 2002). Lal (2016) noted the physical, chemical, biological and ecological soil attributes that are responsible for soils providing different ecosystem services. Soil organic carbon level was identified as a key determinant of ecosystem services. Liniger *et al.* (2011) emphasised the functions that soils contribute to productivity, especially the supply of water and nutrients to plants. Ghuman and Narang (1998) emphasised sodicity and salinity in the assessment of the suitability of soils for irrigation on the upper Gangetic Plains of India, where salinization and sodicity were a high risk. Shepherd (2008, 2009) utilises field observations of soil colour, texture, earthworms, drainage, structure and root growth to assess soil health. A scheme developed in the Kilimanjaro region of Tanzania estimates soil health based on visually assessed indicators including ease of penetration using a penetrometer, ease of infiltration, diversity of macro-life, presence of earthworms, soil structure, root development, aggregate stability of the soil samples at the 10 - 20 cm depth, and plant size and leaf colour (Sangeda *et al.* 2014). Some examples of indicators chosen to monitor specific land degradation problems, and the effectiveness of the SLM practices used to address them, are presented in Table 7. Box 6 provides guidance on selecting suitable indicators for monitoring effectiveness of SLM in addressing land degradation.

Figure 10 Irrigated wheat grown with zero tillage and controlled traffic to maintain soil health, Australia. Photo: B. Murphy

Figure 11 Biochar application, Kenya. Biochar is an effective soil amendment (see Box 4). Photo: E. Barrios

Table 5. Land and soil properties that determine land potential and soil capability

Horizon properties	Profile properties	Site properties
Soil physical properties Matrix colour Texture Content of sand, silt, and clay Clay mineralogy Bulk density* Porosity Self-mulching characteristics Aggregate stability Friability Saturated hydraulic conductivity Rock fragment content 1/3 Bar water holding capacity 15 Bar water holding capacity Infiltration rate	Classification (WRB - IUSS 2015; Soil Taxonomy - Soil Survey Staff 1999; Isbell 2016) Depth to water table Depth to bedrock Depth to a restrictive layer Plant available water storage capacity Profile drainage Salinity profile Incidence of waterlogging Presence of acid sulphate minerals	**Climate** Rainfall – amount, distribution, intensity, erosivity. Drought frequency, duration Temperature – distribution, average annual temperature, extremes, frosts Evaporation – annual total, timing of high evaporative demands Ground cover* Winds – velocity, timing in relation to ground cover temporal trends and growth stages of crops
Engineering properties Particle size distribution (texture) Unified soil classification AASHTO class Plastic and liquid limits Swelling potential Linear shrinkage		**Geomorphology** Parent material Slope (gradient, shape, length, aspect) Landform element Surface stones Rock outcrop Elevation
Soil chemical properties Natural soil pH* Buffering against acidification Cation exchange capacity Exchangeable cations (ESP) Base saturation Organic carbon content* P buffer capacity Toxicities (e.g. exch Al, heavy metals) Electrical conductivity (salinity) Alkalinity		**Hydrology** concentration of flows, flow regimes flood hazards drainage
Soil biological properties** Soil biodiversity Organic carbon content (Organic soils) Total N Soil macrofauna Microbial biomass Enzyme analysis		**Other** Day length Vegetation Land use history Erosion risk

Source: Adapted from USDA (2015) properties used to assign Land Capability Classes and OEH Land Capability system (OEH 2012)

*Properties that can be influenced by management.

**Biological properties are strongly influenced by management.

Table 6. Relationships between ecosystem services, their drivers, supporting soil functions, related land and soil properties, and relevant indicators.
Source: Adapted from Mausbach and Seybold, 1998; Gregorich, 2002; Sanchez et al. 2003; Palm et al., 2007; Dominati et al., 2010; McBratney et al. 2014; Lal 2013, 2016; Hazelton and Murphy 2016; Sangeda et al. 2014.

Ecosystem service	Drivers, Pressures and controlling variables and processes	Soil functions that support ecosystem services	Land and soil properties that influence soil functions	Indicators of soil condition
A. Produce biomass • Provisioning • Structural	* Climate * Soil Formation * Geomorphology and landform processes * Land use	* Provide adequate moisture and heat for plant growth * Provide medium for seed germination and emergence of seedlings * Provide suitable medium for root growth and development * Suitable chemical environment– not saline or sodic, no toxins, suitable pH; * Suitable physical environment – no physical impediments, good aeration); Suitable biological environment – free of pests and diseases.	Climate – rainfall, evaporation, temperature, frosts, occurrence of extended dry seasons or periods of low soil temperatures Soil depth, root restricting layers Rock outcrop Salinity profile Texture, gravel, structure, bulk density, water holding capacity Primary minerals in parent material, pH, cation exchange capacity, Soil organic matter Clay mineralogy, sodicity, fixation of P Toxicities	Crop yield trends Ground cover Soil depth, rock outcrop Gravel content Plant deficiency symptoms Soil organic carbon concentration - *adequate to provide nutrient cycling and influence soil structure.* Soil nutrient levels (N, P, K, S) Soil pH, acidity, Al toxicity, alkalinity Cation exchange capacity - *adequate to hold nutrients and provide buffering capacity* P buffering index Bulk density, soil porosity and soil strength, Water holding capacity Aggregate stability, friability ESP of soils – surface soil, subsoil (6 to 15% sodic, > 15% highly sodic) Presence of compacted layers Surface sealing/crusting Salinity – ECsat > 4 dS/m
B. Store and recycle nutrients • Provisioning • Filter and reservoir	* Mineral weathering * Climate * Plant growth *Mineralization of soil organic matter * Land use (rotations, legumes, fertiliser use)	* Receive, store and release essential nutrients for plant growth * Provide an environment that does not contain toxic compounds or elements that can limit plant growth.	Soil depth Primary minerals in parent material, pH, cation exchange capacity Soil organic matter Nutrients, NPKS, micronutrients Clay mineralogy Texture, water holding capacity, hydraulic conductivity, macroporosity	Soil organic carbon concentration Soil colour Soil Nutrient levels (N, P, K, S) Cation exchange capacity Crop yield trends Plant deficiency symptoms Plant tissue nutrient levels Root nodulation of legumes (See Appendix 2)

			Microbial activity – microbial biomass, enzyme activity, ratio of fungal to bacterial species. Macrofauna activity in soils	Soil biological activity – * microbial biomass, enzyme activity, ratio of fungal to bacterial species * presence of macrofauna (earthworms, mites, nematodes)
C. Regulate water flow and quality • Filter and reservoir	*Climate *Hydrological properties of soils and geology * Geomorphology and landform processes * Plant growth and ground cover * Land use	*Receive, store and release water for plant use * Retain adequate water to buffer and reduce effects of drought * Provide adequate infiltration and storage to use rainfall and reduce runoff, flooding and erosion. * Provide ground cover to regulate overland flows * Efficient and effective use of irrigation water	Climate Soil depth Texture, water holding capacity, hydraulic conductivity, macroporosity Cation exchange capacity, soil organic matter See properties affecting Biomass Production – development of ground cover. Quality of irrigation water and soils used for irrigation	Erosion risk (Revised Universal Soil Loss Equation), rainfall erosivity, slope, slope length. Infiltration rate Hydraulic conductivity Presence of surface ponding Penetrometer resistance after rainfall ESP of soils – surface soil, subsoil (6 to 15% sodic, > 15% highly sodic) Salinity profile (ECsat > 4dS/m) EC and SAR of irrigation water Profile drainage
D. Filter and buffer nutrients, wastes and toxic agents. • Filter and reservoir	Hydrological properties of soils and geology * Geomorphology and landform processes * Plant growth and ground cover * Land use	* remove, adsorb or absorb and deactivate compounds and elements that can cause toxicities in soils or pollution to ecosystems.	Soil depth Texture, water holding capacity, hydraulic conductivity, macroporosity Cation exchange capacity, soil organic matter Toxicities See properties affecting Biomass Production. Acid sulfate soils – production of acidity after drainage	Clay content Cation exchange capacity Soil organic carbon concentration Infiltration rate Microbial activity Presence of toxic agents (heavy metals, pollutants) Plant growth (see A.) Presence of Acid Sulfate Soils
E. Carbon storage and regulation of greenhouse gases Climate regulation	* Climate * Soil Formation * Geomorphology and landform processes * Plant growth and ground cover * Land use	* Mitigate climate change through carbon sequestration, minimisation of carbon dioxide emissions and mitigation of other greenhouse gas emissions (N_2O and CH_4).	Soil organic carbon concentration Soil organic carbon stocks Soil texture See properties affecting Biomass Production Waterlogging and possibility of anaerobic conditions and emission of methane and nitrous oxide	Soil organic carbon concentration Soil organic carbon stocks Indicators of biomass production (see A) Profile drainage

F. Provide structural support for infrastructure and traffic Structural	* Soil Formation * Geomorphology and landform processes * Land use	* Provides stable support for human infrastructure such as buildings, roads, bridges etc.	Climate Soil depth Soil engineering properties Texture, cation exchange capacity, gravel	Soil texture Clay mineralogy Gravel content Cracking clays – high shrink swell Soil organic matter
G. Protecting /enhance biodiversity. • Provisioning – biological resource • Support – nutrient cycling, soil formation	* Climate * Soil Formation * Geomorphology and landform processes * Plant growth and ground cover * Land use	* Soils are a reservoir of biodiversity. They provide habitat for thousands of species regulating for instance pest control or the disposal of wastes. * Soils provide a specific medium for many unique ecosystems and vegetation communities. * Provide medium for microorganisms that decompose organic matter, release nutrients, fix nitrogen.	Climate Soil profile features Ground cover	Soil organic carbon concentration Soil organic carbon fractions Ground cover Soil type
H. Provide a source of materials for construction and raw materials for industry Resource	* Geology * Soil Formation * Geomorphology and landform processes	* Soils can be a source of materials like peat and clay.	Soil engineering properties	Soil texture Clay mineralogy

Table 7. Examples of SLM practices implemented to address specific land degradation processes, and indicators of soil health selected to monitor effectiveness of SLM practices.

Land degradation process	Soil health indicators monitored	Sustainable land management practice implemented	Source
Acidification resulting from use of sulphur powder to control powdery mildew in cashews	**soil pH**: Soil pH values below 5.0 in water. Only soils with low buffering capacity affected.	Liming using local fossil limestone or use alternatives to control powdery mildew such as organic fungicides	Ngatunga *et al.* (2003)
Water erosion from land using conventional cropping practices is 33 to 127 t/ha/yr. Soil loss at this rate is unsustainable.	**erosion – erosion sites and deposition sites**: Measured soil loss from plots and the predicted soil loss from the Revised Universal Soil Loss Equation (Renard *et al.* 1996) are very high for conventional cropping of maize in south-eastern Tanzania. The rainfall erosivity is high.	Implement erosion control measures including: maintaining crop residues on the surface, use of lemon grass strips and use of ridges and furrows to slow the flow of water.	Kabanza *et al.* (2013)
Nutrient depletion and declining levels of soil nutrients in sub-Saharan Africa.	**Crop yields, soil carbon and soil nutrient and plant tissue levels**: Net negative balance of N in relation to the amount of land under fallow in sub-Saharan Africa. The effect of potential arable land per capita.	Integrated nutrient management program using both organic and inorganic inputs of nutrients. Establish an environment that allows for the efficient use and availability of external nutrient sources and measures for the conservation of local fertility levels compatible with local opportunities and constraints.	Drechsel and Penning de Vries (2001)
Nutrient depletion through long-term cropping and erosion.	**Crop yields, soil carbon and soil nutrient and plant tissue levels**: Low soil fertility in semi-arid areas of India.	Soil testing to determine deficiencies (possibly of sulphur, boron and copper). Use of biological N fixation through legumes (pigeon peas and chickpeas). Application of P, but through careful management to ensure right amounts applied and method of placement, timing and quantity are optimised.	Wani *et al.* (2008)
Desertification, fertility decline, reduced soil organic carbon, water and wind erosion, reduction of vegetation cover and species/biodiversity decline, loss of fodder value.	**Ground cover, dust, soil carbon and nutrient levels**: In semi-arid landscapes low ground cover, lack of feed, overgrazing Water and wind erosion combine to create large areas of bare ground.	Integrated crop and livestock management. Management practices include: harvesting and relocating nutrients, dual purpose crops, addition or control of plant species, haymaking, production of forages, grasses and leguminous trees, use of enclosures and stall feeding of animals. Other specific practices include night corralling, rotational fertilization, grazing land improvement, small stock manure production and development of passageways for moving stock through cropping areas (Couloirs de passage)	Liniger *et al.* (2011)

5. Sustainable land management – principles and practice

5.1. Introduction to the principles for SLM interventions

The development of SLM practices requires an understanding of the pressures on land to produce food and other goods and environmental services (described in Chapter 2), as well as the biophysical characteristics of the land that influence its response to these pressures. If these biophysical characteristics are not adequately understood and managed, it may result in long-term deterioration in soil health and ecosystem condition (i.e. land degradation). Interactions between rural livelihoods, water use, climate change mitigation and adaptation and biodiversity conservation can lead to trade-offs or synergies (Scholes and von Maltitz, 2006). These interactions must be considered so as to balance competing objectives and ensure beneficial outcomes across the multiple areas of ecosystem management. An ecosystem approach to SLM based on understanding of the processes of land degradation can separate multiple drivers, pressures and impacts (Kassam *et al.* (2013); this is consistent with the strategic approach of the Millennium Ecosystem Assessment (MA, 2003; Niemeijer and Moran, 2006).

Implementing SLM practices will act to avoid, reduce and in some cases reverse degradation, thus addressing adverse effects of earlier poor management. Agricultural management practices promoted through the "Green Revolution" have, in some regions, been extremely successful in increasing crop yields. Their long-term sustainability, however, is now questioned because of issues such as excessive use of chemical fertilisers that impact on nutrient balances and pollute waterways and reservoirs, depletion of water resources, biodiversity impacts and emissions of greenhouse gases. This has resulted in concerns over the sustainability of management practices in these systems, with respect to food security, climate change and the livelihood of communities.

To be effective, SLM programs require metrics and assessment tools appropriate to the scale and context of intervention activities. They also need institutional and policy support for promotion and adoption of improved practices (ODG, 2006; World Bank, 2008; Kassam *et al.,* 2013).

5.2. Good practice for SLM – principles and strategies

The development of SLM recommendations is context- and scale-dependent. However, high-level principles express the general features of SLM that are applicable at a range of scales.

SLM considers the three pillars of sustainability: environmental, economic and social. It aims to maintain the land-based natural capital, to enhance ecosystem services including production, to minimise offsite impacts, complement natural processes, apply ecosystem-based approaches, enhance the resilience of agro-ecosystems and support sustainable livelihoods. A process of adaptive management, revising practices as new technologies and land management understanding become available, is vital. Therefore, high-level principles of SLM are:

- maintain the productivity of the land resource base
- sustain ecosystem functions
- utilise and complement natural processes for nutrient management, pest management
- minimise disturbance of natural systems
- minimise greenhouse gas emissions
- reduce dependency on inputs derived from fossil fuels (fuel, mineral N fertilisers, pesticides)

- minimise emissions of pollutants to air, water and soil
- enhance agro-diversity
- use resources (nutrients, water, fuel, land, labour) efficiently
- use pesticides prudently
- seek co-benefits, in environmental, social and economic outcomes [balance environmental, economic and social sustainability]
- manage competing objectives at the landscape/catchment scale
- sustain livelihoods, especially for vulnerable communities
- enhance food security
- involve stakeholders, especially land users, and apply local knowledge in devising SLM recommendations
- apply adaptive management, based on results of monitoring and new knowledge.

(based on Cowie *et al.*, 2017; World Bank, 2008; Kassam *et al.* 2013; FAO, 2000; Thiombiano and Meshack, 2009; Sanginga and Woomer, 2009; Liniger *et al.,* 2011; Jat *et al.,* 2014).

At the regional level, good practice for SLM will align with regional and national priorities. These relate largely to the social and economic constraints and benefits of implementation of SLM (World Bank, 2008). Potential benefits of some SLM practices are summarised in Table 8. Regional and national priorities that can be addressed by SLM include:

- agronomic sustainability – assessed according to a range of soil characteristics, including trends in nutrients and organic matter over time
- policy objectives – economic growth and employment opportunities
- smallholders' concerns – their workload, returns for their labour, food security for their family, and start-up costs of new systems or techniques
- policy and institutional barriers to adoption by smallholders, including access to credit, markets and improved technology
- response to global environmental concerns, including carbon stocks in landscapes and biodiversity.

At the field scale, where SLM practices are to be implemented, the high-level principles are translated to the local situation and application. SLM recommendations based on these principles will vary depending on the local soil type, climate, landform, water access and agricultural enterprises, and on socioeconomic circumstances, such as access to finance, labour and markets, and cultural context. For example, the applicability of specific practices will depend on factors such as rainfall amount and distribution, erosivity, and the occurrence of extended dry periods or periods of low temperature (Soane *et al*., 2012; Derpsch *et al.,* 2014). Above all, SLM recommendations must be workable practices that can be applied to current cropping and grazing activities. Examples of strategies for the implementation of SLM at the local level include the following (Dixon *et al.*, 2001; World Bank, 2008; FAO, 2000; Thiombiano and Meshack, 2009; Sanginga and Woomer, 2009; Liniger *et al.,* 2011; Kassam *et al*., 2013; Jat *et al.,* 2014):

- reduced or zero tillage to minimise mechanical disturbance of soil;
- maintenance of cover (vegetation or residues) to protect the soil surface from erosion, enhance infiltration, reduce weeds and conserve soil water;

- species diversification, including use of crop rotations, inter-cropping, agroforestry, addition of perennial grasses and legumes into pastures;
- adjustment of stocking rate and stock management to avoid over-grazing;
- use of fallow or "rest" periods (noting that some form of vegetation cover should be retained on the soil during fallow, rather than a cultivated fallow);
- integrated pest management, that combines biological control, cultural practices, genetic resistance, crop diversity and chemical control, aiming to suppress pest populations and minimise economic damage with minimal use of pesticides;
- integrated soil fertility management using locally appropriate and cost-effective combinations of organic or inorganic and on-farm or off-farm sources of plant nutrients (such as use of organic manures, crop residues and rhizobial nitrogen fixation; transfer of nutrients released by weathering in the deeper soil layers to the surface via tree roots and leaf litter; and strategic use of rock phosphate, lime and mineral fertiliser);
- integrated water management to increase rainfall infiltration and reduce runoff so as to improve soil moisture conditions within the rooting zone, thereby lessening the risk of moisture stress and reducing erosion, using contour cultivation, terracing or pits;
- enhanced soil organic matter to improve water infiltration and storage, nutrient supply, and soil structure through the use of compost, animal manure, biosolids, green manures, surface mulch, enriched fallows, agroforestry, cover crops and crop residue management;
- better agronomy using improved seeds of locally-adapted varieties; improved crop establishment; effective weed control;
- improvement of rooting depth and permeability by breaking cultivation-induced compacted soil layers by strategic tillage (using tractor-drawn subsoilers, ox-drawn chisel ploughs, or hand-hoe planting pits or double-dug beds) or interplanting deep-rooted perennial crops, trees, and shrubs, and use of controlled traffic farming to minimise compaction;
- microclimate management, using windbreaks and mulch to reduce evapotranspiration, optimise temperature and radiation and reduce mechanical damage to plants;
- rehabilitation, where appropriate (that is, if technically feasible and cost effective), of cultivated land that has been severely degraded by processes such as gullying, loss of topsoil from sheet erosion, soil compaction, acidification or salinization;
- integration of pastures, trees and livestock into cropping systems; and
- support from adequate and appropriate farm power and equipment.

Ten "laws" proposed by Lal (2009, 2010b, 2013) provide useful insights for developing sustainable land management practices:

1. The biophysical process of soil degradation is driven by economic, social and political forces.
2. The stewardship concept is only relevant when basic necessities are met.
3. The nutrient and carbon pools in soils can only be maintained if all outputs are balanced by the inputs.
4. Marginal soils cultivated with marginal inputs produce marginal yields and support marginal living.
5. Plants cannot differentiate between nutrients supplied through organic or inorganic sources; it is a question of logistics, cost and availability.
6. Agricultural soils can be a net source or sink for greenhouse gases depending on land use and management.

7. CO_2 released through mineralisation of soil organic matter has the same global warming effect as CO_2 from burning fossil fuels.
8. The yield potential of improved germplasm can be realised only if grown under optimal soils and agronomic conditions.
9. Sustainable land management is the engine of economic development, political stability, and transformation of rural communities, particularly in developing countries.
10. Sustainable management of soil implies the use of modern innovation built upon traditional knowledge.

SLM practices will necessarily vary to address local land degradation problems or vulnerability, and specific land management goals. Practices and programs used to implement SLM will vary between land management systems. For example, SLM practices for rain-fed farming systems in humid areas will differ from those for wetland rice-based farming systems, irrigated farming systems or dry land farming systems, due to the need to manage different constraints and limitations. Potentially effective SLM practices will also depend on the available natural resource base, intensity of production and access to technologies. The land degradation problem of most concern should be first identified and then SLM practices selected to combat that problem. Table 7 provides some examples of SLM practices identified to address specific land degradation issues.

Box 4. Use of Biochar

Biochar is the charcoal-like material produced by heating biomass in an oxygen-limited environment. Suitable sources of biomass for biochar include crop residues, wood, manure, greenwaste such as garden trimmings, or waste from paper mills (Kookana *et al.,* 2011). As well as providing effective waste management, the production of biochar can also produce bioenergy, from the combustible gases released during production of biochar.

Biochar is a useful soil additive that can simultaneously mitigate climate change by providing long-term storage of carbon in soils, while improving soil fertility and soil health (Verheijen *et al.,* 2009). Properties of biochars, which determine their value in nutrient cycling and for improving soil physical properties, depend on the biomass source and the temperature of biochar production (Verheijen *et al.,* 2009; Kookana *et al.,* 2011). Biochars can provide agronomic and environmental benefits in nutrient-poor or degraded soils through increased cation exchange capacity, reduced nutrient leaching, enhanced water holding capacity, reduced soil acidity and stimulation of microbial activity (Kookana *et al.,* 2011; Lehmann and Joseph, 2015). Biochar should be chosen to address the particular soil constraints at the site of application. The effectiveness of biochar can be enhanced by mixing with organic or mineral fertilisers prior to application.

The carbon sequestration value of biochar depends on the biomass materials used to make the biochar, and their alternative fate. A life-cycle approach that quantifies the energy and carbon balance across the supply chain, compared with a “no biochar” scenario, is needed to determine the climate change impacts of biochar (Cowie et al., 2015).

Table 8. Example of impacts of SLM for integrated soil fertility management, and constraints to adoption, in sub-Saharan Africa.
Integrated Soil Fertility Management (ISFM) aims at managing soil by combining different methods of soil fertility amendment together with soil and water conservation. It takes into account all farm resources and is based on 3 principles: (1) maximising the use of organic sources of fertiliser; (2) minimising the loss of nutrients; (3) judiciously using inorganic fertiliser according to needs and economic availability (Liniger et al. 2011).

Ecosystem services	**Benefits/constraints of SLM practices or program**			
	Land users	***Watershed/catchment/landscape***	***National / global***	***Constraints***
Production	+++ increased crop yields ++ fodder production/quality increase + diversification of production	++ reduced risk and loss of production	+++ improved food security	·· need for water for composting ·· availability of manure and organic residues for compost, mulching ·· competition with use of straw for animal feed; manure for house construction or fuel
Economic	++ increased farm income ++ easy to maintain and establish ++ simple technology using local available material + reduced expenses on agricultural inputs	++ Stimulation of economic growth +less damage to off-site land, water and infrastructure	+++ improved livelihood and well-being	·· increased labour demands e.g. For using organic nutrient sources ··transportation of manure over long distances too costly ··affordability of inorganic fertilisers for small-scale land users – inflexible packaging in 50 kg bags ··lack of access to credit for investments (especially for inorganic fertilisers)
Ecological	+++ increased soil organic matter and soil fertility ++ improved soil cover ++ reduced soil erosion by wind and water ++ improved excess drainage ++ improved rainwater productivity ++biodiversity enhancement + increased soil moisture + improved microclimate	+ increased water availability + reduced degradation and sedimentation + functioning ecosystem	++ reduced degradation and desertification incidence and intensity ++ increased resilience to climate change +enhanced biodiversity	·· requires time to rejuvenate poor soils – the amount of organic material added is small relative to the mineral proportion ··Waterlogging ··Termites eating trash; trash can harbour pests and diseases ··Source of weeds; green manure could become a weed ·· nutrient addition can stimulate unhealthy plant growth and increase decomposition of soil organic matter
Socio/cultural	++ improved conservation / erosion knowledge ++ "is owned by the farmer" + community institution strengthening + changing the traditional gender roles of men, women	+ increased awareness for "environmental health" + attractive landscapes	+ protecting national heritage	·· Requires adequate knowledge of the right rate, elemental mix, timing and application method, of inorganic fertiliser ··Some efforts do not have an immediate visible impact (e.g. rock phosphate, compost)

Source: Adapted from Liniger *et al.* (2011)

5.2.1. WOCAT – guidelines and best practices for SLM

In collaboration with local landholders and advisers, the World Overview of Conservation Approaches and Technologies (WOCAT) has developed principles and strategies for SLM and a database of SLM practices, with practical guidance on the application of SLM practices at the field scale (Liniger *et al.,* 2011). WOCAT advocates the following principles:

Principle 1 : Water-use efficiency and productivity

- Increase plant water availability in rain-fed agriculture
  Strategies include:
  - minimise runoff and maximise infiltration and storage of water in the soil
    - achieved using soil cover, contour cultivation, stone bunds, terracing, etc.
  - reduce non-productive evaporation
    - achieved through good plant cover, windbreaks, agroforestry
  - harvest and concentrate rainfall through runoff to crop area
    - achieved through planting pits, bunds, micro-basins, etc.
- Increase plant water availability in irrigated agriculture
  Strategies include:
  - minimise water losses from the irrigation system
    - lining of channels, use of pipes
  - efficient and effective application of water
    - water can irrigation, drip irrigation, deficit irrigation, etc.
  - recharge aquifer, groundwater collection to enable off-season irrigation
    - small dams, farm ponds, diversion structures, etc.
- Increase plant water uptake
  Strategies include:
  - increase productive transpiration
    - agroforestry, intercropping, improved crop varieties, soil fertility management, pest and disease control.

Principle 2 – Soil fertility

- Reduce nutrient mining and losses
  Strategies include:
  - integrated fertility management, manuring and composting, rotations including legumes, micro-fertilization, improved fallows
- Improve soil nutrient holding capacity and plant nutrient uptake capacity
  Strategies include:
  - minimum to no-till, improved soil biological activity, increased soil organic matter, improved plant varieties, etc.

Principle 3 – Plants and their management

- Maximise yields
  Strategies include:
  - Use best-suited plant materials and optimise management
    - choice of species, drought tolerance, planting dates, pest and disease resistance.

Principle 4 – Micro-climate management

- Create favourable growing conditions
  Strategies include:
  - reduce evapotranspiration
    - windbreaks, agroforestry, good soil cover, etc.
  - optimise temperature and radiation
    - agroforestry, mulching
  - reduce mechanical damage to plants
    - windbreaks, mulching.

The implementation of the WOCAT principles requires the identification of relevant SLM practices, that will vary from region to region, depending on climate, soil type and local socioeconomic constraints. WOCAT is developing a decision support framework to assist land managers to identify applicable SLM practices.

5.3. Examples of specific SLM strategies

5.3.1. Integrated Soil Fertility Management (ISFM)

ISFM practices combine judicious use of inorganic fertilisers with inputs of locally available organic materials (crop residues, compost) and mineral amendments (lime, rock phosphate), to maximise the efficiency of nutrient and water use and improve agricultural productivity (Sanginga and Woomer 2009; Winterbottom *et al*., 2013). In addition, ISFM promotes use of improved germplasm, diversified cropping systems (agroforestry, crop rotations) and good agronomy, to ensure efficient use of nutrients. Improved efficiency requires maintaining nutrient balance, correcting soil acidity and making effective use of organic sources of nutrients. Maximum benefits can only be achieved with adequate and affordable supplies of farm inputs, as well as effective support services and policies.

ISFM aims to deliver nutrients in a resource-, labour- and cost-effective manner, which can vary between different agroecological zones. For example, in the lowland savannah of Africa, emphasis is on micro-dosing of fertilisers and the use of rock phosphate; in the lowland moist savannah, there is more emphasis on cereal legume rotations. Biochar, a product rich in stable carbon that is promoted for storing carbon in soils, may also improve soil health, water holding capacity and productivity (Box 4). The overall aim of ISFM is to enhance productivity and nutrient-use efficiency. The use of improved seeds and varieties is also an important way of obtaining full benefit from improved nutrient levels (Winterbottom *et al.*, 2013).

ISFM contributes to SLM through practices that lead to the sustainable management of nutrient levels in soils. ISFM recognises the importance of recycling organic sources of nutrients, and of N fixation by plants. However, it also acknowledges the potential contribution of strategically using mineral fertilisers to maintain the nutrient balance in soils. It is perhaps timely to consider that one of the drivers for development of ISFM is the quote from Dr Norman Borlaug (14 March 2003, Alabama, US): "The soil nutrient losses in sub-Saharan Africa are an environmental, social and political time bomb. Unless we wake up soon and reverse these disastrous trends, the future viability of African food systems will indeed be imperilled."

Synthetic nitrogen is considered necessary to supply sufficient nutrients to ensure food security in the future. However, the additional active N in the environment in the form of nitrates, ammonium and various nitrous oxide gases causes environmental problems. These problems result from changes to the global N cycle. They include increased soil acidification, pollution of rivers and groundwater, and global warming due to emissions of nitrous oxide, a powerful greenhouse gas (Smil, 1997; White, 2000; Galloway and Cowling, 2002). ISFM helps to manage the trade-off between productivity and environmental damage, minimizing addition of active N compounds to the environment.

Principles and strategies to support ISFM (adapted from Sanginga and Woomer 2009) are:

Principle 1 – Apply fertiliser strategically

Strategies include:

- Test soil and foliage to identify nutrient deficiencies
- Replenish nutrients lost through harvest, leaching and runoff.
- Apply fertiliser regularly at rates matched to plant needs during the growth season, to minimise leaching losses.
- Micro-dose individual plants or apply fertiliser in band below the seeding row, to maximise plant uptake especially in high P-fixing soils.
- Apply nitrogen top-dressing.
- Use foliar application especially for micronutrients
- Provide combined seed and fertiliser packages in small quantities that are affordable for smallholders.
- Recover organic nutrients and process by composting
- Combine mineral and organic inputs, to give slow release of nutrients, and potentially add micronutrients, and biomass for the maintenance of soil organic matter.
- Apply lime to acid soils to reduce aluminium toxicity and improve nutrient availability.

Principle 2 – Increase biological nitrogen fixation and soil biological activity

Strategies include:

- Practise legume intercropping or rotations.
- Inoculate legume seed with rhizobia.
- Cultivate legume cover crops and green manures.
- Establish N-fixing trees along boundaries.
- Maintain or enhance soil organic matter levels through organic amendments, stubble retention, and enhancing plant growth.
- Minimise soil disturbance through cultivation

Principle 3 – Improve nutrient recycling (reduce nutrient loss)

Strategies include:

- Establish trash lines along the contour.
- Recover and spread biomass from boundary areas.
- Revegetate degraded and eroded areas.
- Utilise biosolids and composted food waste for fertiliser.

Principle 4 – Promote livestock-crop interactions

Strategies include:

- Utilise ruminant livestock to graze stubble and weeds
- Use manure to improve compost and biochar
- Feed food waste to poultry and pigs

- Make biogas from manure and use digestate for fertiliser
- Use straw for animal bedding, then add to compost

5.3.2. Increasing soil organic matter to improve soil health

Soil organic matter has several key functions in soils, although its importance can vary with soil texture and the soil clay minerals. These key functions include (Krull *et al.*, 2004; Bot and Benites, 2005; Murphy *et al.,* 2015; Sarker *et al.* 2018):

- Nutrient source: soil organic matter is a major source of nutrients in soils and a key part of the cycling of nutrients in soils.
- Cation exchange capacity: organic matter provides charged sites that hold exchangeable cations. This becomes especially important for soils with lower clay contents or soils with more highly weathered clays such as the kaolinites.
- Buffering capacity: soil organic matter can help buffer soils against acidification from agricultural land use.
- Detoxification: soil organic matter can bind heavy metals and pollutants, preventing them from being leached into the groundwater and into streams. The effects are complex, but the capacity of organic matter to bind at least some pollutants is known.
- Improved structure and aggregate stability: organic matter favours the formation and stabilization of soil aggregates, which is important for aeration, infiltration, the friability of soils for tillage and resistance to compaction. Well-aggregated soils are less susceptible to crusting, surface sealing and compaction.
- Water holding and retention: additional soil organic matter can increase soil water holding capacity.
- Soil conservation: increased aggregation promoted by organic matter can reduce the susceptibility of soil to wind and water erosion.

Additionally, soil organic matter is a key reservoir of carbon, since carbon comprises around 58% of soil organic matter. Soil carbon, which is readily measured, is a key indicator of soil organic matter trends.

Soil organic matter level reflects the balance between inputs of organic materials, and losses of soil organic matter through decomposition or erosion. Practices that increase organic matter are those that increase inputs and/or decrease losses. Inputs may be increased by:

- increased plant growth
- retaining crop stubble
- applying organic amendments (compost, manure, biochar – see Box 4)
- including a green manure or pasture phase in crop rotation.

Losses may be reduced by:

- reduced soil disturbance, through minimum tillage
- reduced erosion by maintaining ground cover, contour cultivation, terracing, mulching.

When soil organic carbon levels are low (< 1.0 to 1.5 g/100g) and the soil is somewhat degraded, use of conservation agriculture practices can increase soil carbon levels (Govers *et al.,* 2013). The threshold for “low” soil organic carbon will vary from region to region and between soil types depending on rainfall, temperature and soil properties such as texture and fertility (Allen *et al.,* 2013; Badgery *et al.,* 2013). Bationo *et al.* 2007 illustrate the importance of soil organic matter in maintaining the fertility and productivity of the soils in the agroecosystems of West Africa. Tittonell and Giller (2013) found that the maximum yield of biomass (not grain) increased from 8t/ha for soils with organic carbon concentrations of 0.6 g/100g to 20 t/ha for soils with organic carbon concentrations of 2.1 g/100g.

Govers *et al.* (2013) note that sequestration rates with changed land management practice may be in the order of 0.5 MgC/ha/yr resulting in longer-term changes in soil carbon stocks of 2 to 2.5 Mg C/ha; this is at the limit of detection using sampling methodologies and intensities generally in use. Consequently, the level of uncertainty is high. They observed it is difficult to achieve substantial gains in soil organic carbon storage under well-managed, productive systems where residues are already recycled. In these systems, the objective should be to maintain soil organic carbon levels and productivity.

Where conservation agriculture (reduced tillage and stubble retention) has been widely adopted, there is little variation in cropping practices and often cropping systems differ by one or two tillage operations. Soil carbon levels are similar, and there is limited potential to increase soil carbon through changes in management (Murphy *et al.* 2011). Systems and soils that are degraded offer more potential for improving productivity and for increasing soil organic carbon stocks (Lipper *et al.,* 2010; Powlson *et al.,* 2011; Bayala *et al.,* 2012; Read *et al*., 2012). Soil analysis (see Box 5) can assess how far current soil organic carbon stocks are below the potential under a well-managed system (Hassink, 1997; Verheijen *et al.,* 2005).

There is potential conflict between the objectives of increasing soil organic carbon (SOC) levels and ensuring adequate nitrogen, phosphorus and sulphur nutrition for crops and pastures (Janzen, 2006). Use of the nutrient pool in soil organic matter requires mineralization of the soil organic matter; by definition, this requires the breakdown of the soil organic matter pool. Both objectives may be met by well-balanced and specialised management strategies illustrated by the nutrient management plans outlined above under ISFM (Sanginga and Woomer, 2009).

Soil carbon has become a tradeable commodity under greenhouse gas emissions trading schemes (e.g. Australian Emissions Reduction Fund, DEE, 2017). In future, the sale of soil carbon credits may help fund improved land management practices. At present, however, insufficient knowledge to accurately predict the long-term sequestration resulting from specific management practices has hampered development of cost-effective estimation methods for soil carbon trading.

Box 5. Measurement of Soil Organic Matter and Soil Organic Carbon

The amount of soil organic matter in soils is usually estimated from the amount of combustible carbon in soils. Soil carbon concentration is reported in g C per 100 g oven dry soil. Gravel (soil particles > 2 mm) and plant material are excluded from the analysis).

The amount of soil organic matter is estimated by multiplying the soil organic carbon value by 1.72, based on the assumption that soil organic matter averages 58% carbon by mass. However, the conversion factor can vary between 1.72 and 2.0 (Baldock and Skjemstad 1999).

The soil carbon stock is the mass of soil carbon per ha and is calculated from the concentration and the soil bulk density. The soil carbon stocks are reported as tonnes/ha or kg/m^2 to a specified depth, often 30 cm (Badgery et al. 2013).

5.3.3. Conservation agriculture

Conservation agriculture practices are similar to those used in integrated soil fertility management (see 5.3.1) and to increase soil organic matter (see 5.3.2). They include direct seeding and minimal disturbance by cultivation, crop residues left on the soil surface and the use of cover crops, crop rotations and intercropping (FAO, 2000; Thiombiano and Meshack, 2009; Kassim *et al*., 2013; Jat *et al.,* 2014; Lal 2015).

Conservation Agriculture is described by Kassam *et al.* (2013) thus:

> *"The modern successor of no-till farming—now generally known as conservation agriculture (CA)—………involves simultaneous application of three practical principles based on locally formulated practices ………..: minimizing soil disturbance (no-till seeding); maintaining a continuous soil cover of organic mulch of crop residues and plants (main crops and cover crops including legumes); and cultivation of diverse plant species that, in different farming systems, can include annual or perennial crops, trees, shrubs, and pastures in associations, sequences, or rotations, all contributing to enhance system resilience."*

The implementation of conservation agriculture including manure and composting, vegetation strips, agroforestry, rainwater harvesting, gully rehabilitation and terraces or earthworks is a vital component of any SLM program. However, the adoption of conservation agriculture can be limited by factors such as access to the required inputs and markets for outputs (Govaerts *et al.* 2009), the need for crop residues as stock feed (Jaleta *et al.* 2013) and the need for continued technical support to overcome the challenges and constraints to the adoption of conservation agriculture (Pedzisa *et al.* 2015).

5.3.4. Organic agriculture

Organic agriculture uses ecosystem processes, biodiversity and natural cycles to achieve production benefits rather than using industrial inputs such as fertilisers, herbicides and pesticides (Stewart *et al*., 2013). Therefore, organic agriculture is perceived as more sustainable, enhancing the health of soil, ecosystems and people.

Practices are developed through a combination of tradition, innovation and science. While the objectives of organic agriculture and sustainability are generally consistent, there is much doubt that increasing demands for food production can be met without inputs of synthetic fertilisers (Smil, 1997; White, 2000; Stewart *et al*., 2013). Weed competition is also seen as a major problem for organic agriculture (Stewart *et al.,* 2013), particularly when trying to minimise soil disturbance and use of fossil fuels.

When considering the benefits of organic agriculture, it is also worth remembering the conclusion of Lal (2013), that plants cannot differentiate the nutrient supplied through organic or inorganic sources; it is a question of logistics and availability. On the other hand, macronutrients (N, P,K) supplied as manure or compost are accompanied by a range of other minor and micronutrients that are required by plants but usually not present in chemical fertilisers.

5.3.5. SLM for land restoration and rehabilitation

SLM practices can arrest and reverse the effects of land degradation, and thus can restore or rehabilitate degraded land (Wade *et al.* 2008; Bekunda *et al.*,2010; Liniger *et al.,* 2011; Winterbottom *et al.,* 2013). Winterbottom *et al.* (2013) identified four of the most promising SLM practices for restoring degraded lands as agroforestry, conservation agriculture, rainwater harvesting and integrated soil fertility management (ISFM). From agroforestry, landholders receive wood, fodder, edible leaves and other products; leguminous trees (e.g. *Faidherbia albida*) that fix nitrogen, and increased yields of undersown crops. Use of the leaves as mulch can increase availability of nitrogen and phosphorus to crops. "Farmer-managed natural regeneration" is a low-cost approach to agroforestry, in which regeneration of tree stumps and roots is encouraged and managed, enhancing soil fertility and crop production (Weston *et al.*, 2015).

Repairing severely degraded land may require intensive interventions. In a study in Australia, building banks to pond water was shown to regenerate vegetation and increase soil organic matter on scalded areas (Read *et al.,* 2012).

"Regenerative agriculture" (e.g. Sherwood and Uphoff, 2000; Toensmeier, 2016) and agroecology (e.g. Altieri, 2002) are holistic farm management approaches that encompass a wide range of practices in different environments and farming systems, with a focus on restoration of ecological integrity, landscape function, agrobiodiversity and soil health. They often integrate animal production with cropping, to reduce the need for herbicides and chemical fertilisers. Yields are often lower, but profitability can be higher due to lower input costs (LaCanne and Lundgren, 2018), and they are likely to be more resilient than conventional farming systems.

Landscape Function Analysis (LFA) is a tool to support restoration of degraded lands, especially in more arid areas (Tongway and Hindlay, 2004). Tongway and Ludwig (2005) identified that minimising loss of water and nutrients, and creating spatial heterogeneity, including zones where water and nutrients are concentrated, is key to supporting growth of vascular plants in dryland environments.

Restoration to the natural potential level of productivity may be limited by biophysical factors such as the nature of the soils and the cost of the inputs required for restoration (Bell, 2002). Rehabilitation to a valuable (though lower) level of productivity may be more achievable in the timeframes of interest for SLM investment.

5.4. Integrating soil health, land degradation management and sustainability

5.4.1. Framework for defining good practice in SLM

A framework to identify, develop and support sustainable land management practices is presented in Figure 12. It integrates soil health, land degradation and sustainable development objectives, and will assist in understanding the capacity of SLM to generate global environmental benefits. The framework describes logical steps for defining suitable SLM practices for a site, ecosystem or region, and monitor the impact of the SLM practices. The framework relies on principles and strategies for SLM presented in Section 5.2, and integrates indicators of soil health, ecosystem services and sustainable development. The framework is presented as a linear sequence, but the order should be adapted to suit local circumstances.

5.4.2. Framework overview

The first step assesses the existing situation in terms of the sustainability of current land management practices based on an evaluation of soil health, drivers of degradation, alignment of land use with land potential, the presence and magnitude of yield gaps and socio-economic factors. The second step considers and develops alternative land management practices if necessary. Once selected, the identified SLM practices are implemented and this can take place at different scales ranging from the local, district, regional to national. Finally, a monitoring program is implemented to assess the effectiveness of the selected land management practices.

In summary, the framework involves identifying limitations of current land management practices, and drivers of land degradation, and developing a set of SLM practices to combat land degradation processes that are compatible with the economic and social constraints and goals of the land managers. The final step is to evaluate the impact of the SLM practices on ecosystem services at different scales. The framework is described further in subsequent parts of this chapter.

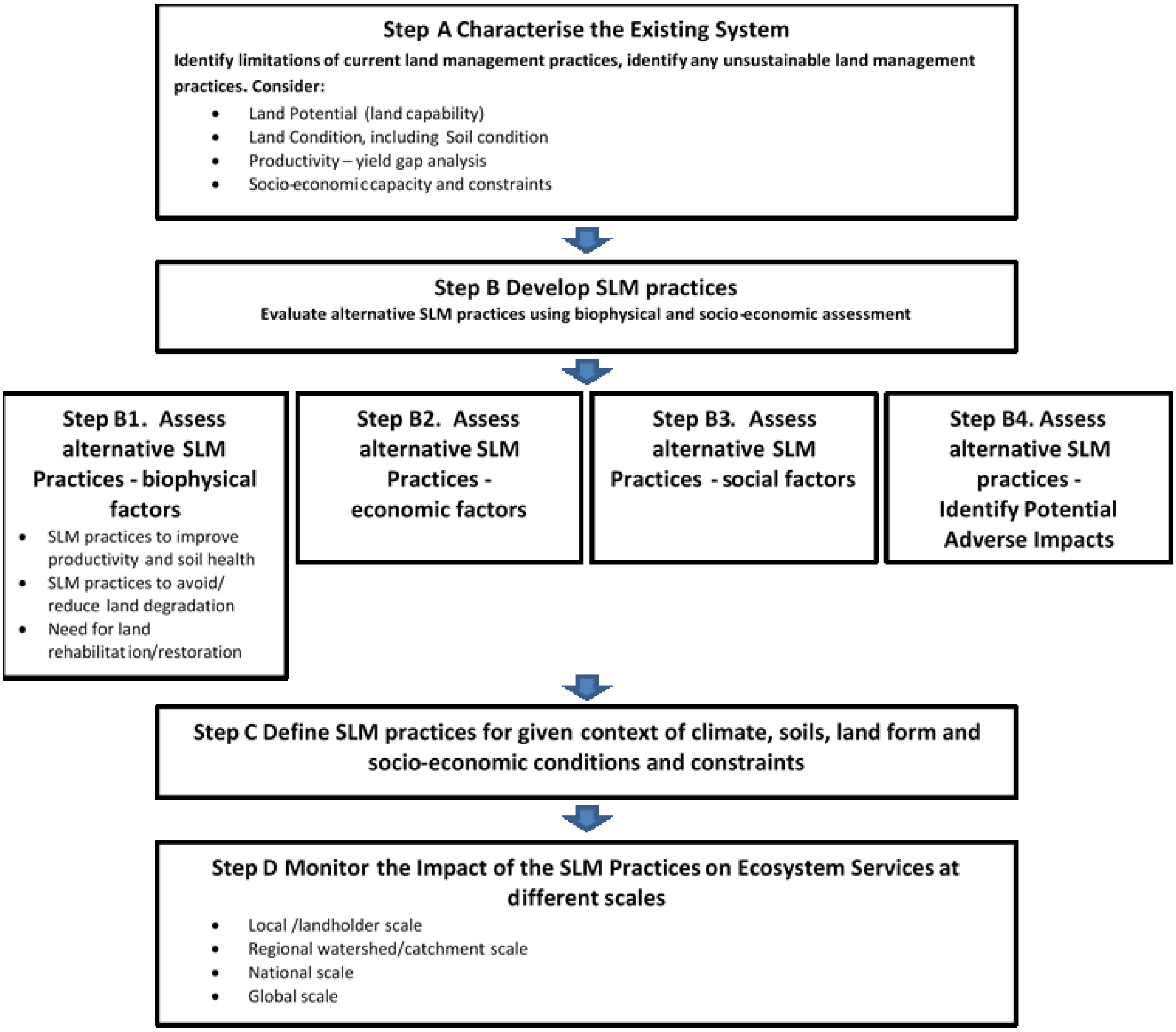

Figure 12 Framework for integrating indicators of soil health, land potential, yield gap and socio-economic objectives to inform sustainable land management. Adapted from World Bank, 2008; Sanginga and Woomer, 2009; Liniger et al., 2011.

5.4.3. Step A – Characterising the Existing System

(i) Land potential assessment

Land potential refers to the inherent capacity of the land to sustain land use and generate ecosystem services (see 4.3). It has two components: (1) the natural capital, determined by soil and site attributes that together determine the capacity to deliver ecosystem services : and (2) resilience, which determines the ability to absorb disturbances without change to the functionality of the system. To reduce the risk of land degradation, land use should be consistent with land potential (OEH,2012; Gray *et al.* 2015; USDA 2015; Orr *et al.*, 2017; Herrick *et al.* 2016). Where the land management practices result in the land being used beyond its potential or capability, land degradation will occur (Gray *et al.* 2015).

Land potential can be assessed using inherent properties such as those listed in Table 5. The Land Potential Knowledge System (Land PKS) is a tool that uses mobile phone and cloud computing technologies to guide the user in land potential assessment based on easily observed site properties, and provides site specific information about long term production and degradation risk under different management scenarios (Herrick *et al.* 2013, 2016).

The Global Soil Partnership (Omuto *et al.*, 2013; Hengl 2014, 2015) has begun collating, organizing and analysing information on soil properties at a global scale. It aims to develop global data sets of derived soil properties such as texture, colour, soil depth and basic soil type. These key soil properties influence land management practices, productivity and land degradation processes. The program aims to develop regional and continental soil information products such as the Soils Atlas of Africa (Jones *et al.*, 2013). While these sources of broad based data are potentially useful, there is still the need for locally based information on soils using defined agro-ecological zones/productive human landscapes to develop implementation programs (Noe 2016) and to develop locally based assessment programs of soil health (Sangeda *et al.* 2014).

(ii) Soil health assessment

Soil health determines the capacity of a soil to deliver ecosystem services, and comprises the soil capability and the soil condition. Soil health assessment is used to detect unsustainable land use, existing land degradation and risk of degradation, and to identify requirements for regionally-specific preventative measures. Soil health information can help to identify the causes of land degradation and how further degradation can be prevented.

Assessment of soil health for a given site is based on identifying the specific ecosystem services critical for that site and context, the likely land degradation processes, and the purpose of the assessment (see Tables 2, 3 and 4, Appendix 2). Relevant indicators of soil health vary regionally with climate, soil type and land management system, and the purpose and scale of assessment. Indicators of soil capability (Table 5) assess inherent soil properties that influence potential. Soil is condition is generally assessed using indicators of specific soil limitations or properties that are responsive to land management (Table 6, Table 7). Box 6 provides a sequential guide to identify indicators of soil health, and Section 0 provides further information on the selection of indicators. The process in Box 6 is designed to identify the purpose, key soil functions and degradation processes, and then the relevant soil properties needed to quantify and monitor soil health and effectiveness of SLM in maintaining those functions. Emphasis is given to soil properties that affect plant productivity. Examples of indicators chosen to monitor specific land degradation problems, and the effectiveness of SLM practices, are given in Table 7. A key step is interpreting the data with respect to critical thresholds and desirable values. Carter (2002) presents critical values for some soil properties, including hydraulic conductivity, bulk density and penetrometer resistance; however, the critical values will vary with the purpose and functions associated with the assessment of soil health in any context. Biophysical information about soils at local and regional levels is needed to identify the major limitations that will be the focus of SLM interventions and monitoring (Table 6, Table 7). A scientifically rigorous approach, based on strong understanding of the target system, should be the basis for selecting indicators for assessing soil health and monitoring land management interventions (Palm *et al.*, 2007; Shepherd *et al.*, 2008; Orr *et al.*, 2017). Effective and efficient sampling schemes to monitor soil health are needed (Shepherd *et al.*, 2008; Sanginga and Woomer, 2009). At the local scale, specific schemes can be designed that are tailored to local soil conditions and agricultural systems. A field tool to assess soil condition using readily assessed indicators such as penetrometer resistance, infiltration, cloddiness, root development, earthworm activity, pH and plant size and leaf colour was developed for the Kilimanjaro region in Tanzania (Sangeda *et al.* 2014). Other schemes using visual assessment of soils have also been developed (Shepherd *et al.* 2008b; Shepherd 2009). Recent developments in use of spectral analysis allow rapid, inexpensive assessment of a range of soil properties (Shepherd and Walsh, 2007; Viscarra Rossel *et al.*, 2007) and could be deployed for in-field measurement (Viscarra Rossel *et al.*, 2017). Researchers are also developing methods to assess soil health from remote-sensing data from satellites, aerial reconnaissance and digital elevation models (radiometrics, electromagnetic data, terrain analysis) (Viscarra Rossel *et al.*, 2017; Vagen *et al.* 2013; 2016; El Gammal *et al.* 2015), and crowd-sourced on-ground information (e.g. Herrick *et al.*, 2013, 2016).

Soil maps and soil classifications can be valuable tools in assessing soil health. Palm *et al.* (2007) presented a framework based on relationships of soil properties to major soil classifications. It uses tools such as soil taxonomy, digital soil mapping, pedotransfer functions, remote sensing, spectral analysis and soil inference systems. Monitoring of soil properties could be linked with the Global Soil Map program to provide a framework for interpreting the data at a range of scales (Omuto *et al.*, 2013; Arrouays *et al.*, 2014; Hengl 2014, 2015). A soil map can convey inherent soil properties such as texture, clay type, often soil depth, nature of the subsoil, and natural soil nutrient levels, which are useful indicators of land potential (McBratney *et al.*, 2014), that can be used in the assessment of soil health and land potential (Murphy 2014). Much of this information is potentially available from soil maps such as the soil map of Africa (Jones *et al.*, 2013) which is a product of the Global Soil Map program.

(iii) Yield gap analysis

Yield gap analysis quantifies the difference between actual and potential crop or pasture yield (Bruinsma, 2009; van Ittersun *et al.*, 2013; Yengoh and Ardo, 2014). Together with water-use efficiency (Hochman *et al.*, 2009), these measures assist in identifying sites suitable for sustainable intensification, sites where land degradation has affected soil health, and in developing regionally appropriate SLM practices for enhanced food security. Yield gaps may be caused by land degradation, by poor selection of plant varieties or by poor agronomic practices. Small refinements such as changing sowing date, improving sowing practices and better weed control can be effective (e.g. Lal, 2013; van Ittersum *et al.*, 2013; van Wart *et al.*, 2013).

Yield gap analysis can also provide a useful input in upscaling the adoption of SLM practices (van Wart *et al.*, 2013; van Bussel *et al.*, 2015). For crop models to effectively estimate yield potentials (see also Grassini *et al.*, 2015), data requirements include:

- Quality long-term climate data, including rainfall, temperature, evapotranspiration.
- Quality soil and landform data – slope, soil rooting depth (USDA, 2015), sand content, plant available water (texture, layer depth). The Global Soil Map program (Omutu *et al.*, 2013) is a useful source for these data, at coarse resolution.
- Quality crop and pasture management data – including yields, fertiliser use, sowing dates.

(iv) Socioeconomic analysis

Socioeconomic trends indicating land degradation and unsustainable land management include declining yields, increasing malnutrition and food insecurity, reduced human health and well-being, increased land-clearing in forested areas, changes in market orientation from subsistence to commercial production, and increased conflicts. (FAO, 2007; World Bank, 2008; Liniger 2011).

The suitability of SLM practices may be limited by economic or policy factors such as systems of land tenure, the supply and cost of agricultural inputs and market access (Liniger *et al.*, 2011).

Figure 13 Sowing into a stubble with minimum disturbance is a conservation farming practice. Stubble protects the soil from raindrop impact. Photo: B. Murphy.

5.4.4. Step B – Developing SLM practices

Developing SLM practices involves defining a set of operations and practices that can meet the biophysical, economic and social constraints for a given area of land. Matching practices to land capability is a key principle for designing SLM interventions (Liniger *et al.,* 2011; OEH, 2012; Gray *et al.,* 2015). Suitability of SLM practices for a site or region will depend, in part, on factors such as soil type, climate and land use. For example, land management practices that result in bare ground, especially on slopes, leave the soil susceptible to erosion and are classed as unsustainable. Where a yield gap exists (See Sections 3.3.3), either socioeconomic support structures or land management practices are not optimised for conditions and production levels. Identifying whether the yield gap is due to soil health problems, cultivars with low yield potential, pest or disease attack, or poor agronomic practices can help develop better SLM practices.

Recommended SLM practices may be a complete farming system or a narrow set of practices to address a particular constraint such as nutrient decline, weed and pest control, water erosion or low yields due to unsuitable crop varieties. Some practices may be difficult to implement because of social constraints such as the availability of labour or customs. The costs of implementing some practises, such as increased use of fertilisers or superior plant varieties, may limit their adoption. Some practices may solve a specific problem such as water erosion - but may lead to lower yields. Therefore, the SLM practices need to be developed with the participation of local land holders, to enhance the likelihood of their adoption (Pedzisa *et al.* 2015). However, the promotion and upscaling of conservation agriculture needs to take account of the local biophysical, economic and social factors in local areas if there is to be successful long-term adoption (Pedzisa *et al.* 2015).

Step B1 – Biophysical assessment of land management practices

Based on current soil health, identified land degradation processes and their drivers, risk of further degradation, yield gap, and land potential (from Step A), this step identifies SLM practices that will address key needs. Examples of SLM practices to address specific land degradation processes include:

- Improve productivity and soil health (World Bank, 2008; Liniger *et al.,* 2011) through
    - Increased water-use efficiency – increase plant available water under rain-fed agriculture and/or irrigation, increased plant water uptake, increased rooting depth.
    - Increased soil fertility – increase nutrient availability and uptake, through strategic use of fertilisers, recycling organic sources of nutrients, N-fixation, increased rooting depth.
    - Management of plant genome and agronomic management – maximise yields using most suitable varieties, crop diversification, more effective agronomic management for sowing, weed and pest control, top-dressing.
    - Improved microclimate for plant growth – create favourable growing conditions, reduce evapotranspiration, use tree planting programs.
- Combat land degradation (see Appendix 1) through addressing:
    - Nutrient decline – replace nutrients removed in harvest, maintain nutrient levels in soils, avoid intensive cropping of soils with low nutrient levels, encourage soil biological activity to increase nutrient cycling.
    - Deforestation – preserve forests, apply sustainable intensification on existing agricultural land.
    - Desertification – increase ground cover, manage stocking rates to match available feed, use effective drought management strategies.
    - Soil organic matter decline – maintain ground cover, retain stubble, grow perennial plants, encourage plant growth to increase biomass inputs, manage nutrient levels, apply organic amendments, reduce soil disturbance.
    - Water erosion – maintain ground cover particularly on erodible soils, undertake structural works.
    - Wind erosion – maintain ground cover, modify microenvironment with windbreaks.
    - Soil acidification – use acid-tolerant plant species, minimise loss of bases and nitrate leaching, minimise drainage for vulnerable acid sulfate soils.
    - Salinization – manage water balance to prevent rising water table, avoid use of low quality irrigation water that could cause salinization and increasing soil sodicity.

- Soil contamination – identification of contaminated soils, removal of contaminated soils or implementation of strategies to minimise toxic effects.

Step B2 – Economic assessment of SLM practices

SLM practices will not be widely adopted unless they are economically feasible *(*World Bank, 2008; Sanginga and Woomer, 2009; Liniger *et al., 2011*). Economic aspects that influence adoption include:

- The farmers' financial position (access to finance, cash reserves), which determines capacity to invest in SLM infrastructure (e.g. zero tillage planter; fencing) or to survive a period of reduced returns.
- Pattern of costs and benefits. When both short-term and long-term benefits are high, adoption of SLM practices is more likely, whereas low short-term benefits but high long-term benefits make funding for adoption of SLM practices problematic. This is particularly a problem for poorer or more marginalised land holders because of their dependency on the available resources.
- Access to, and costs of, machinery and inputs (e.g. seed, fertiliser), the level of mechanization required and the availability of fertiliser and seeds in small, affordable quantities.
- Access to labour. The availability and cost of labour may be affected by competition from off-farm labour demands or chronic to acute health problems.
- Access to knowledge and expertise. Monitoring soil health, identifying appropriate SLM practices, and implementing them, requires technical expertise. SLM practices must be flexible to allow for local adaptations.
- Access and security of markets – includes the capacity and licences to participate in a market, the infrastructure and mechanism for transporting produce to market, and the influence of consumer preferences, which may lead to demand for sustainability certification, with added transaction costs for producers.

Step B3 – Social assessment of SLM practices

Adoption of SLM practices will also be influenced by social and governance aspects (World Bank, 2008; Sanginga and Woomer, 2009; Liniger *et al*., 2011) such as:

- Food security – quantity, timeliness, access and nutritive value of food. SLM practices may lead to short term reduction in yields, or changes in crops produced.
- Perception and impact for human well-being – SLM practices should be seen to add to the quality of life and well-being of the community.
- Socially and culturally acceptable – SLM practices must be socially and culturally acceptable.
- Land tenure and water rights – land tenure should not restrict adoption of SLM practices.
- Flexibility in SLM practices – to allow for local adaptations and innovation and facilitate capacity to overcome specific barriers to adoption at the local scale.
- Gender balance of labour and responsibilities – in communities where women do much of the farm management and labour, and men are more involved in off-farm work, there may be difficulties implementing SLM practices that have a requirement for heavy labour.
- Access to fuel and energy – developing alternative sources of energy for cooking and heating would minimise tree and scrub clearing and allow manure to be used as fertiliser.
- Potential for up-scaling and expansion of practices – the extent of the area where the SLM practices are applicable, based on climate, soil type, agricultural systems.

Step B4 – Assessment of potential adverse impacts

The potential for trade-offs and adverse impacts as a result of changed land management must be carefully considered and evaluated to determine the real sustainability of practices. For example, use of groundwater for drinking and irrigation through building wells in Bangladesh and the southern Himalayas has led to serious health problems due to presence of arsenic (Hossain, 2006). Planting woody perennials for windbreaks may reduce downstream water availability. Promoting biochar use could lead to production in poorly-operated facilities that cause air pollution. These risks should be identified and managed. Some adverse impacts may be unexpected and it is necessary to consider local knowledge and undertake effective risk management to reduce risk of potential unknown adverse impacts.

Bouman *et al.* (1999) developed a framework for land-use analysis at different scales based on biophysical (e.g. N, P, K balance, biocide use and impact, greenhouse gas emissions, N leaching and volatilization) and economic factors (e.g. economic surplus and labour requirements). The analysis can identify land management practices that satisfy both economic and biophysical sustainability, and can clearly identify where trade-offs may occur.

5.4.5. Step C – Defining and facilitating adoption of recommended SLM practices for a given set of climate, soils, landform and socioeconomic conditions and constraints

The site assessment (Step A) and evaluations of alternative SLM practices from environmental, economic and social perspectives (Step B), form the basis for identifying SLM practices that are most suitable for dealing with constraints and risks, and are most likely to be implementable in the specific local context. Step C involves formulating a recommended set of SLM practices, and developing and implementing a strategy to encourage their adoption. The strategy may include development of guidelines for applying the recommended practices, and extension methods such as field demonstrations, farmer field schools and radio programs. Once suitable SLM practices are defined and guidelines for implementation established, these practices can then be extended to other suitable areas of land (upscaling) (see section 5.4.9).

5.4.6. Step D – Evaluating the impact of SLM practices at different scales

Based on the framework outlined in Figure 12 and process presented in Box 6, indicators and metrics for evaluating the benefits and impacts of SLM can be chosen as suited to each context, including categories of land use such as agriculture, forestry or urban development. The metrics used to quantify the indicators can be applied to evaluate management systems or practices, monitor the effectiveness of SLM actions on local to global scales over time or against a benchmark, understand trade-offs between impact categories and provide a basis for documenting and communicating sustainability claims. Individual indicators such as soil carbon have value; they can be matched to specific priorities on a land use or regional basis. However, no single indicator or metric can assess “sustainability”. In reality, a set of indicators in a framework is needed to understand and monitor the sustainability of land management and to identify trade-offs and detect unexpected perverse outcomes. For example, Sangedo *et al.* (2014) concluded that monitoring impacts of land management in the Kilimanjaro Region of Tanzania required indicators for the assessment of soil health, carbon stocks and water resources. As well as biophysical indicators, assessment of SLM should include socioeconomic criteria.

Indicators for monitoring SLM should be selected to reflect key variables that relate to the identified land degradation processes, risks and ecosystem services being targeted, and that are likely to respond to SLM interventions. They should reflect change in ecosystem services delivered and also the condition of the underpinning resource base, to determine impact on sustainability (Hansen, 1996, Bouma, 2002; Palm *et al.*, 2007). Regional monitoring should be used to supplement locally relevant indicators. Evaluating the impact of SLM practices on ecosystem services at national and global scales will support policy and planning by governments and international agencies. Ideally, the same indicator would be applicable at different scales, though the metric may differ between scales. Metrics cannot be prescribed because specific conditions being evaluated will be context-dependent.

Section 4.3 including Table 6 and Table 7 provide guidance on indicators of soil condition. These indicators are widely applicable, but suitable metrics for their measurement will depend on the biophysical context, the scale of assessment and also the capacity, resources and data sources available for monitoring. Table 9 illustrates how scale can influence the relative importance of different indicators and the analysis of the data from the indicators. For example, at the field and landholder scale, the emphasis is on soil tests and the availability of fertiliser at a suitable price in manageable quantities. At the regional scale the emphasis is on the identification of areas where there are problem soils, the development of new seeds and varieties, overall yield trends and ensuring fertiliser companies can supply fertilisers in quantities suitable for low input agricultural systems. At the national scale, the emphasis is on a national nutrient budget to manage any overall nutrient decline as demonstrated by Craswell and Vlek (2013). The monitoring program advocated by Shepherd *et al.* (2008a) collates data at a range of scales using a variety of technologies including satellite imagery to assess the sustainability of land management practices. Liniger *et al.* (2011) also provide a framework that proposes the assessment of the effectiveness of land management practices in promoting sustainability in terms of the impact on ecosystem services across scales.

5.4.7. Monitoring for technical and policy needs

There is a disjunct between indicators used for technical and policy purposes. On the one hand, science-based quantifiable indicators of sustainability are needed for detailed technical assessment of the outcomes of scientific research or investment in local on-ground trials. On the other, broader, multi-faceted data are needed for more qualitative monitoring for policy needs. The detailed assessment of SLM targeting nutrient decline described in Table 9, for example, may provide valuable technical information. However, it will not necessarily be ideal for policy objectives unless interpreted through broad conclusions more relevant in a regional policy context.

The value of technical indicators for policy depends largely on the degradation process or sustainability constraint being monitored. Walter and Stützel (2009) proposed a system for bridging the gap between policy and research needs in developing metrics for “sustainability”. This framework uses a structured procedure to select indicators that can be normalised and assessed according to their perceived environmental, social or economic impacts.

Box 6. A guide to selecting indicators for monitoring and evaluating sustainable land management

1. Steps in selecting indicators of soil health

a. Determine the purpose
- The land use will influence selection of indicators applied to the soil

b. Assess the functional requirements for managing for soil health

c. Selection of indicators will depend on the function and scale of monitoring. For example, the soil health issue at a local scale may be crop growth, at a regional or catchment scale it may be combating erosion to stop siltation of a water reservoir, while at a global scale the critical issue may be mitigating greenhouse gas emissions from soil carbon loss or fertiliser use. (see Table 9)

d. Determine the processes that support each function of interest

e. Determine the soil properties relevant for each process (see Section 4.3)

f. Derive critical values for each soil property
- Critical values should relate the impact of the property to soil health.
- Locally derived values will likely be most effective but useful published sources include: Carter (2002), Hartemink (1998), Peverill *et al.* (1999), Sanchez *et al.* (2003), Hazelton and Murphy (2016), Palm *et al.* (2007).
- Indicators may rely on surrogates or pedotransfer functions when it is not possible or practical to measure a soil property directly. For example, the Universal Soil Loss Equation (Renard et al. 1996) can be used to estimate soil erosion.

g. Develop a methodology or standardised approach for each soil property
- Evaluate available methods to measure each soil property of interest
- Develop protocols for soil sampling, handling, storage and analysis
- Develop rules for interpreting data, to ensure consistency over time and space.

2. Steps in selecting indicators for social benefits

a. Determine the scale of the social impact to be monitored
- Selection of indicators depends on the scale of targeted social benefits, e.g. alleviating local food shortages versus enhancing global food security

b. Determine practices that are socially and culturally acceptable
- Compare SLM practices to traditional practices
- Flexibility may be needed to accommodate local customs, beliefs, and spiritual value for land
- Consider practical constraints such as access to fuel and labour

c. Develop indicators that take into account local customs and beliefs
- Indicators may need to allow for spiritual value of land or land tenure and water rights

d. Develop indicator values for social benefits
- Indicators should be quantitative where possible but may be qualitative, e.g. progress in human rights including gender balance; optimisation of working conditions and individual dignity; and maintenance of rural communities

e. Develop a monitoring and evaluation approach for social indicators that can demonstrate progress over time resulting from SLM through consistent reporting
- For local and regional scale, consultation with local land users and stakeholders will support evaluation, review and iterative improvement in SLM for social benefits.

3. Steps in selecting indicators for economic progress

a. Determine the scale and objectives of economic monitoring and evaluation

b. Determine constraints on realising economic benefits of SLM activities
- Access to knowledge and expertise may prevent implementation of SLM practices
- Initial finance may be required to access sufficient quantities of seed and fertiliser
- Access to machinery and labour may be required for implementation of SLM practices
- Access to markets may be constrained by lack of transport or licence requirements

c. Derive indicators of appropriate economic progress, such as:
- Financial position of holdings
- Improved income through optimisation of food and fibre production
- Decreased volatility in income resulting from climate and market variability

d. Develop monitoring and evaluation protocols for economic progress due to SLM

References: Carter (2002); Brouisma (2007); Palm *et al.* (2007); World Bank (2008); Liniger *et al.* (2011); Kassam *et al.* (2013); Lal, (2013).

Table 9 Indicators to assess the ecosystem service of nutrient supply across different scales.

Measurement, indicator	Local/field	District/Regional/catchment	National
Nutrient Supply	Soil tests for NPK, pH, soil organic matter and other nutrient levels Local yields on fields and farms Cost of fertiliser and source of fertiliser Amount and type of organic additives used, when applied Implementation of rotation practices for disease control Implementation of rotation practices for nutrient management	Availability of regional soil maps Information on soil map units to identify inherent fertility of soils and limitations such as P-fixation, acidity and low buffering capacity or erosion risk at a regional scale Collation of local soil tests to confirm results from soil maps Establishment of regional soil database Average yields across the region and trends Yield gap analysis (actual v potential yields) Plant tissue testing program for region Cost of fertiliser – regional average Sources of fertiliser Availability of fertilisers in small quantities suitable for smallholders. Development and supply of improved seeds and varieties at regional level Development of rotation practices for disease control Development of rotation practices for nutrient management	Nutrient balance for nation (see Craswell and Vlek, 2013) Amount of fertiliser used in nation Cost of fertiliser – national average Source of fertiliser – national average National maps Identify inherent fertility of soils and P-fixation, pH and buffering capacity, erosion at national scale Soil testing program for nation Establish national soil database Average yields across the nation and trends – compare different regions Funding allocated and programs established for research, demonstration, education and training related to sustainable nutrient management

Source: Adapted from Bouman *et al.,* 1999; Dumanski and Pieri, 2000; Cowie *et al.,* 2007; Sanginga and Woomer, 2009; Liniger *et al.,* 2011

The Walter and Stützel (2009) framework, as well as other proposed systems (e.g. Smith *et al.,* 2000; Bouma, 2002; Gomez-Limon and Sanchez-Fernandez, 2010) have predominantly focused on sustainability of agricultural production. Ideally, indicators that can support the design, implementation and monitoring of investment in SLM and also provide appropriate metrics to support policy development on regional or national scales will consider multiple land uses within a geographical area and the implications of changing land use, e.g. between agricultural production and forestry, including any trade-offs or synergies (Sandewall and Nilsson, 2001).

On a global scale, however, these indicators need to be supplemented by broader information and assessments to ensure the global good. To borrow a term from climate change mitigation policy, the avoidance of “leakage” is important. Leakage refers to indirect negative impacts – in this context, the potential for SLM practices that combat land degradation in one location to leave land more vulnerable to degradation at another site. Leakage could be due, for example, to deforestation or farm intensification in other areas to compensate for restoration and rehabilitation in the target area.

Through the development of voluntary certification schemes for sustainable production of agricultural products (e.g. Roundtable on Sustainable Biomaterials, Bonsucro), International standards for assessing the sustainability of bioenergy (ISO, 2015) and for reducing the risk of land degradation (ISO, 2017), standards and schemes promoting the sustainability of agriculture (e.g. The American National Standard for Sustainable Agriculture ANSI/LEO-4000) and initiatives for sustainable forest management (e.g. Forest Stewardship Council) there is growing consensus on how to evaluate the sustainability of land management. Most of these initiatives are aimed at the level of the producer. While these schemes tend to be most applicable to larger commercial enterprises, some have devised mechanisms such as group certification to allow participation by smallholders. Due to the focus on the individual producer, these initiatives tend not to capture issues such as trade-offs and leakage that are important for policy analysis.

The principles presented in section 5.2 and the framework presented in section 5.4 , including the guidance on identifying indicators (section 5.4.6 and background in section 4.3), provide a structured approach that can be used to select indicators to monitor the effectiveness of SLM programs, focusing on the key issues and objectives relevant to the context. Recent initiatives at global scale will provide methods and data suitable for monitoring SLM at regional and national levels, and may also be applied at subnational level aligned with the scale of implementation of SLM programs. Data sources identified for reporting on the land degradation neutrality initiative of the UNCCD, and SDG 15.3 land degradation neutrality will enable monitoring of the three biophysical indicators, land cover, productivity and soil carbon stock (Orr *et al.*, 2017; Cowie *et al.*, 2018; Sims *et al.*, 2017), while other SDG indicators will provide socio-economic data relevant for monitoring broader impacts of SLM programs.

5.4.8. Use of long-term monitoring sites

Given the pressures on ecosystems around the world, there is a need for "places where we press our ears to the earth and strain to hear its pulse" (Janzen, 2009). Such monitoring sites have to remain intact and relevant for decades if they are to maximise the value of information on the condition of ecosystems (McKenzie *et al.,* 2002). In order to manage the changes and pressures on agriculture, and find solutions to global food security, Sachs *et al.* (2010, 2012) recommend the development of effective agricultural monitoring networks. These would undertake site-specific assessments of sustainability of land use and also apply metrics that are universal and operate across scales. They emphasise it is necessary to simultaneously measure indicators of the three pillars of sustainability (environmentally sound, socially responsible and economically viable).

5.4.9. Scaling up sustainable land management

Sustainable land management is relevant across scales, from field, to landscape, to regional and global levels (Gundel *et al.,* 2001). There can be multiple benefits, not only at the local scale but regionally, nationally and globally. This is the case whether investment occurs to promote SLM practices in response to crisis situations in a key region such as sub-Saharan Africa, or is more strategic.

The benefits of SLM practices for farmers and rural communities include better crop yields and fodder production and the flow-on effects for increased livestock productivity, more sustainable supplies of co-products such as fuel (firewood and manure) and more efficient recycling of nutrients (animal excreta). These benefits, in turn, increase income, strengthen resilience in poor seasons and promote human nutrition and health.

The first step is successfully identifying SLM best practice programs for diverse local conditions and ensuring adoption by involving local landholders in devising SLM programs, providing adequate knowledge, training and decision-support tools to local landholders, agricultural advisers and policy makers. Successful up-scaling from this local level requires a common body of knowledge on SLM techniques and mechanisms for implementing practices and disseminating knowledge. This information and experience also needs to be integrated with tools for comparing, selecting and fine-tuning SLM practices for different environments and ecological, economic, social and cultural conditions.

Resources for SLM are limited but the need is large, due to the current and potential extent of land degradation worldwide. Investments in scaling up SLM in low-input agricultural systems are potentially most beneficial (Liniger *et al.,* 2011). Hence, the challenge in horizontal scaling is to involve more people in better practices for sufficient geographic coverage of SLM to achieve ecosystem benefits. This requires developing recommendations for major soil type/agricultural systems that are at risk of degradation and using maps of soil and land properties to identify suitable areas for expansion. Global data sets and maps being developed by the Global Soil Partnership (e.g. Jones et al, 2013) may be useful in identifying potential spatial extent and suitable locations for scaling up specific SLM practices.

Investment in upscaling SLM, such as through programs targeting land degradation neutrality, should seek cost-effective mechanisms that maximise opportunities for high on-site and off-site benefits. Policies and institutional factors that can stimulate widespread smallholder adoption are important, along with developing training and support structures to build capacity for the adoption of SLM practices (Kessy 2014; Kessy and Kaswamila 2014). Upscaling the adoption of SLM practices is enhanced by the engagement and participation of local landholders in demonstrations, and facilitating interactions between researchers, extension workers and farmers (Bertin *et al.* 2014).

A variety of public policy measures, including international or multinational mechanisms, can be used to encourage SLM. Examples of policy measures that may be applied in appropriate circumstances include: (a) sharing the upfront and/or operating costs of adopting more sustainable practices in agriculture and forestry; (b) providing favourable terms of credit for upfront costs; and (c) providing enhanced security of land tenure as an incentive for better land stewardship. There is a dynamic and emerging knowledge base on the drivers of land degradation and its interactions with other environmental priorities. This knowledge is informing a range of policy responses to support SLM in conjunction with broader sustainable development goals.

The complex range of pressures on land resources means that multi-disciplinary approaches to SLM are needed. These should be supported by research and development, education, capacity building (especially in developing countries), partnerships, and appropriate policy structures integrated across sectors. Khedri Gharibvand *et al*. (2015) argue that to achieve sustainable rangeland management, a greater emphasis should be placed on sustainable livelihoods for pastoralists through policies that enable appropriate livelihood alternatives that are maintained in a sustainable state. Thus, policy must be developed for regional and land-use circumstances. For evidence-based policy, research is needed to understand: constraints to growth in productivity; ecosystem and biodiversity responses; interactions and trade-offs between impact categories; climate change impacts and adaptive strategies and; soil processes affecting degradation and recovery. Research is also needed to develop suitable indicators to benchmark and monitor the effects of practice change and to understand socioeconomic and cultural barriers to adoption of more sustainable management practices, so as to inform policy development.

5.4.10. Identifying SLM best practices for up-scaling

Key criteria for identifying best practices suitable for up-scaling SLM (Liniger *et al.,* 2011) include:

- cover major land-use systems
- represent solutions to various degradation types in different agroecological zones
- consider a broad variety of technologies and approaches
- deliver benefits in terms of production and conservation
- capture local innovation and recent developments, as well as long-term project experience
- strike a balance between prevention, mitigation and rehabilitation of land degradation.

Sustainable land management practices that focus on increased crop yields locally, can have multiple benefits beyond increased crop production (Uvin *et al.*, 2000). Winterbottom *et al.* (2013) proposed the following practices to improve the management of land and water in sub-Saharan Africa as an integral component of agricultural development strategies with potential for horizontal scaling:

- integration of woody perennial plants, notably nitrogen-fixing legumes, with crops and livestock
- conservation agriculture such as reduced tillage, use of cover crops and/or crop rotations, and retention of crop residues
- integrated soil fertility management through conservative use of mineral fertilisers in combination with manure, crop residues, compost and other soil amendments
- water harvesting using techniques such as stone bunds and planting pits.

Winterbottom *et al.* (2013) estimate that scaling up these proven practices to 25% of the potential cropland area of 300 million ha in sub-Saharan Africa would increase crop yields by an average of 50%. This would enable farmers to produce an additional 22 million tonnes of food per year. Such up-scaling would provide 285 million people living in Africa's drylands with an additional 615 kcal per person per day which, in combination with reducing both pre- and post-harvest food waste, would contribute to reducing pressure to intensify production or expand into new areas.

5.4.11. Overcoming constraints to adoption

It is important to understand potential barriers to adoption and how they can be addressed at different scales. Constraints to adoption of improved practices can include biophysical or agronomic causes, social and economic factors such as market access, and policy barriers.

Defining good practices for resource-use efficiency and achieving adoption of sustainable land management are difficult where the climate is highly variable and production systems are marginal or where maximizing yield is perceived as essential for survival (e.g. McKeon *et al.,* 2004). Liniger *et al.* (2011) present data similar to those in Table 8 for a wide range of SLM practices proposed for addressing land degradation in sub-Saharan Africa. They identify constraints, such as lack of finance and availability of manure and compost to use as ground cover and fertiliser, to implementing these practices, and present strategies to overcome constraints. For example, it is useful for smallholders to be able to obtain small amounts of fertilisers.

Aune and Bationo (2008) identified that land managers in the African Sahel adopted improved practices in sequential steps rather than through a radical change of practices. In Nepal, intensification involved a similar stepwise process; it depended, however, on a major initial move to eradicate malaria so as to improve the welfare and capacity of the people (Raut *et al*., 2011). In this case, questions of sustainability have arisen for two reasons: reduced use of farmyard manure and the increased dependence on mineral fertilisers (with its related impacts on water quality and nitrous oxide emissions).

Understanding why unsustainable management is applied can provide insights to encourage adoption of SLM. Reasons for use of unsustainable practices include (World Bank, 2008):

- prioritising maximum production and/or short-term economic returns regardless of potential negative biophysical or social effects, to maximise profit, service debt, or address hunger in impoverished communities
- constraints of poor land-use policies such as insecure land tenure that provides no incentive for land stewardship
- lack of education and/or incentive programs providing knowledge and support for SLM
- population pressure, economic growth and urbanization
- policy failures or distortions (stagnant technology, delayed intensification)
- imperfect markets (lack of markets, distortion of markets and poor market access)
- transaction costs and imperfect information (limited access to market information)
- social inequity and poverty
- cost-price squeeze: rising costs of inputs relative to farm commodity prices, limited negotiating power of smallholders
- political and social instability.

None of these elements acts in isolation from the others. Understanding the socio-economic, policy and infrastructure factors and circumstances influencing choice of land management practices enables effective programs to be designed that encourage change towards more sustainable practices that will support local productivity goals and also contribute to global environmental benefits and food security.

The following pathways, based on Winterbottom *et al.* (2013), are recommended to accelerate the scaling up of improved practices:

1. Strengthen knowledge management systems and access to information.
2. Increase communication and outreach, using champions and direct engagement with farmers.
3. Foster connections between communities and government and non- government institutions to enhance knowledge sharing.
4. Establish demonstration sites on landholders' properties, and develop networks of landholders (or use existing networks where applicable), to encourage cooperation and communication between landholders and provide a focal point for promoting SLM practices.
5. Support institutional and policy reforms, particularly for strengthening property rights.
6. Support capacity building, particularly in community-based management of natural resources.
7. Increase support for integrated landscape management that brings together sectors and stakeholders from agriculture (including grazing and cropping), intensive agriculture, forestry, urban and conservation to jointly plan, design, and manage their landscapes and institutional resources for improved agricultural production, biodiversity and ecosystem conservation and sustainable livelihoods.
8. Reinforce economic incentives and private sector engagement.

9. Mainstream investments to catalyse adoption of these practices as a strategic component of food security and climate change adaptation programs.

Local trials and demonstration sites are effective to show to land managers the merits of an approach, to promote adoption regionally, providing a basis for scaling up horizontally (to larger land areas) and vertically (e.g. to promote institutional and policy support), and as an evidence base for investment.

Pretty *et al.* (2011) stressed the need to be aware of gender issues and to actively include women as primary participants in training and in projects aimed at the adoption and scaling up of SLM. Success also requires the involvement of multiple stakeholders including the public sector at all levels, private sector investors, scientists and extension providers and non-governmental organizations (Winterbottom *et al*., 2013). Social and economic outcomes arising from increased agricultural productivity, enhanced rural livelihoods and health, as well as environmental outcomes (including improved ecosystem services and biodiversity) will scale up to global benefits which include improved food security and capacity for climate change adaptation and mitigation.

Appropriate codification is an important step to the successful implementation of SLM practices (McBratney *et al.* 2015; Murphy 2017). Codification refers to the regulation and policy to support implementation of SLM including aspects such as land tenure mechanisms, mechanisms to provide finance, market structures for inputs including fertilisers and seeds, market structures for outputs such as grain and animal products, infrastructure and nature of technical support institutions including government and non-government organisations, energy policy including for biofuels, and environmental laws.

Support activities for scaling up SLM noted by the GEF (GEF, 2013a) include:

- institutional capacity development and institutional finance for SLM
- innovative market and financing mechanisms that provide incentives for reducing the pressures and competition between land use systems
- integrated watershed management where SLM interventions can improve hydrological functions and services for agroecosystem productivity
- multi-stakeholder landscape planning involving both public and private sectors to inform decision-making on integrated management of ecosystem services
- improved agricultural land management near protected areas.

A great deal of research is still needed to provide confidence in the development and implementation of effective SLM practices and integrated response strategies to combat land degradation in the face of current and future pressures on resources. This review has identified some key knowledge gaps that are barriers to successful adoption of SLM. Fundamental needs include a better understanding of the drivers of land degradation, and an improved capacity to identify and implement effective SLM practices across a range of scales. Promoting adoption of SLM practices is affected by a limited capacity to explain the interactions between environmental variables and social and economic factors, and by the non-linearity of responses to multiple stressors.

Key knowledge gaps identified in this review include:
(1) understanding of how SLM programs can realistically address chronic and acute under-nutrition, which is an urgent priority in some regions; and
(2) how to help the world's poorest people to improve the sustainability of land management in

regions with naturally fragile soils, water scarcity and high climate variability that increase vulnerability to anthropogenic climate change.

In addition, enabling policies are fundamental to many interventions to combat land degradation and establish SLM practices, as are supporting arrangements for nutrition security. Without addressing crisis hunger situations, it is impossible for farmers or land managers to consider decisions for longer-term sustainability.

Figure 14 Oasis agriculture, Morocco. Photo: M.Hewes

6. International programs in sustainable land management

Developing and implementing SLM programs must consider international organizations and activities in this area. The UNCCD and the GEF play critical parts in addressing land degradation, and in building efforts that support the integrated nature of land management. A description of the UNCCD's and GEF's work in sustainable land management follows.

6.1. United Nations Convention to Combat Desertification

The UNCCD was established during the 1992 Rio Earth Summit in recognition that desertification is a major challenge to sustainable development. The UNCCD is the sole legally binding international agreement linking environment and development to sustainable land management. The convention addresses specifically the arid, semi-arid and dry sub-humid areas that are home to some of the most vulnerable ecosystems and peoples. The goal of the UNCCD for 2008-2018 is: "to forge a global partnership to reverse and prevent desertification/land degradation and to mitigate the effects of drought in affected areas in order to support poverty reduction and environmental sustainability."

The Convention aims to improve the living conditions for people in the drylands, to maintain and restore land and soil productivity and to mitigate the effects of drought. The dynamics of land, climate and biodiversity are intimately connected. Therefore, the UNCCD collaborates closely with the other two Rio Conventions, UNCBD and UNFCCC, to meet these complex challenges with an integrated approach and the best possible use of natural resources.

In 2002, the GEF became a funding source for the UNCCD. It developed a set of operational programs for sustainable land management that enabled control of investment in global environmental benefits from production landscapes, i.e. in sustainable land management, to combat land degradation and desertification (GEF, 2011).

6.2. The Global Environment Facility

As its core mission, the GEF helps ensure the sustainable use of ecosystems and resources upon which all life depends through the support of global environmental outcomes that transcend national boundaries. An overview of GEF themes provides a structural context for understanding global investment in SLM to address the critical issues of land degradation and food security.

The main areas of the GEF's work are: climate change, biodiversity, international waters, land degradation, chemicals and waste, and sustainable forest management.

Since 2002, the mechanism for GEF investment in sustainable land management has been the Land Degradation Focal Area Strategy. Support for SLM has been a major thrust of the strategy.

Strategic planning for investment in SLM must consider the pressures on a variety of factors. These include: land resources; drivers of land degradation; impacts of, and adaptation to, climate variability and climate change; imperatives for mitigating greenhouse gas emissions; and regional vulnerability to food insecurity due to population increases, poverty and lack of capacity. Recognising these connections, the GEF supports integrated approaches which address the drivers of environmental degradation at scale. An example of this effort is the food security program "Fostering Sustainability and Resilience for Food Security in Sub-Saharan Africa", and the commodity supply-chain program

"Taking Deforestation out of the Commodity Supply Chain". Links between land degradation and other GEF areas of work are illustrated in Table 10.

Linkages between themes, complementarity with other initiatives and incentive mechanisms, and benefits across both geographical and political scales influence the effectiveness of investment strategies. The GEF's work on land management has focused on "long-term integrated strategies that focus simultaneously in affected areas, on improved productivity of land and on the rehabilitation, conservation, and sustainable management of land and water resources, leading to improved living conditions, in particular at the community level." It considers the impacts of land degradation on the poor and on women in supporting actions and innovations to improve livelihoods and global environmental benefits through sustainable land management. The GEF relies on SLM to address "the need for sustaining flows of ecosystem services that underpin productivity of agricultural and rangeland systems" (GEF, 2013c, 2013d). In production systems, SLM seeks to combat land degradation arising from land use or a combination of processes involving human impacts, consistent with the emergence of food security as a high priority. SLM focuses on maintaining land resources and ecosystem services to support the sustainable intensification of agricultural, rangelands and forest landscapes. Investment in the sustainable management of agroecosystem services is encouraged as a pathway to better climate risk management for agricultural production and food security in drylands; this, in turn, will contribute to building resilience to the impacts of climate variability and change, further assisting efforts to combat land degradation.

GEF's work on SLM is consistent with the Millennium Ecosystem Assessment recommendations for two kinds of investments: target prevention and control of land degradation in areas with medium to high production potential; and target affected areas where the social consequences of continuing land degradation will result in serious environmental and developmental problems. GEF investment in SLM is now based on a diversified suite of interventions across scales and sectors. Land degradation has clear impacts on a local or regional scale, such as water quality decline, loss of soil structure and increased erosion. However, the interconnectivity between ecosystems across scales means that downstream impacts can occur across the biosphere.

To complement its focus on sustainable land management, the GEF is committed to supporting countries which implement Land Degradation Neutrality (LDN) as an approach to manage land resources more sustainably, and increase opportunities for land restoration. The GEF will encourage LDN as an integrated planning approach to assist communities meet their food security and livelihood needs without degrading land resources (Box 7).

Table 10 Linkages between land degradation objectives and other GEF focal areas showing the relevance of integration of sustainable land management activities across focal area priorities.

	Land Degradation			
	LD-1	LD-2	LD-3	LD-4
Climate Change	+++	+++	+++	++
Biodiversity	++	++	+++	+++
Sustainable Forest Management	+	+++	+++	++
International Waters	++	+	+	+
Chemicals and Waste	++	+	+	+
Corporate programs	+	+	++	+
Private Sector	++	+	+	+

Note: The depth of colour in the first column highlights the importance and benefits of integration. Land degradation objectives LD-1 to LD-4 are: LD-1: Maintain or improve flow of agroecosystem services to sustain food production and livelihoods; LD-2: Generate sustainable flows of ecosystem services from forests, including in drylands; LD-3: Reduce pressures on natural resources by managing competing land uses in broader landscapes; LD-4: Maximise transformational impact through mainstreaming of SLM for agro-ecosystem services. +++ Strong linkages across all or most objectives of the themes; ++ Strong or moderate linkages across most objectives of the themes; + Moderate or weak linkages across some objectives.

Figure 15 Terraced rice cultivation, Indonesia. Photo: A. Cowie

Box 7. Objectives of the GEF land degradation focal area

Objective 1. Support on the ground implementation of SLM to achieve LDN

Objective 1 will be addressed through three Impact Programs:

1) **Food Systems, Land Use and Restoration Impact Program**: the program seeks to implement sustainable land management to improve food security and strengthen livelihoods. The program will target opportunities to restore agricultural productivity in agro-forestry systems through soil management, increasing vegetation and tree coverage, and other activities. The program will assist countries meet their growing demand for increased crop and livestock production, without the risk of further expansion of farmland, and inefficient practices that further exacerbate environmental degradation.

2) **Sustainable Forest Management Impact Program**: the program seeks to avoid further degradation, desertification, and deforestation of land and ecosystems in drylands through sustainable management of production landscapes. By supporting countries' voluntary Land Degradation Neutrality (LDN) target implementation, the program will support activities on sustainable management of dryland forests and trees outside forests; promote diversified agro-ecological food production systems in drylands; integrate landscape management on rangelands and livestock production; and, create an enabling environment to support the program. In addition to dryland areas, the program will focus in tropical landscapes in the Amazon and Congo Basins.

3) **Sustainable Cities Impact Program**: the program will enable opportunities to integrate voluntary LDN targets into urban planning. Cities will be encouraged to implement improved production practices in the "urban-scape" as a way of tackling land degradation, and increasing diversification of food systems in urban contexts.

   In terms of LDN, the program expects to achieve the following outcomes:

   - In dryland sustainable landscapes: avoid further degradation and desertification of land and ecosystems through the sustainable management of production landscapes in drylands. Activities will address the complex nexus of local livelihoods, land degradation, climate change, and environmental security including mitigating the effects of drought.
   - In diversified agro-ecological food production systems: aim to improve productivity and maintain or improve food production and livelihoods. Efficient use of land, soil, water, and vegetation in crop and livestock production systems will be supported.
   - In integrated landscape management and restoration: address the physical, biological and socio-economic aspects of the processes of land degradation, with specific attention to desertification and deforestation to maximise the delivery of multiple benefits in the context of food security and livelihoods of affected communities.

Objective 2. Creating an enabling environment to support voluntary LDN target implementation

Through this objective, the GEF will support countries wishing to set LDN targets to develop national frameworks to implement, monitor, and evaluate LDN. Activities that will be supported include:

- Embed LDN into existing planning frameworks and participatory land-use planning to meaningfully involve local governments, cities and urban municipalities, local communities, indigenous peoples, and women;
- Promote good governance especially in view of land tenure and efforts in securing livelihoods of smallholders;
- Develop monitoring and information systems on impacts, trade-offs, and costs-benefits analysis of restoration. Targeted research to inform these elements is encouraged.

In addition, this objective will address countries' requests to support the implementation of the UNCCD strategy.

7. Summary and recommendations

7.1. Context for sustainable land management

Pressure on the land resource is increasing at all scales from local to global due to human factors, notably: (1) growing demand for food in terms of both quantity (kilojoules of energy) and quality (proportion of animal protein in the diet) for an expanding and wealthier world population; (2) competition for productive land for biofuel, urban expansion and other non-food uses; (3) unsustainable land use practices that result in ongoing land degradation and which diminish soil health, indicated by lower nutrient status and organic content; (4) global agribusiness systems that drive down prices for farmers, pressuring them to farm intensively and unsustainably; and (5) the mounting impacts of anthropogenic climate change, which is projected to exacerbate variations in year-to-year yields and income from agriculture, threatening the resilience of agroecosystems and the stability of food production systems worldwide. Pressures also arise from natural factors such as natural climate variability, extreme weather events and wildfire; these add to the challenge of matching management practices to environmental conditions for optimal yields and for sustainable use of the land resource.

Land degradation may result from these natural and human pressures on land resources, and their interaction. In Australia, for example, rangeland degradation results from the coincidence of prolonged drought with high grazing pressure from both domestic stock and native animals. The ability to reduce stock numbers to match feed availability during drought may be affected by economic and logistical circumstances (e.g. labour and distances). Similarly, extended dry periods have been a factor in land degradation in sub-Saharan Africa. But, in this case, as in other developing countries, the direct impact on human populations suffering under-nutrition and with little or no capacity to rehabilitate land is often much greater. Thus, while the combination of human and natural pressures leads to risk of land degradation, land-holder capacity, and biophysical, logistical, policy and socioeconomic constraints can hinder the adoption of sustainable practices.

Sustainable land management (SLM) is the use of land resources, i.e. soils, water and the plants and animals they support, for production and other ecosystem services, while protecting their long-term potential to continue to provide these benefits. While applicable across all lands, SLM has focused predominantly on: agricultural systems because of their extent; direct impact on human well-being through provision of nutrition; scope for interventions in management; and, more recently, critical concerns for global food security. Within the definition of SLM, the environmental, social and economic values are inexorably linked, although the specific indicators for each pillar of sustainability differ. Land degradation, which occurs as a result of unsustainable management, threatens the global environmental commons in relation to biodiversity loss, effects on climate, effects on water scarcity and water quality, and long-term impacts on productivity of agricultural, forest and natural ecosystems. These impacts affect the well-being and livelihoods of people, particularly the poor and vulnerable (UNCCD, 2011).

The multiple benefits from SLM are increasingly being recognised. The key role of the land in delivering the objectives of the environmental conventions and the sustainable development goals has been acknowledged. Achieving land degradation neutrality (LDN) has been adopted as SGD Target 15.3, and many countries have set LDN targets at national level. Pursuit of LDN will provide impetus for

SLM, which is recognised as the major strategy to avoid, reduce and reverse land degradation in order to achieve LDN. SLM is also critical to achieving SDG 2, "End hunger, achieve food security and improved nutrition and promote sustainable agriculture".

This review examined a large cross-section of research papers and reports on land management and its impacts. These included impacts on global food security, and potential responses to the challenges across geographical and governance scales. It addresses all three pillars of sustainability. It focuses particularly on the environmental elements of SLM, including those relating to soil health, due to their fundamental importance in productive landscapes and for global food security.

The recommendations support a range of approaches to development and implementation of programs in SLM to minimise the risk of land degradation and to rehabilitate and restore land with diminished capacity for production and provision of ecosystem services. The report discusses examples of programs that have potential for benefits such as the sustainable intensification of productive areas, addressing the yield gap to fulfil potential productivity, conservation agriculture practices and "wildlife farming" approaches.

A key strategy for SLM for production of food crops and livestock is optimizing the efficient use of land, soil, water and vegetation in existing agroecosystems. Potential practices include diversification of farming systems, improvement of soil health and conservation of water resources, while taking into account the need to conserve biodiversity outside, as well as within protected areas. Further, the use of land within its capability/potential will help to prevent land degradation, loss of soil health and decline in other ecosystem services.

The language of SLM has evolved over time. Changes in focus and scope of studies have led to inconsistent use of terms and, consequently, communication problems for some stakeholders. We define the key terms in a way that is consistent with current technical literature and authoritative international sources such as the United Nations.

7.2. Investment in sustainable land management

The Global Environment Facility (GEF) has identified that a comprehensive landscape SLM approach is needed to address the broad multi-faceted nature of land degradation in order to "maintain or improve flow of agroecosystem services to sustain food production and livelihoods" (GEF, 2013). Well-structured and resourced programs in SLM have the potential to provide an effective and consistent response to land degradation in arid, semi-arid, sub-humid and humid areas of the world. They can also contribute to the global response to challenges such as food security and climate change.

Sustainable land management is a priority for increasing resilience to climate variability, especially drought and climate change. So-called climate-smart agriculture (Paustian *et al.* 2016) promotes SLM practices for an integrated approach to mitigation and adaptation to climate change; ultimately, it seeks to enhance climate resilience and decrease the vulnerability of agroecosystems to land degradation under projected changes in climate. Climate-smart agricultural land management includes social and economic pillars of sustainability; it specifically seeks to identify and promote concrete SLM practices and actions that diversify income and improve livelihoods of farmers and pastoralists, and relieve the pressure on land resources, especially at times of "crisis". These practices take into account gender-specific needs and help address the threat of anthropogenic change to future food security. They are relevant also to the GEF's climate change mitigation theme.

Numerous publications reinforce the link between SLM practices and ecosystem services on the one hand and land degradation on the other. In turn, land degradation is characterised by loss of soil health and the capacity of the land to provide human needs for food, fibre and environmental services.

To summarise these links:

- The sustainability of land management practices can be evaluated against indicators of soil health, assessment of current productivity against potential productivity (yield gap analysis), and assessment of existing land management practices against both soil and land capability and socioeconomic indicators of sustainability (See Figure 12).
- Soil health is a key indicator of land degradation processes at a site, catchment or regional scale. It is most effective in assessing land degradation and developing SLM practices if targeted to specific land use or ecosystem services at a site (Carter, 2002; Sanchez *et al.* 2003; Liniger *et al.,* 2011).
- Processes of land degradation of greatest significance in agroecosystems include:
    - nutrient decline, particularly for low-input agricultural systems (Sanginga and Woomer, 2009; Craswell and Vlek, 2013; Jones *et al.,* 2013)
    - loss of soil organic matter and soil organic carbon and the flow-on impacts on nutrient cycling, water availability and physical support for plants (Govers *et al.,* 2013)
    - water and wind erosion in arid regions and shallow agricultural soils (Tengberg and Stocking, 2001; Stocking, 2003), which include downstream impacts of water erosion, notably sedimentation of international waters and water reservoirs
    - soil acidification due to agricultural management or naturally acid soils, which can have high levels of aluminium that in solution are toxic to plants roots (Sanchez *et al*., 2003)
    - soil salinization, which may become a problem when the hydrological balance and water table are altered by human intervention (Kijne and Kuper, 1998; Sanchez *et al.,* 2003; Jones *et al*., 2013)
    - soil sealing, where productive agricultural lands are covered by expanding urbanization and infrastructure development (Jones *et al.,* 2013; d'Amour *et al.* 2017)
    - heavy metal contamination (e.g. mercury), which can be associated with mining activities (Dondeyne *et al.*, 2009).

A first step in prioritizing SLM activities for prevention and rehabilitation of land degradation is to understand, respectively, the risks for declines in productivity and ecosystem services in currently productive land, and the extent and severity of existing land degradation. This assessment will be facilitated by reviewing published information, including the use of systematic frameworks and quantitative models for land degradation processes (e.g. Foster *et al*., 1996; Environment Agency, 2009; OEH, 2012; Cowie *et al.* 2018).

Scaling up SLM initiatives

Initiatives in SLM are required across scales from field to landscape to regional and global levels. Decisions for investment of finite available resources must be aimed at maximizing the benefits from each project input through scaling up (Liniger *et al.,* 2011) across bio-geographical scales. The challenge is to achieve adoption of better practices for broader ecosystem benefits. Locally, SLM practices at the farm scale are critical to increased production of crops, fodder and livestock; these provide nutrition and health outcomes, but also more sustainable supplies of co-products such as fuel (firewood and manure), more efficient recycling of nutrients (including animal excreta), and potentially improved incomes and resilience to poor seasons. Additional benefits from large-scale change and/or trans-boundary cooperation may include more sustainable water supplies, decreased erosion and reduced risk of conflict due to competition for resources and food.

Adoption of LDN targets by countries, in pursuit of SDG Target 15.3 ("By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world") is anticipated to stimulate investment in SLM. This will also contribute to meeting SDG Target 2.4: "By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality".

This paper has sought to synthesise current knowledge on SLM and to evaluate how investment in SLM programs may be effective in combating land degradation. Ultimately, the aim of SLM is to deliver global environmental benefits and enhanced food security, particularly for the poorest and most vulnerable people. The paper is intended to be relevant to a wide range of stakeholders. It specifically targets, however, the needs for a strong evidence base for GEF investment programs. These programs include those supported through the Facility's role as the financial mechanism for the UNCCD.

7.3. Sustainable land management for the great global challenges

Recent advances in understanding the great global challenges facing the world today, including climate change and food security, have emphasised the urgency of addressing environmental issues. Sustainable land management, encompassing social and economic as well as environmental priorities, is fundamental to addressing these challenges to human development and well-being. Important considerations in planning and implementing programs of action for SLM include:

- understanding local biogeographical, political and economic capacity and broader scalability of interventions to inform the potential outcomes of investment at local, national or global scales
- evaluating any trade-offs and synergies between environmental objectives and socioeconomic and cultural needs and between local benefits and off-site impacts
- understanding and overcoming constraints to adoption of good practice for SLM due to social, economic, cultural or policy barriers
- developing practical and robust indicators and metrics for benchmarking the condition of agroecosystems and monitoring the effectiveness of interventions for SLM.

Investment in programs of ongoing biophysical and socioeconomic research combined with on-ground education and communication will increase capacity and knowledge. These programs are a global responsibility of the highest priority for the environment and for future food security. This need is exacerbated by climate change, global economics and population growth.

Global benefits from addressing land degradation potentially include:

- improved provision of agroecosystem and forest ecosystem goods and services, including clean air and water and reliable food and fibre production

- lower greenhouse gas emissions and increased carbon sequestration in landscapes managed for production
- reduced vulnerability of agroecosystems and forest ecosystems to climate change and other human-induced impacts
- conservation of, and sustainable use of, biodiversity in both natural and production landscapes
- reduced pollution, eutrophication and siltation of international waters and enhanced buffering of flood damage.

Scaling up of SLM projects involves:

- identifying SLM best practice programs for diverse local conditions
- achieving rapid adoption through the provision of knowledge and decision-support tools to landholders, agricultural advisers and policy makers
- expanding and sharing a common body of knowledge on SLM techniques through review and integration of local experience with research tools for iterative improvements in SLM practices and advisory services that are regionally applicable to different environments and to diverse ecological, economic, social and cultural conditions
- mapping areas of land degradation and monitoring the impact of SLM programs, to inform cost-effective decisions on new SLM investments that will maximise opportunities for high on-site and off-site benefits
- introducing policies and institutional mechanisms that can stimulate widespread smallholder investment along with developing training and support structures to build capacity for the adoption of SLM practices
- seeking synergies between environmental and sustainable development objectives, to attract funding such as through the LDN fund.

Gender is a key consideration, including the need to actively include women as primary participants in training and projects aimed at the adoption and scaling up of SLM.

Assessing the effectiveness of sustainable land management initiatives

A particular challenge for SLM initiatives is to develop tools for evaluating and monitoring the effectiveness of projects. This should take place within the context of the capacity of communities and farming systems to implement practices or change production systems. It is difficult to develop a universal set of indicators or metrics to assess sustainability because of the diversity of soils, environments, land management options and socioeconomic circumstances. Ideally, metrics for benchmarking and monitoring SLM should be comprehensive. Preferably, they should consider a wide range of factors including environmental (soil health, biodiversity, water-use efficiency and water quality, greenhouse gas emissions), social (resilience of rural communities, working conditions, food security, spiritual values), and economic (optimizing productivity of food and fibre, farm income, minimizing income volatility due to climate and market variability or market access).

We propose a framework (Figure 12 and Section 5.4) for integrating soil health, land degradation and sustainable development objectives, to identify priority impacts or processes associated with environmental degradation, develop SLM practices and then evaluate the impact of those practices on ecosystem services. The SLM principles and guidelines for identification of suitable indicators provide a defensible basis for prioritization of SLM activities and for monitoring progress across the diverse conditions relevant to investment in this area, to assess the effectiveness of SLM programs. At the global scale, evaluation against the GEF focal areas is possible by considering impacts on:

- climate change mitigation (forest cover and modelled soil carbon levels)
- climate change adaptive capacity
- extent and severity of land degradation
- contribution to food production and food security
- improved livelihoods
- resilient ecosystems
- biodiversity

Planning and implementing an SLM program is complex. Examples of factors (adapted from Liniger *et al*., 2011), that may influence successful development and implementation across a diverse range of regional or local circumstances include:

- identifying land degradation processes correctly
- implementing technically appropriate land management practices
- optimizing and stabilizing food production systems to match land and climate conditions
- optimizing yields
- improving nutrient availability and uptake, including micronutrients
- increasing plant water availability
- providing access to plant genetic material that is well-adapted to the local conditions
- identifying potential barriers to adoption of SLM
- embracing participatory land-use planning and decision-making – provision of options
- undertaking financial, material and technical support – market incentives and private investment
- building capacity and training
- monitoring and assessment.

Soil health is a valuable indicator of land degradation and the effectiveness of SLM practices. It can be linked to broader environmental services assessment, however, the framework (Section 5.4) shows that soil health is only one part of an evaluation of SLM practices. Indicators of land potential estimate the capacity of land to provide a range of ecosystem services and the risk of land degradation.

The lack of precise definitions for some ecosystem services makes assignment and relevant quantification of soil properties difficult. Making assessments across a range of scales from local, field levels to national and global scales is complex. As one of its recommendations, this report suggests available information and data be used to establish similar frameworks and tables for a range of the most important ecosystems services, global goals and land degradation problems.

Food security

Sustainable land management is fundamental to food security now, and to meet food demand for the projected additional 2 billion people who will need to be fed by 2050. Managing food waste and "overnutrition" is part of the solution. But there is no doubt that additional food will need to be produced without increased resources and in the face of growing climate impacts that will reduce yield and quality of farm products. This further emphasises the importance of developing practices for sustainable intensification of production on existing agricultural and grazing lands. The connectivity between agricultural and natural ecosystems through SLM provides benefits to productive land through processes such as hydrology, climate, human health, biodiversity and other ecosystem services.

Sustainable intensification should be viewed as a key component of SLM, linked with matching approaches such as wildlife-friendly farming ("land sharing") and "land sparing" to local and regional agroecosystem characteristics. Land sharing and land sparing are sometimes seen as a trade-off to meet future food demand, while balancing current agricultural and biodiversity conservation land uses (Green *et al.,* 2005). Both have relevance for developing sustainable land management practices and combating land degradation. Which approach is more practical and more "sustainable" will depend on the particular location, socioeconomic situation and policy environment (Fischer *et al.,* 2008); a combination of approaches is likely to be most effective.

Policy constraints

Policy commonly focuses on shorter term socioeconomic growth, whereas the environmental benefits of SLM are typically more diffuse and long term. There are initiatives to analyse the economic benefits of ecosystem services (e.g. www.teebweb.org). Questions remain, however, about how to properly value non-material ecosystem services (benefits) that people obtain from land. These benefits include cultural associations, spiritual enrichment, cognitive development, reflection, recreation and aesthetic experience.

Land managers, particularly smallholders, have to balance their interests. On the one hand, they must preserve the longer-term productive capacity and environmental integrity of their land for future generations. On the other, they are concerned about immediate food security, workload and lack of capacity and resources for changing practices or adopting new technologies. Strategic support (credit, schemes to provide seeds and fertiliser in small amounts, access to markets, improved technology) can help smallholders to overcome economic, policy and institutional barriers to the adoption of good practices for environmental stewardship while meeting their immediate needs as well.

Knowledge gaps

Key knowledge gaps identified in this review include: (1) understanding of how SLM programs can realistically address chronic and acute under-nutrition, which is an urgent priority in some regions; and (2) how to help the world's poorest people to improve the sustainability of land management in regions with naturally fragile soils, water scarcity and high climate variability that increase vulnerability to anthropogenic climate change. Better understanding of the drivers of land degradation is needed along with improved capacity to identify and implement appropriate SLM practices across a range of scales to develop integrated response strategies. The complexity of implementing SLM practices is exacerbated by interactions between environmental variables and social and economic factors, and by the non-linearity of responses to multiple stressors. A great deal of on-ground, practical research is still needed to provide confidence in developing and implementing the best practices for SLM into the future.

7.4. Recommendations for programs in sustainable land management

7.4.1. Overarching strategies

The Bruntland report, *Our Common Future* (United Nations, 1987), warned that the Earth's natural resources must be conserved to meet human needs. It also stressed that land use for agriculture and forestry must be based on a scientific assessment of both land capacity and the annual depletion of topsoil. The Global Footprint Network suggests that humans have already significantly exceeded the capacity of the planet to sustain our needs (Global Footprint Network, undated). Addressing the problem of land degradation through SLM approaches is a core issue for the future of humanity. It is also a multi-faceted and complex challenge involving many levels of environmental, social and economic knowledge and cultural values. Land degradation, climate change and food security are arguably among the greatest challenges facing the world today – and sustainable land management underpins all three. The UNCCD (2011) stated that:

> *Poverty and hunger, food insecurity and vulnerability to climatic shocks are likely to remain the major global challenges for sustainable development in the next decades. For the large majority of the poor and the most vulnerable and the ecosystems they depend on, adaptation and resilience will be better ensured through addressing DLDD [Desertification, Land Degradation and Drought] issues.*

The GEF, through GEF–6 (GEF, 2013d), has applied a program of activities built on better understanding of the causal chains of environmental degradation and focusing on the drivers of global environmental degradation. As such, it lays the foundation for effective multidisciplinary solutions, as planned for GEF-7 (GEF, 2018). There is also much to be gained from not delaying investment. Immediate action can rely on experience and analysis of previous successes together with local knowledge; these will continue to have value in combination with ongoing research into process understanding.

Achieving sustainable land management involves considering many intersecting natural and anthropogenic drivers of land degradation as well as the consequences of unsustainable land management. In view of this complexity, it is imperative that the drivers of environmental degradation increasingly underpin future investment in SLM. In addition, building on the synergies across programs as described in Chapter 6 will help to improve the cost effectiveness of investments, and provide multi-faceted benefits, including socioeconomic outcomes.

Thus, to enhance the effectiveness of the GEF, future investment in SLM should be based on research into the drivers of land degradation; robust assessment of experience and existing knowledge; and ongoing trials. This approach should focus on locally-applicable programs that can be scaled up to maximise global benefits for the environment and address the critical issue of food security. It should include policy reform to facilitate wider adoption. Assessment issues include:

- **Biophysical processes** that affect agricultural production and food security such as the impacts of climate change, including the risks of drought and the impact of increasing competition for use of agricultural land. Understanding the drivers of land degradation combined with local knowledge of the biophysical properties of a site, catchment or region will inform investment in appropriate response strategies as conditions change.
- **Socioeconomic issues** to raise awareness of the costs of land degradation and economic benefits of management decisions that affect productivity of agricultural and forestry systems

and linkages with the natural environment. Innovative methods to value ecosystem services and the on-site and off-site benefits of sustainable land management will facilitate consideration of the environment and natural resource base in policy and the provision of incentives.

- **Cultural and aesthetic aspects** that, with social and economic factors, influence responses to land degradation and the capacity and willingness to adopt of sustainable management practices.
- **Understanding trade-offs** to avoid perverse outcomes and to inform decisions on good practices for SLM. There will be both positive and negative interactions between environmental impacts, resource condition and production objectives, e.g. between agricultural yield and climate change mitigation, and between environmental, social and economic goals.
- **Cascading benefits from local action to global levels** will help prioritise investment across scales and maximise synergies between GEF focal areas. Causal chains often contain multiple drivers of environmental pressure. As a result, upstream interventions that tackle indirect drivers may create cascading benefits by reducing the environmental pressures.

Balancing investment between restoring degraded areas and preventing further loss of productive land is difficult. The Land Degradation Neutrality (LDN) initiative promotes a hierarchy of Avoid > Reduce > Reverse land degradation, to guide investment in interventions. Restoration or rehabilitation of highly degraded land may not be achievable due to lack of resources, capacity and/or knowledge, and may not be the optimal use of scarce resources. The long time horizon for results may also be a deterrent when benefits are needed in the form of improved production in the short term. While examples of successful restoration and rehabilitation exist, there is a need for improved knowledge of cost-effective measures for restoration and rehabilitation. Balancing the use of resources for restoration – focused on ecological outcomes – and rehabilitation – focused on production outcomes – is also a challenge.

Investment in agricultural research and development has declined in recent years, including support for long term monitoring of field trials. Yet targeted funding for long term monitoring is critical to understanding impacts of land management practices under the influence of climate change. Funding for research into sustainable agriculture and forestry practices is an enabling tool for combating land degradation. Oldeman (1998) noted the value for food security systems, to have a "natural resources conservation and enhancement strategy" with high priority given to combating desertification and deforestation and rehabilitating degraded land.

7.4.2. Recommendations for sustainable land management programs

Global environmental benefits from addressing land degradation potentially include:

- improved provision of agroecosystem and forest ecosystem goods and services, including food and fibre production
- mitigated/avoided greenhouse gas emissions and increased carbon sequestration in landscapes managed for production
- reduced vulnerability of agroecosystems and forest ecosystems to climate change and other human-induced impacts
- conservation of, and sustainable use of, biodiversity in natural and production landscapes

- reduced pollution, eutrophication and siltation of international waters and enhanced buffering of flood damage.

Sustainable land management (SLM) is critical to the global response to food security, climate change, land degradation and threats to biodiversity and loss of other ecosystem services critical to human well-being. The timeframe for realizing benefits following interventions for SLM will vary. It can take decades to achieve measurable improvements. However, the need is both immediate and growing. Delaying SLM practices until full certainty in the outcomes is known creates the risk of cumulative degradation of the environment and greater human suffering from food insecurity.

The following strategy is recommended for prioritizing SLM investment:

1. *Encourage early intervention:* Early adoption of SLM practices can avoid or reduce land degradation at least cost. Addressing land degradation effectively demands immediate action based on existing scientific and local/indigenous knowledge, and a willingness to trial and improve "best-bet" systems using adaptive management. Apply the LDN response hierarchy of Avoid > Reduce > Reverse land degradation, in prioritising SLM interventions. Apply strategies such as conservation agriculture, agroforestry, increasing soil organic matter, integrated soil fertility management and sustainable intensification to reduce or reverse land degradation. Delaying the initiation of SLM programs until impacts become severe will likely increase both the financial burden and recovery time with adverse production and socioeconomic outcomes for communities.
2. *Utilise land potential assessment:* Land use planning and management decisions should seek to use land within its capability, according to its potential, to minimise risk of land degradation. Use indicators of inherent soil, climate, landform and water properties to determine land capability/potential, identify site-specific land degradation risks, and assess whether specific land management practices are sustainable in that context.
3. *Utilise Yield Gap Analysis*: Yield gap analysis can indicate the adequacy of current land management practices and the condition of the land. In planning interventions to reverse degradation, priority should be given to areas where yield of crops and pasture are markedly below the yield potential to firstly identify the reasons and, where feasible, close the yield gap. The highest priority will be those areas also associated with under-nutrition in vulnerable communities. Closing the yield gap on existing managed lands can contribute to conserving natural landscapes for biodiversity and other ecosystem services, as well as meeting current and future food demands.
4. *Promote appropriate SLM practices* that 1) suit the local biophysical and socio-economic context; 2) are informed by expert and local knowledge, including field trials; 3) are applied in an integrated landscape management approach, targeting suitable areas for sustainable intensification and other areas for "land sparing"; 4) enhance resilience of the land resource base and nutritive value of food produced.
5. *Implement enabling policy* to facilitate development, promotion and implementation of SLM practices through codification. Relevant aspects include land tenure mechanisms, market structures to support availability of inputs such as fertiliser and seed in quantities appropriate for low input smallholder systems; enhancing access to markets for produce; infrastructure and nature of technical support institutions including government and non-government

organisations, energy policy and environmental laws. Also important are mechanisms that enable smallholders to focus on longer-term sustainability objectives, in addition to the critical immediate needs for nutrition, health and financial survival.

6. *Build capacity*: Widespread implementation of SLM requires investment in capacity building at local level, to identify, develop and scale-up locally-applicable SLM practices. It requires commitment and investment in research, innovation, governance and implementation programs on a global scale. Investment in research is needed to develop novel methods to improve efficiency of resource use and to increase production on fragile soils with limited water availability.
7. *Apply suitable indicators to monitor effectiveness of SLM:* Scientifically-sound locally-relevant SLM indicators and metrics are required to measure baselines (benchmarking current condition) and monitor change. Indicators should be selected to reflect soil health and land condition, including identified site-specific constraints and land degradation risks, and to detect off-site impacts. Important indicators for land management generally include soil health, soil organic carbon, water resource measures (water scarcity and water quality) and biodiversity loss. A long-term commitment to monitoring is needed to detect slow recovery or slow decline in land condition. Indicators of locally-relevant social and economic status and change also need to be monitored. These can include changes in demands on labour, energy requirements, access to markets and changes to farm incomes.
8. *Apply adaptive management:* Modify SLM recommendations where new knowledge and learning from monitoring indicate adverse impacts or opportunities for enhanced outcomes.

Concluding remarks

Land degradation, climate change and food security are arguably among the greatest challenges facing the world today and SLM is fundamental to all three. In 1987, the Brundtland report, *Our Common Future* (United Nations, 1987), warned that if human needs are to be met, the Earth's natural resources must be conserved and, in particular, land use for agriculture and forestry must be based on a scientific assessment of both land capacity and the annual depletion of topsoil. Addressing the problem of land degradation through SLM approaches is truly multi-faceted with challenges on multiple levels of environmental, social and economic disciplines, as well as human well-being and socio-cultural values.

In its sixth investment cycle, the GEF encouraged a focus on better understanding the causal chains of environmental degradation, including the drivers of global land degradation, as the basis for actions (GEF, 2013d). In so doing, it laid the foundation for effective multidisciplinary solutions, that can be expanded in GEF-7, to support the achievement of land degradation neutrality, amongst other goals. Devising effective programs for interventions to increase sustainable land management relies on analysis of the many intersecting natural and anthropogenic pressures on agroecosystems. Understanding the consequences of unsustainable land management for key global issues of concern, including the compounding problems of food security and anthropogenic climate change, will help to prioritise these interventions. In view of these complex interactions, a focus on the drivers of environmental degradation which, in its many forms, is the clearest manifestation of unsustainable land management will assist in directing investment.

Harnessing the potential synergies across the GEF's programs that relate to land, through integrated approaches, can improve the cost effectiveness of interventions, and deliver multi-faceted outcomes that enhance environmental, social and economic sustainability.

Figure 16 Integration of cropping and conservation, Brazil. Photo: A. Cowie

8. References

Adhikari, K., Hartemink, A.E., 2016. Linking soils to ecosystem services—a global review. *Geoderma* 262, 101–111.

Akhtar-Schuster, M., Stringer, L.C., Erlewein, A., Metternicht, G., Minelli, S., Safriel, U. and Sommer, S., 2017. Unpacking the concept of land degradation neutrality and addressing its operation through the Rio Conventions. *Journal of environmental management*, 195, pp.4-15.

Allen, D.E., and others (2013). What determines soil organic carbon stocks in the grazing lands of north-eastern Australia. *Soil Research,* vol. 51, pp. 695-706.

Alt, K. F., Osborn, C. T., & Colacicco, D. (1989). Soil Erosion: What Effect on Agricultural Productivity? (No. 556). US Department of Agriculture, Economic Research Service.

Altieri, M.A., 2002. Agroecology: the science of natural resource management for poor farmers in marginal environments. *Agriculture, ecosystems & environment*, 93(1-3), pp.1-24.

Aronson, James, and others (1993). Restoration and rehabilitation of degraded ecosystems in arid and semi-arid lands. A view from the South. *Restoration Ecology,* vol. 1, pp. 8-17.

Arrouays, Dominique, and others, (eds) (2014). *GlobalSoilMap : Basis of the Global Spatial Soil Information System*. CRC Press, London.

Aune, Jens, and André Bationo (2008). Agricultural intensification in the Sahel – The ladder approach. *Agricultural System,* vol. 98, pp. 119-125.

Ayers, Robert, and D.W. Westcot (1994). *Water Quality for Agriculture*. Rome: Food and Agriculture Organization of the United Nations.

Badgery, Warwick, and others (2013). Relationship between environmental and land-use variables on soil carbon levels at the regional scale in central New South Wales, Australia. *Soil Research*, vol. 51, pp. 645-656.

Baldock, Jeff, and Jan Skjemstad (1999). Soil organic carbon /Soil organic matter. In *Soil Analysis - an interpretation manual*. K.I. Peverill, and others, (eds). Collingwood: CSIRO Publishing.

Ball, BC and Munkholm, LJ (eds). (2015). Visual Soil Evaluation. Realizing Potential Crop Production with Minimal Environmental Impact. (CAB International. Wallingford, Oxfordshire, United Kingdom).

Balmford, Andrew, and others (2005). Sparing land for nature: exploring the potential impact of changes in agricultural yield on the area needed for crop production. *Global Change Biology,* vol. 11, pp. 1594-1605.

Bambrick, Hilary, and others (2015). Climate change and health vulnerability in informal urban settlements in the Ethiopian Rift Valley. *Environmental Research Letters*, vol. 10, pp. 054014.

Bationo, André, and others (2007). Soil organic carbon dynamics, functions and management in West Africa agroecosystems. *Agricultural Systems,* vol. 94, pp. 13-25.

Batjes, NH. (1996). Global assessment of vulnerability to water erosion using ½ by ½ degree grid. Land Degradation and Development 7, 353 – 65.

Bayala, Jules, and others (2012). Cereal yield response to conservation agriculture practices in drylands of West Africa. A quantitative synthesis. *Journal of Arid Environments*, vol. 78, pp. 13-25.

Beddington, John, and others (2011). *Achieving Food Security in the Face of Climate Change: Summary for Policy Makers from the Commission on Sustainable Agriculture and Climate Change*. Copenhagen: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

Bega, Noreen, and others (2002). Linkages between climate change and sustainable development. *Climate Policy*, vol. 2, pp. 129-144.

Beinroth, Freidrich, and others (1994). Land-related stresses in agroecosystems. In *Stressed Ecosystems and Sustainable Agriculture*. S.M. Virmani, and others, eds. New Delhi: Oxford and IBH.

Bekunda, Mateete, Nteranya Sanginga, and Paul Woomer (2010). Restoring soil fertility in sub-Saharan Africa. *Advances in Agronomy*, vol. 108, pp. 183-236.

Bell, Richard (2002). Land restoration: principles. In *Encyclopedia of Soil Science.* Rattan Lal, ed. New York: Marcel Dekker.

Benton, Tim, Juliet Vickery, and Jeremy Wilson (2003). Farmland biodiversity: is heterogeneity the key? *Trends in Ecology & Evolution*, vol. 18, pp. 182-188.

Bertin, T, Zacharie, T, Ann, D, Ebenezar, A and Alain, T (2014). Scaling-up Sustainable Land Management Practices through the Concept of the Rural Resource Centre: Reconciling Farmers' Interests with Research Agendas. *The Journal of Agricultural Education and Extension.* 20 (5), 463 – 483.

Bot, Alexandra, and José Benites (2005). The importance of soil organic matter: Key to drought-resistant soil and sustained food and production. *FAO Soils Bulletin*, No. 80. Rome: Food and Agriculture Organization of the United Nations.

Bouma, Johan (2002). Land quality indicators of sustainable land management across scales. *Agriculture, Ecosystems & Environment*, vol. 88, pp. 129-136.

Bouman, Bas, and others (1999). A framework for integrated biophysical and economic land use analysis at different scales. *Agriculture, Ecosystems & Environment*, vol. 75, pp. 55-73.

Brandes, Elke, Gabe S. McNunn, Lisa A. Schulte, David J. Muth, Andy VanLoocke, and Emily A. Heaton. (2018). Targeted subfield switchgrass integration could improve the farm economy, water quality, and bioenergy feedstock production. *Global Change Biology Bioenergy* 10, no. 3: 199-212.

Brown, Sandra, and others (1999). Modelling of soil nutrient budgets: an assessment of agricultural sustainability in Nepal. *Soil Use and Management*, vol. I5, pp. 101-108.

Bruinsma, Jelle (2009). The resource outlook to 2050: by how much do land, water and crop yields need to increase by 2050? Paper presented at the FAO Expert Meeting, *How to Feed the World in 2050.* 24-26 June 2009, Rome.

Bui, Elisabeth, and others (2010). *Evaluation of Tolerable Erosion Rates and Time to Critical Topsoil Loss in Australia*. Commonwealth of Australia: Caring for our Country.

Butsic, Van, and Tobias Kuemmerle (2015). Using optimization methods to align food production and biodiversity conservation beyond land sharing and land sparing. *Ecological Applications*, vol. 25, pp. 589-295.

Byrnes, Bernard, and Deborah Hellums (1998). Strategies for fertilizer research in the tropics. In *Soil Quality and Agricultural Sustainability*. Rattan Lal, ed. Chelsea, Michigan: Ann Arbor Press.

Carsky, Robert, and others (1998). Maintenance of soil organic matter and nitrogen supply in the moist savannah zone of West Africa. In *Soil Quality and Agricultural Sustainability*. Rattan Lal, ed., Chelsea, Michigan: Ann Arbor Press.

Carter, Martin (2002). Quality (soil), critical limits and standardization. In *Encyclopedia of Soil Science*. Rattan Lal, ed. New York: Marcel Dekker.

CAST (2013). Food fuel and plant nutrition use in the future. Issue Paper No. 51. Ames, Iowa: Council for Agricultural Science and Technology.

CAWMA (2007). *Water for Food, Water for Life. Comprehensive Assessment of Water Management in Agriculture*. David Molden, ed. London: Earthscan, and Colombo: International Water Management Institute.

Challinor, Andy, and others (2014). A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*, vol. 4, pp. 287-291.

Chan, Yin, and others (2010). Soil carbon stocks under different pastures and pasture management in the higher rainfall areas of south-eastern Australia. *Soil Research*, vol. 48, pp. 7-15.

Charman, Peter, and Andrew Wooldridge (2007). Soil salinisation. In *Soils, their Properties and Management*, third edition. Peter Charman and Brian Murphy, eds. Melbourne: Oxford University Press.

Ciais, Philippe, and others (2013). Carbon and other biogeochemical cycles. In *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, T.F. Stocker, and others, eds. Cambridge and New York: Cambridge University Press.

Cobo, Juan, Gerd Dercon, and Georg Cadisch (2010). Nutrient balances in African land use systems across different spatial scales: a review of approaches, challenges and progress. *Agriculture Ecosystems & Environment*, vol. 136, pp. 1-15.

Costa, Marcos, Aurélie Botta, and Jeff Cardille (2003). Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. *Journal of Hydrology*, vol. 283, pp. 206-217.

Cowie, Annette L., Barron J. Orr, Victor M. Castillo Sanchez, Pamela Chasek, Neville D. Crossman, Alexander Erlewein, Geertrui Louwagie, Martine Maron, Graciela Metternicht, Sara Minelli, and Anna Tengberg, Sven Walter and Shelley Welton. (2018) Land in balance: The scientific conceptual framework for Land Degradation Neutrality. *Environmental Science & Policy* 79: 25-35.

Cowie, Annette, Uwe Schneider and Luca Montanarella (2007). Potential synergies between existing multilateral environmental agreements in the implementation of land use, land use change and forestry activities. *Environmental Science & Policy,* vol. 10, pp. 335-352.

Cowie, A., Woolf, D., Gaunt, J., Brandão, M., Anaya de la Rosa, R. and Cowie, A., 2015. Biochar, carbon accounting and climate change. *Biochar for Environmental Management: Science, Technology and Implementation*, pp.763-794.

Craswell, Eric (2001). A decade of progress at IBSRAM and future priorities. In *Responses to Land Degradation*. Proceedings, second International Conference on Land Degradation and Desertification, E.M. Bridges, and others, eds. Khon Kaen and New Delhi: Oxford Press.

Craswell, Eric, and Paul L.G. Vlek (2013). Mining of nutrients in African soils due to agricultural intensification. In *Principles of Sustainable Management in Agroecosystem*s. Rattan Lal and Bobby A. Stewart, eds. London and New York: CRC Press.

Critchley, William, Samran Sombatpanit, and SM Medina (2001). Uncertain steps? Terraces in the tropics. In: *Responses to Land Degradation*. Proceedings, second International Conference on Land Degradation and Desertification, E.M. Bridges, and others, eds. Khon Kaen and New Delhi: India.

Crosson, P. (1995). Soil Erosion Estimates and Costs. *Science* 269: 461-464.

__________(1997). Will erosion threaten agricultural productivity. Environment: *Science and Policy for Sustainable Development*, 39(8), 4-31.

d'Amour, CB, Reitsma, F, Baiocchi, G, Barthel, S, Güneralp, B, Erb, K, Haberl, H, Creutzig, F, and Seto. KC. (2017). Future urban land expansion and implications for global croplands. Proceedings of the National Academy of Sciences (PNAS) 114, 8939 – 8944.

Davis, Sarah C., Robert M. Boddey, Bruno JR Alves, Annette L. Cowie, Brendan H. George, Stephen M. Ogle, Pete Smith, Meine Noordwijk, and Mark T. Wijk. (2013). Management swing potential for bioenergy crops. *Global Change Biology Bioenergy* 5, no. 6: 623-638.

DEE (2017). Department of Environment and Energy, Australian Government. http://www.environment.gov.au/climate-change/government/emissions-reduction-fund/methods/measurement-of-soil-carbon-sequestration-in-agricultural-systems

D'elia, Christopher, and Gene Likens (2012). Four words that can make us cringe. *Bioscience*, vol. 62, pp. 1012-1013.

Dent, David, and Anthony Young (1981). *Soil Survey and Land Evaluation*. London: George Allen and Unwin.

Dent, David, and Leen Pons (1995). A world perspective on acid sulphate soils. *Geoderma*, vol. 67, pp. 263-276.

Derpsch, Rolf, and others (2014). Why do we need to standardize no-tillage research? *Soil and Tillage Research*, vol. 137, pp. 16–22.

Dixon, John, David Gibbon, and Aidan Gulliver (2001). *Farming Systems and Poverty: Improving Farmers' Livelihoods in a Changing World*. Rome: Food and Agricultural Organization of the United Nations.

Dominati, Estelle, Murray Patterson, and Alec MacKay (2010). A framework for classifying and quantifying the natural capital and ecosystem services of soils. *Ecological Economics*, vol. 69, pp. 1858-1868.

Donald, Paul (2004). Biodiversity impacts of some agricultural commodity production systems. *Conservation Biology*, vol. 18, pp. 17-37.

Dondeyne, Stefaan, Eduardo Ndunguru, P. Rafael, and James Bannerman (2009). Artisanal mining in central Mozambique: policy and environmental issues of concern. *Resources Policy*, vol**.** 34, pp. 45-50.

Doran, John, Marianne Sarrantonio, and M. Lieberg (1996). Soil health and sustainability. *Advances in Agronomy*, vol. 56, pp. 1-54.

Doran, John, and Michael Zeiss (2000). Soil health and sustainability: managing the biotic component of soil quality. *Applied Soil Ecology*, vol. 15, pp. 3-11.

Drechsel, Pay, and Frits Penning de Vries (2001). Land pressure and soil nutrient depletion in sub-Saharan Africa. In: *Responses to Land Degradation*. Proceedings, second International Conference on Land Degradation and Desertification, E.M. Bridges, and others, eds. Khon Kaen and New Delhi: Oxford Press.

Dumanski, Julian and Christian Pieri (2000). Land quality indicators: research plan. *Agriculture, Ecosystems & Environment*, vol. 81, pp. 93-102.

El Gammal, MI, Ali, RR, Abou Samra, RM. (2015). GIS-based land degradation risk assessment of Damietta governorate, Egypt. *Egyptian Journal of Basic and Applied Science* 2, 183 – 189.

Eldridge DJ. 2001. Chapter 17. Soils and rangeland management. In Soils: their Properties and Management, Charman PEV, Murphy B (eds). Oxford University Press: Melbourne, Australia; 318–327.

Environment Agency (2009). Updated technical background to the CLEA Model (Contaminated Land Exposure Assessment). Science Report SC050021/SR3. Bristol. Available from www.environment-agency.gov.uk/.

Eswaran, Hari, and others (1997). Soil quality and soil productivity in Africa. *Journal of Sustainable Agriculture*, vol. 10, pp. 75-94.

Eswaran, Hari, Rattan Lal, and PF Reich (2001). Land degradation – an overview. In: *Responses to Land Degradation*. Proceedings, second International Conference on Land Degradation and Desertification, E.M. Bridges, and others, eds. Khon Kaen and New Delhi: Oxford Press.

European Environment Agency (2002). Environmental signals 2002: benchmarking the millennium. Environmental Assessment Report No 9. Luxembourg: Office for Official Publications of the European Communities.

FAO (1976). A framework for land evaluation. *FAO Soils Bulletin,* No. 32. Rome: Food and Agriculture Organization of the United Nations.

__________(2000). Manual on integrated management and conservation practices. *FAO Land and Water Bulletin,* No 8. Ibadan and Rome: International Institute of Tropical Agriculture and Food and Agriculture Organization of the United Nations.

FAO (The Food and Agriculture Organization of the United Nations) (2002). Towards 2015/2030 World Agriculture; Summary Report; FAO: Rome, Italy, 2002. Available online: ftp://ftp.fao.org/docrep/fao/004/y3557e/y3557e.pdf (accessed June 2017)

__________(2007). Land evaluation: towards a revised framework. Land and Water Discussion Paper No 6. Rome: Food and Agriculture Organization of the United Nations.

__________(2008). FAOSTAT. Available from http://faostat3.fao.org/home/index.html Accessed 05 December 2013.

__________(2009). *How to Feed the World in 2050*. Report of Expert Meeting, Rome, Italy, 24-26 June 2009. Rome: Food and Agriculture Organization of the United Nations.

---------------(2011). The state of the world's land and water resources for food and agriculture (SOLAW) – Managing systems at risk. Food and Agriculture Organization of the United Nations, Rome and Earthscan, London.

__________(2013). Land resources – Sustainable Land Management. Available from www.fao.org/nr/land/sustainable-land-management/en/.

__________(2015). International Year of Soil Conference. Available from http://www.fao.org/soils-2015/events/detail/en/c/338738/ Accessed April 2018.

__________(2017). Voluntary Guidelines for Sustainable Soil Management Food and Agriculture Organization of the United Nations Rome, Italy. http://www.fao.org/3/a-bl813e.pdf

FAO and ITPS (2015). *Status of the World's Soil Resources (SWSR) – Main Report*. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome, Italy.

FAO, IFAD and WFP (2013). *The State of Food Insecurity in the World 2013. The Multiple Dimensions of Food Security.* Rome: Food and Agricultural Organization of the United Nations, International Fund for Agricultural Development and World Food Programme.

FAO, IFAD, UNICEF, WFP and WHO (2017). *The State of Food Security and Nutrition in the World 2017. Building resilience for peace and food security*. Rome, FAO

Fenton, Greg and Keith Helyar (2007). Soil acidification. In *Soils–Their Properties and Management,* third edition. Peter Charman and Brian Murphy, eds. Melbourne: Oxford University Press.

Fernandez, R.J., Archer, E.R., Ash, A.J., Dowlatabadi, H., Hiernaux, P., Reynolds, J.F., Vogel, C.H., Walker, B.H. and Wiegand, T., 2002. Degradation and recovery in socio-ecological systems: a view from the household/farm level. In: Global Desertification: Do Humans Cause Deserts? Editors: J. F. Reynolds, and D. M. Stafford Smith, 297-323. Berlin: Dahlem University Press.https://www.researchgate.net/profile/Andrew_Ash/publication/268057044_A_View_from_the_Household_Farm_Level/links/546f434c0cf216f8cfa9cecd.pdf

Fischer, C. G., & Garnett, T. (2016). *Plates, Pyramids, and Planets: Developments in National Healthy and Sustainable Dietary Guidelines: a State of Play Assessment*. Food and Agriculture Organization of the United Nations.

Fischer, Joern, and others (2008). Should agricultural policies encourage land sparing or wildlife-friendly farming? *Frontiers in Ecology and the Environment,* vol. 6, pp. 380-385.

Foley, Jonathan, and others (2005). Global consequences of land use. *Science,* vol. 309, pp. 570-574.

__________ (2011). Solutions for a cultivated planet. *Nature*, vol. 478, pp. 337-342.

Foresight (2011). *The Future of Food and Farming*. Final Project Report. London: Government Office for Science.

Forster, P., and others (2007). Changes in atmospheric constituents and in radiative forcing. In *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, and others, eds. Cambridge and New York: Cambridge University Press.

Foster, George, and others (1996). *RUSLE User's Guide***.** City: Soil and Water Conservation Society.

FRA (2010). *Global Forest Resources Assessment*. Rome: Food and Agriculture Organization of the United Nations.

Galloway, James, and Ellis Cowling (2002). Reactive nitrogen and the world: 200 years of change. *Ambio*, vol. 31, pp. 64-71.

García-Ponce, E., H. Gómez-Macpherson, O. Diallo, M. Djibril, C. Baba, O. Porcel, B. Mathieu, J. Comas, *et al.* 2012. Contribution of sorghum to productivity of small-holder irrigation schemes: On-farm research in the Senegal River Valley, Mauritania. Agricultural Systems 115: 72–82.

Garnett, Tara (2013). Three perspectives on sustainable food security: efficiency, demand restraint, food system transformation. What role for LCA? *Journal of Cleaner Production*, vol 73, pp. 10-18.

Garnett, Tara, and others (2013). Sustainable intensification in agriculture: premises and policies. *Science*, vol. 341, pp. 33-34.

GEF (2005). *Scope and coherence of the land degradation activities in the GEF*. GEF/C.24/6/Rev.2 18 May 2005. Washington, D.C.: Global Environment Facility.

GEF (2006). *Land Degradation as a Global Environmental Issue: A Synthesis of Three Studies Commissioned by the Global Environment Facility to Strengthen the Knowledge Base to support the Land Degradation Focal Area.* GEF/C.30/Inf.8, 15 November 2006. Washington, D.C.: Global Environment Facility.

GEF (2011). *Linking the GEF Land Degradation Focal Area Strategy and the UNCCD Ten-year Strategy to Streamline Investments in Sustainable Land Management.* ICCD/CRIC(10)/CRP., 1 August 2011. Washington, D.C.: Global Environment Facility.

Ghuman, Birinder Singh, and R.S. Narang (1998). Sustainable management of soil and water resources in the upper and trans-Gangetic Plains of India. In *Soil Quality and Agricultural Sustainability*. Rattan Lal, ed. Chelsea, Michigan: Ann Arbor Press.

Gleick, Peter (2003). Global freshwater resources: soft-path solutions for the 21st century. *Science*, vol. 302, pp. 1524-1528.

Global Footprint Network. Undated. Available from: https://www.footprintnetwork.org/ (Accessed April 2018).

Global Soil Partnership (2014). *Plan of Action for Pillar One of the Global Soil Partnership. Pillar One - Promote Sustainable Management of Soil Resources for Soil Protection, Conservation and Sustainable Productivity*. Rome: Global Soil Partnership, Food and Agriculture Organization of the United Nations. Available from: *www.fao.org/fileadmin/user_upload/GSP/docs/ITPS_Pillars/annexII_pillar1.pdf*.

Godfray, H.C.J., and others (2010). Food security: the challenge of feeding 9 billion people. *Science*, vol 327, pp. 812.

Govaerts, B., *et al.*, 2009. Conservation agriculture and soil carbon sequestration: between myth and farmer reality. *Critical Reviews in Plant Sciences*, 28 (3), 97–122.

Gómez-Limón, José, and Gabriela Sanchez-Fernandez (2010). Empirical evaluation of agricultural sustainability using composite indicators. *Ecological Economics*, vol. 69, pp. 1062-1075.

Goudie, Andrew, and Nick Middleton (2001). Saharan dust storms: nature and consequences. *Earth Science Reviews*, vol. 56, pp. 179-204.

Govers, Gerard, and others (2013). *Managing Soil Organic Carbon for Global Benefits: A STAP Technical Report*. Washington, D.C.: Global Environmental Facility.

Grainger, Alan (2014). Is land degradation neutrality feasible in dry areas? *Journal of Arid Environments*, vol. 112, pp. 14-24.

Grassini, Patricio, and others (2015). How good is good enough? Data requirements for reliable crop yield simulations and yield-gap analysis. *Field Crop Research*, vol. 177, pp. 49-63.

Gray, Jonathan, Geoff Humphreys, and Jozef Deckers (2009). Relationships in soil distribution as revealed by a global soil data base. *Geoderma,* vol. 150, pp. 309-323.

Gray, Jonathan, Greg Chapman, and Brian Murphy (2015). Land management within capability: a new scheme to guide sustainable land management within NSW, Australia. *Soil Research*, vol. 10, 1071/SR14196.

Green, Rhys, and others (2005). Farming and the fate of wild nature. *Science*, vol. 307, pp. 550-555.

Greene, Richard, and Irene Wilson (1989). Amelioration of some physical and chemical properties and nutrient availability of exposed B-horizons of a red-brown earth. *Soil Use and Management,* vol. 5, pp. 66-71.

Gregorich, Edward (2002). Quality (soil). In *Encyclopaedia of Soil Science*. Rattan Lal, ed. New York: Marcel Dekker.

Gregory, Peter, John Ingram, and Michael Brklacich (2005). Climate change and food security. *Philosophical Transactions of the Royal Society B,* vol. 360, pp. 2139-2148.

Gundel, Sabine, Jim Hancock, and Simon Anderson (2001). *Scaling Up Strategies For Research In Natural Resource Management: A Comparative Review.* Chatham: Natural Resources Institute.

Gupta, RK and Abrol, IP. (1990). Salt-affected soils: Their reclamation and management for crop production. In R. Lal and BA Stewart (eds). Soil Degradation. Advances in Soil Science. Vol 11. (Springer-Verlag, New York).

Hamdy, A., & Aly, A. (2015, June). Land degradation, agriculture productivity and food security. In Fifth international scientific agricultural symposium, Agrosym2014. http://www. agrosym. rs. ba/agrosym/agrosym_2014/documents/4epnm/epnm9. pdf. Accessed (Vol. 3).

Hanao, Juan and Carlos Baanante (1999). *Estimating Rates of Nutrient Depletion in Soils of Agricultural Lands of Africa*. Muscle Shoals, Alabama: International Fertilizer Development Centre.

__________ (2006). *Agricultural Production and Soil Nutrient Mining in Africa. Implications for Resource Conservation and Policy Development*. Muscle Shoals, Alabama: International Fertilizer Development Centre.

Hansen, James (1996). Is agricultural sustainability a useful concept? *Agricultural Systems,* vol. 50, pp. 117-143.

Harris, David, and Alastair Orr (2014). Is rainfed agriculture really a pathway from poverty? *Agricultural Systems*, vol. 23, pp. 4-96.

Hartemink, Alfred (1998). Soil chemical and physical properties as indicators of sustainable land management under sugar cane in Papua New Guinea. *Geoderma,* vol. 85, pp. 283-306.

__________ (2006). Soil fertility decline: definitions and assessment. In *Encyclopaedia of Soil Science.* Rattan Lal, ed. pp. 1618-1621. New York: Marcel Dekker.

Hassink, Jan (1997). The capacity of soils to preserve organic C and N by association with clay and silt particles. *Plant and Soil*, vol**.** 191, pp. 77-87.

Hatfield, Jerry, and Lois Wright Morton (2013). Marginality principle. In *Principles of Sustainable Management in Agroecosystems*. Rattan Lal and Bobby A. Stewart, eds. Boca Raton, London, New York: CRC Press.

Hatfield, JL Sauer, TJ and Cruse, RM. (2017). Soil: The forgotten piece of the Water, Food energy Nexus. Advances in Agronomy 143, 1 – 46.

Hazelton, P.A., and Murphy, B.W. (2016). Third Edition. *What Do All the Numbers Mean? A Guide to the Interpretation of Soil Test Results.* Melbourne: CSIRO Publishing.

Heller, Nicole, and Erika Zavaleta (2009). Biodiversity management in the face of climate change: a review of 22 years of recommendations. *Biological Conservation*, vol. 142, pp. 14-32.

Hengl, T., *et al.* (2014). SoilGrids1 km — Global Soil Information Based on Automated Mapping. PLoS ONE 9:e105992.

Hengl, T., *et al.* (2015). Mapping Soil Properties of Africa at 250 m Resolution: Random Forests Significantly Improve Current Predictions. PLoS ONE 10:e0125814.

Herrick, J. E., K. C. Urama, J. W. Karl, J. Boos, M.-V, Herrero, Mario, and Philip Thornton (2013). Livestock and global change: emerging issues for sustainable food systems. *Proceedings of the National Academy of Sciences*, vol. 110, pp. 20878-20831.

Herrick, JE, Urama, KC, Karl, JW, Boos, J. Johnson, M-VV, Shepherd, KD, Hemple, J, Bestelmeyer, BT, Davies, J, Guerra, JL, Kosnik, C, Kimiti, DW, Ekai, AL, Muller, Norfleet, KL, Ozor, M, Reinsch, T, Sarukhan, J and West. TL, (2013). The global Land-Potential Knowledge System (LandPKS): supporting evidence-based, site-specific land use and management through cloud computing, mobile applications, and crowdsourcing. *Journal of Soil and Water Conservation* 68:5A–12A.

Herrick J. E., A. Beh, E. Barrios, I. Bouvier, M. Coetzee, D. Dent, E. Elias, T. Hengl, J. W. Karl, H. Liniger, J. Matuszak, J. C. Neff, L. W. Ndungu, M. Obersteiner, K. D. Shepherd, K. C. Urama, R. van den Bosch, and N. P. Webb. (2016). The Land-Potential Knowledge System (LandPKS): mobile apps and collaboration for optimizing climate change investments*. Ecosystem Health and Sustainability* 2(3):e01209. doi: 10.1002/ehs2.1209

Hobbs, Richard, and Viki Cramer (2008). Restoration ecology: interventionist approaches for restoring and maintaining ecosystem function in the face of rapid environmental change. *Annual Review of Environment and Resources*, vol. 33, pp. 39-61.

HOC (2013). *House of Commons International Development Committee Global Food Security First Report of Session 2013-14*. HC 176.

Hochman, Zvi, Dean Holzworth, and James Hunt (2009). Potential to improve on-farm wheat yield and WUE in Australia. *Crop and Pasture Science*, vol. 60, pp. 708-716.

Hochman, Zvi, and others (2013). Prospects for ecological intensification of Australian agriculture. *European Journal of Agronomy*, vol. 44, pp. 109-123.

Hossain, Faruque (2006). Arsenic contamination in Bangladesh: an overview*. Agriculture, Ecosystems & Environment,* vol. 113, pp. 1-16.

Howden, S. Mark, and others (2007). Adapting agriculture to climate change. *Proceedings of the National Academy of Sciences,* vol. 104, pp**.** 19691-19696.

Hulme, M.F., J.A. Vickery, R.E. Green, *et al.* (2013) 'Conserving the birds of Uganda's banana–coffee arc: Land sparing and land sharing compared', PLOS ONE 8: e5459

International Energy Agency (2012). *Medium-term Oil Market Report*. Paris. Available from www.iea.org/publications/freepublications/publication/name,38112,en.html.

International Food Policy Research Institute (2013). *2013 Global Food policy Report.* Washington, D.C.

Intergovernmental Panel on Climate Change (2007). *Climate Change 2007: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*,* Martin Parry, and others, eds. Cambridge: Cambridge University Press.

__________ (2013). *Climate Change 2013: The Physical Science Basis.* Working Group 1 Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva.

__________ (2014). *Climate Change 2014: Impacts, Adaptation and Vulnerability.* Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva. Available from http://ipcc-wg2.gov/AR5/.

Isbell, R., (2016). The Australian soil classification. CSIRO publishing.

ISO (2015) *ISO 13065:2015 Sustainability criteria for bioenergy*. The International Organization for Standardization. 57p

__________ (2017) *ISO 14055-1:2017 Environmental management -- Guidelines for establishing good practices for combatting land degradation and desertification -- Part 1: Good practices framework*. The International Organization for Standardization. 31p

IUSS (2015). World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps. IUSS Working Group WRB, World Soil Resources Reports No. 106. Rome: Food and Agriculture Organization of the United Nations.

Jaleta, M., Kassie, M. and Shiferaw, B. (2013). Tradeoffs in crop residue utilization in mixed crop- livestock systems and implication for conservation agriculture. *Agricultural Systems*, 121, 96-105.

Janzen, H. Henry (2006). The soil carbon dilemma: shall we hoard it or use it? *Soil Biology & Biochemistry*, vol. 38, pp. 419-424.

Jat, Ram A., Kanwar L. Sahrawat, and Amir H. Kassam, eds. (2014). *Conservation Agriculture*: *Global Prospects and Challenges.* CAB International.

Jayakody, Ananda N. (2001). Soil degradation in Sri Lanka. In *Responses to Land Degradation. Proceedings*, second International Conference on Land Degradation and Desertification, E.M. Bridges, and others, eds. Khon Kaen and New Delhi: Oxford Press.

Jenny, Hans (1941). *Factors of Soil Formation*. New York and London: McGraw-Hill Book Company.

Jones, Arwyn, and others, eds. (2013). *Soil Atlas of Africa.* European Commission. Luxembourg: Publications Office of the European Union.

Kabanza, Andrew, and others (2013). Effectiveness of soil conservation measures in two contrasting landscape units of South Eastern Tanzania. *Zeitschrift für Geomorphologie*, Online, February.

Kanmegne, J., and others (2006). Nutrient flows in smallholder production systems in the humid forest zone of southern Cameroon. *Nutrient Cycling in Agroecosystems*, vol. 76, pp. 233-248.

Karlen, Douglas L., Craig A. Ditzler, and Susan S. Andrews (2003). Soil quality: why and how? *Geoderma,* vol. 114, pp. 145-156.

Kassam, Amir, and others (2013). Sustainable soil management is more than what and how crops are grown. In *Principles of Sustainable Management in Agroecosystems,* Rattan Lal and Bobby A. Stewart, eds. Boca Raton, London, New York: CRC Press.

Kessy, JF, (2014). Analysis of staffing and training needs for effective delivery of extension service in sustainable land management in Kilimanjaro Region, Tanzania. Open Journal of Soil Science 4, 459-468

Kessy, JF and Kaswamila, A. (2014). Analytical framework model for capacity needs assessment and strategic capacity development within the local government structure in Tanzania. Open Journal of Soil Science 4, 502-508

Kelley, C.P., Mohtadi, S., Cane, M.A., Seager, R. and Kushnir, Y., (2015). Climate change in the Fertile Crescent and implications of the recent Syrian drought. *Proceedings of the National Academy of Sciences*, 112(11), pp.3241-3246.

Khedri Gharibvand, Hojatollah, Hossein Azadi, and Frank Witlox (2015). Exploring appropriate livelihood alternatives for sustainable rangeland management. *The Rangeland Journal,* vol. 37, pp. 345-356.

Kijne, Jacob W., and Marcel Kuper (1998). Sustainable management of land and water resources in irrigated semiarid and tropical regions. In *Soil Quality and Agricultural Sustainability,* Rattan Lal, ed. Chelsea, Michigan: Ann Arbor Press.

Kim, Seundgo, and Bruce E. Dale (2004). Global potential bioethanol production from wasted crops and crop residues. *Biomass Bioenergy,* vol. 26, pp. 361-375.

Klingebiel, A.A., and P.H. Montgomery (1961). Land capability classification. Agriculture Handbook No. 210. Washington, D.C.: Soil Conservation Service, Department of Agriculture.

Koch, Andrea, and others (2013). Soil security: solving the global soil crisis. *Global Policy,* vol. 4, pp. 434-441.

Kookana, Rai S., and others (2011). Biochar application to soil: agronomic and environmental benefits and consequences. In *Advances in Agronomy,* Donald L. Sparks, ed., vol. 112: 103-143. Academic Press, Elsevier Inc.

Krull, Evelyn S., Jan O. Skjemstad, and Jeffrey A. Baldock (2004). Functions of soil organic matter and the effect on soil properties. CSIRO Land and Water, PMB2, Glen Osmond SA 5064. GRDC Project No CSO 00029. Residue, Soil Organic Carbon and Crop Performance. Kingston, Australia: Grains Research and Development Corporation.

LaCanne, C.E. and Lundgren, J.G., (2018). Regenerative agriculture: merging farming and natural resource conservation profitably. PeerJ, 6, p.e4428.

Lado, Luis R., Tomislav Hengl, and Hannes I. Reuter (2008). Heavy metals in European soils: A geostatistical analysis of the FOREGS Geochemical database. *Geoderma,* vol. 148, pp. 189-199.

Lal, Rattan (1987). Response of maize and cassava to removal of surface soil from an Alfisol in Nigeria. *International Journal of Tropical Agriculture,* vol. 5, pp. 77-92.

Lal, R. (1990). Soil erosion and land degradation and degradation: the global risks. In R. Lal and BA Stewart (eds). Soil Degradation. Advances in Soil Science. Vol 11. (Springer-Verlag, New York).

Lal, R. (2001). Soil degradation by erosion. Land Degradation and Development 12, 519 – 539.

__________ (2003). Soil erosion and the global carbon budget. *Environment International*, vol. 29, pp. 437-450.

__________ (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, vol. 304, pp. 1623-1627.

__________ (2009). Ten tenets of sustainable soil management. *Journal of Soil and Water Conservation,* vol. 64, pp. 20A-21A.

__________ (2010a). Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. *Bioscience*, vol. 60, pp. 708-712.

__________ (2010b). Managing soils for a warming earth in a food-insecure and energy-starved world. *Journal of Plant Nutrition and Soil Science,* vol. 173, pp. 4-15.

__________ (2013). Chapter 1. Principles of soil management. In *Principles of Sustainable Soil Management in Agroecosytems.* Rattan Lal and Bobby A. Stewart, eds. Boca Raton, London, New York: CRC Press, Taylor and Francis Group.

__________ (2015). A systems approach to conservation agriculture. *Journal of Soil and Water Conservation,* vol. 70, pp. 82A-88A.

------------------.(2016). Soil health and carbon management. Food and Energy Security5, (4), 212–222

Lal, Rattan, Ronald Follett, Bobby A. Stewart, and John M. Kimble (2007). Soil carbon sequestration to mitigate climate change and advance food security. *Soil Science*, vol. 172, pp. 943-956.

Lal, R and Stewart, BA. (eds). (1990). Soil Degradation. Advances in Soil Science. Vol 11. (Springer-Verlag, New York).

Lal, R and Stewart, RA.. (2013) Soil management for sustaining ecosystem services. Chapter 19 In *Principles of Sustainable Soil Management in Agroecosytems.* Rattan Lal and Bobby A. Stewart, eds. Boca Raton, London, New York: CRC Press, Taylor and Francis Group.

Lamourdia, Thiombiano, and Malo Meshack (2009). *Scaling-Up Conservation Agriculture in Africa: Strategy and Approaches*. Addis Ababa: Food and Agriculture Organization of the United Nations, FAO Subregional Office for Eastern Africa.

Lee, C.Y. and Huh, S.Y., (2017). Forecasting Long-Term Crude Oil Prices Using a Bayesian Model with Informative Priors. *Sustainability*, 9(2),190.

Lehmann, J. and Joseph, S. eds., 2015. Biochar for environmental management: science, technology and implementation. Routledge.

Le Houerou, Henry N. (2002). Desertization. In *Encyclopedia of Soil Science*, Rattan Lal, ed. New York: Marcel Dekker.

Leys, John (2002). Erosion by wind, effects on soil quality and productivity. In *Encyclopedia of Soil Science,* Rattan Lal, ed. New York: Marcel Dekker.

Liniger, Hanspeter, and others (2011). *Sustainable Land Management in Practice. Guidelines and Best Practices for sub-Saharan Africa.* TerrAfrica, World Overview of Conservation Approaches and Technologies (WOCAT) and Food and Agricultural Organization of the United Nations (FAO).

Lipper, Leslie, Celine Dutilly-Dane, and Nancy McCarthy (2010). Supplying carbon sequestration from West African rangelands: opportunities and barriers. *Rangeland Ecology and Management*, vol. 63, pp. 155-166.

Liu, Hong-bin, and others (2011). Assessment of soil arsenic, chromium, mercury and lead at an agricultural landscape scale. *Soil and Sediment Contamination*, vol. 20, pp. 995-1007.

Liu, H. and Li, J., (2018). The US Shale Gas Revolution and Its Externality on Crude Oil Prices: A Counterfactual Analysis. Sustainability, 10(3), 697.

MA (2005). *Millennium Ecosystem Assessment: Ecosystems and Human Well-being – A Framework for Assessment.* Washington, D.C.: World Resources Institute.

McBratney, Alex, Damien J. Field, and Andrea Koch (2014). The dimensions of soil security. *Geoderma*, vol. 213, pp. 203-213.

McBratney, AB, Field, DJ, Morgan, CLS and Jarret, LE. (2017). Soil Security: A rationale. Chapter 1. In Field, Damien, Morgan, Cristine L., McBratney, Alex B. (Eds.) Global Soil Security Symposium. Progress in Soil Science Series. (Springer Publishers).

McCormack, D.E. (1987). Land evaluations that consider soil compaction. *Soil and Tillage Research*, vol. 10, pp. 21-27.

McKeon, Greg M., and others (2004). *Pasture degradation and recovery in Australia's rangelands: learning from history.* Queensland: Department of Natural Resources, Mines and Energy.

McKenzie, Neil J., Brent Henderson, and W.S. McDonald (2002). Monitoring soil change: principles and practices for Australian conditions. CSIRO Land and Water Technical Report 18/02. Canberra.

Marston, Landon, and others (2015). Virtual groundwater transfers from overexploited aquifers in the United States. *PNAS* doi/10.1073/pnas.1500457112

Matson, Pamela A., and Peter M. Vitousek (2006). Agricultural intensification: will land spared from farming be land spared for nature? *Conservation Biology,* vol. 20, pp. 709-10.

Mausbach, Maurice J., and Cathy A. Seybold (1998). Assessment of soil quality. In *Soil Quality and Agricultural Sustainability,* Rattan Lal, ed. Chelsea, Michigan: Ann Arbor Press.

Mbagwu, Joe S., Rattan Lal, and Trevor W. Scott (1984). Effects of desurfacing of Alfisols and Ultisols in southern Nigeria 1. Crop performance*. Soil Science of America Journal*, vol 48, pp. 828-833.

Mekonnen, M. M., & Hoekstra, A. Y. (2016). Four billion people facing severe water scarcity. Science advances, 2(2), e1500323. Available from: http://advances.sciencemag.org/content/2/2/e1500323.full

Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.S., Cheng, K., Das, B.S. and Field, D.J., (2017). Soil carbon 4 per mille. Geoderma, 292, pp.59-86.

Murphy, B.W., Packer, I.J., Cowie, A.L. and Singh, B.P., (2011). Tillage and crop stubble management and soil health in a changing climate. In *Soil Health and Climate Change* (pp. 181-206). Springer, Berlin, Heidelberg.

Murphy, BW. (2014). Estimating information levels - Using interpretation to convert data into useable information. In Arrouays, D, McKenzie, N, Hempel, J, Richer de Forges, A and McBratney, A (eds). "GlobalSoilMap. Basis of the Global Spatial Soil Information System". CRC Press, London.

Murphy, BW. (2015). Impact of soil organic matter on soil properties—a review with emphasis on Australian soils. *Soil Research,* vol. 53, pp. 605-635.

Murphy, B. (2016). Testing the Links between Soil Security, Sustainable Land Management Practices and Land Evaluation. Chapter 10. In Field, Damien, Morgan, Cristine L., McBratney, Alex B. (Eds.) Global Soil Security Symposium. Progress in Soil Science Series. (Springer Publishers).

Myers, S. S., Smith, M. R., Guth, S., Golden, C. D., Vaitla, B., Mueller, N. D., ... & Huybers, P. (2017). Climate change and global food systems: potential impacts on food security and undernutrition. *Annual review of public health*, 38, 259-277.

Naab, Francis Z., Romanus D. Dinye, and R. Kasim Kasanga (2013). Urbanization and its impact on agricultural lands in growing cities in developing countries: a case study of Tamale in Ghana. *Modern Social Science Journal*, vol. 2, pp. 256-287.

Naidoo, Robin (2004). Species richness and community composition of songbirds in a tropical forest-agricultural landscape*. Animal Conservation*, vol 7, pp. 93-105.

Naidu, R., Kookana, R. S., Oliver, D. P., Rogers, S., and McLaughlin, M. J. (Eds) (1996). 'Contaminants and the soil environment in the Australasian–Pacific Region.' (Kluwer Academic Publishers: Netherlands.)

NASA (2015) Study: Third of Big Groundwater Basins in Distress https://www.nasa.gov/jpl/grace/study-third-of-big-groundwater-basins-in-distress
Accessed 17/05/2018

National Research Council (1992). *Restoration of Aquatic Ecosystems: Science, Technology and Public Policy*. Washington, D.C.: National Academy Press.

Ngatunga, E.L., Stefaan Dondeyne, and Jozef A. Deckers (2003). Is sulphur acidifying cashew soils of south eastern Tanzania? *Agriculture Ecosystems & Environment*, vol. 95, pp. 179-184.

Ngoze, Soloman, and others (2008). Nutrient constraints to tropical agrosystem productivity in long term degrading soils. *Global Change Biology*, vol. 14, pp. 2810-2822.

Niemeijer, David, and Daniel S. Moran (2006). *Determining Global Environmental Benefits of Land Degradation Interventions using the Millennium Ecosystem Services Framework*. A report prepared for the Global Environmental Facility (GEF) Scientific and Technical Advisory Panel (STAP). Washington, D.C.: Global Environmental Facility.

Nkonya, Ephraim, and others (2013). Global extent of land degradation and its human dimensions. In *Principles of Sustainable Soil Management in Agroecosystems,* Rattan Lal and Bobby A. Stewart, eds. Boca Raton: CRC Press, Taylor and Francis Group.

Nkonya E, Mirzabaev A, von Braun J. (2015). Economics of Land Degradation and Improvement: A Global Assessment for Sustainable Development. ZEF Policy Brief No. 24, Zentrum für Entwicklungsforschung. Center for Development Research, University of Bonn

Noble, Andrew (2012). *The Slumbering Giant: Land and Water Degradation*. Canberra: Crawford Fund Proceedings.

Noble, Andrew, and others (2001). Soil acidification under Styloantheses seed production systems in Thailand and Australia. In *Responses to Land Degradation*. Proceedings, second International Conference on Land Degradation and Desertification, E.M. Bridges, and others, eds. Khon Kaen and New Delhi: Oxford Press.

Noe, C (2014). Reducing Land Degradation on the Highlands of Kilimanjaro Region: A Biogeographical Perspective. *Open Journal of Soil Science,* 4, 437-445

OECD, 2017. Water Risk Hotspots for Agriculture, OECD Studies on Water, OECD Publishing, Paris. DOI:http://dx.doi.org/10.1787/9789264279551-en

Office of Environment and Heritage (2012). *The Land and Soil Capability Assessment Scheme: Second Approximation. A General Rural Land Evaluation System for New South Wales.* Sydney. Available from: www.environment.nsw.gov.au.

Oldeman, L.R., R.T.A. Hakkeling, and W.G. Sombroek. (1990). World Map of the Status of Human-Induced Soil Degradation: An Explanatory Note. Revised Second Edition. Wageningen: International Soil Reference and Information Centre.

Oldeman, L. Roel (1998). Soil degradation: a threat to food security? Report 98/01. Waginengen: International Soil Reference and Information Centre.

Omuto, C. Thine, Nachtergaele, Freddy, and Ronald V. Rojas (2013). *State of the Art Report on Global and Regional Soil Information: Where are we? Where to go?* Rome: Food and Agriculture Organization of the United Nations.

Orr, B.J., A.L. Cowie, V.M. Castillo Sanchez, P. Chasek, N.D. Crossman, A. Erlewein, G. Louwagie, M. Maron, G.I. Metternicht, S. Minelli, A.E. Tengberg, S. Walter, and S. Welton. (2017). *Scientific Conceptual Framework for Land Degradation Neutrality*. A Report of the Science-Policy Interface. United Nations Convention to Combat Desertification (UNCCD), Bonn, Germany. ISBN 978-92-95110-42-7 (hard copy), 978-92-95110-41-0 (electronic copy).

Overseas Development Group (2006). *Global Impacts of Land Degradation*. A report prepared for the Global Environmental Facility (GEF) Scientific and Technical Advisory Panel (STAP). University of East Anglia.

Pagiola, S. (1999). The global environmental benefits of land degradation control on agricultural land. World Bank. Environment Paper No. 16. The World Bank, Washington, DC.

Palm, Cheryl, and others (2007). Soils: a contemporary perspective. *Annual Review of Environmental Resources,* vol. 32, pp. 99-129.

Pandey, Vimal Chandra, Omesh Bajpai, and Nandita Singh. (2016). Energy crops in sustainable phytoremediation. *Renewable and Sustainable Energy Reviews* 54: 58-73.

Parry, Martin (2009). *Climate Change and Hunger, Responding to the Challenge.* Rome: World Food Programme.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, *532*(7597), 49.

Pedzisa, Tarisayi, and others (2015). Abandonment of conservation agriculture by smallholder farmers in Zimbabwe. *Journal of Sustainable Development*, vol. 8, pp. 69-81.

Peverill, K.I., L.A. Sparrow, and D.J. Reuter, D.J. (1999). *Soil Analysis: An Interpretation Manual.* Collingwood, Victoria: CSIRO Publishing.

Phalan, Ben, and others (2011). Reconciling food production and biodiversity conservation: land sharing and land sparing compared. *Science*, vol. 333, pp. 1289-1291.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., ... & Blair, R. (1995). Environmental and economic costs of soil erosion and conservation benefits. Science, 267(5201), 1117-1123.

Pimm, Stuart L., and Peter Raven (2000). Biodiversity: extinction by numbers. *Nature*, vol. 403, pp. 843-845.

Powlson, David S., Andrew P. Whitmore, and Keith W.T. Goulding (2011). Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. *European Journal of Soil Science*, vol. 62, pp. 42-55.

Pretorius, J.R., and J. Cooks (1989). Soil loss tolerance limits: an environmental management tool. *Geo Journal*, vol. 19, pp. 67-75.

Pretty, Jules, Camilla Toulmin, and Stella Williams (2011). Sustainable intensification in African agriculture. *International Journal of Agricultural Sustainability*, vol. 9, pp. 5-14.

Qishlaqi, A., Moore, F., Forghani, A. (2010). Assessing the spatial variability of total and available cadmium in soils of the Angouran Area, NW Iran. *Soil and Sediment Contamination,* vol. 19, pp. 707 – 724.

Rahman, M.M., and others (2001). Land degradation in Bangladesh. In: *Responses to Land Degradation*. Proceedings, second International Conference on Land Degradation and Desertification, E.M. Bridges, and others, eds. Khon Kaen and New Delhi: Oxford Press.

Ramankutty, Navin, and Jeanine M. Rhemtulla (2013). Land sparing or land sharing: context dependent. *Frontiers in Ecology and the Environment,* vol. 11, pp. 178-178.

Raut, N., and others (2011). Evolution and future direction of intensified agriculture in the central, mid-hills of Nepal. *International Journal of Agricultural Sustainability*, vol. 9, pp. 537-550.

Ray, Deepak K., and others (2015). Climate variation explains a third of global crop yield variability. *Nature Communications*, vol. 6, pp. 1-9.

Read, Z.J., Brian Murphy, and Richard Greene (2012). Soil carbon sequestration potential of revegetated scalded soils following waterponding. Paper presented at Australian and New Zealand Soils Conference. Hobart, 2-7 December.

Renard, K. G., Foster, G. R., Weesies, G. A., McCool, D. K. & Yoder, D. C. (1996). Predicting soil erosion by water: a guide to conservation planning with Revised Universal Soil Loss Equation (RUSLE). – Agriculture, Handbook No. 703, USDA, ARS, Washington DC.

Rengasamy, P. (2006). World Salinization with emphasis on Australia. Journal of Experimental Biology. 57 (5) 1017 – 1023.

Renwick, A., & Schellhorn, N. (2016). A perspective on land sparing versus land sharing. Chapter 9 in Dean Ansell, Fiona Gibson and David Salt (eds), *Learning from agri-environment schemes in Australia: Investing in biodiversity and other ecosystem services on farms*. 117 - 126. (ANU Press, The Australian National University, Canberra, Australia.)

Ringrose-Voase, A.J., Geeves, G.W., Merry, R.H. and Wood, J.T. (1997). Soil indicators of changing land quality and capital value. CSIRO (Australia), Land and Water Technical Report, 17, p.97.

Rosegrant, Mark W., Ximing Cai, and Sarah A. Cline (2002). *Global Water Outlook to 2025: Dealing with Scarcity.* International Food Policy Research Institute, September.

Sachs, Jeffrey D., and others (2010). Monitoring the world's agriculture. *Nature*, vol. 466, pp. 558-560.

__________ (2012). Effective monitoring of agriculture: a response. *Journal of Environmental Monitoring,* vol. 14, pp. 738-42.

Sage, Colin (2013). The interconnected challenges for food security from a food regimes perspective: energy, climate and malconsumption. *Journal of Rural Studies*, vol. 29, pp. 71-80.

Sanchez, Pedro A., and others (1997). Soil fertility replenishment in Africa: an investment in natural resource capital. In *Replenishing Soil Fertility in Africa,* Roland J. Buresh, Pedro A. Sanchez, and Frank Calhoun, eds. Special Publication, vol. 51. Madison: Soil Science Society of America.

Sanchez, Pedro A., Cheryl A. Palm, and Stanley W. Buol (2003). Fertility capability classification: a tool to help assess soil quality in the tropics. *Geoderma,* vol. 114, pp. 157-185.

Sanchez, Pedro A., and Mankombu S. Swaminathan (2005). Cutting world hunger in half. *Science,* vol. 307, pp. 357-359.

Sandewall, Mats, and N.E. Nilsson (2001). The area production model: a tool and concept for sustainable land-use and forest-resource management. *Journal of Environmental Management*, vol. 62, pp**.** 415-427.

Sanginga, Nteranya, and Paul L. Woomer, eds. (2009). *Integrated Fertilizer Management for Africa: Principles, Practices and Development Processes*. Nairobi: Tropical Soil Biology and Fertilizer Institute of the Institute of Tropical Agriculture (TSBI-CIAT).

Sarker, JR, Singh, BP, Dougherty, WJ, Fang,Y, Badgery, W, Hoyle, FC, Dalal, RC Cowie, AL. (2018). Impact of agricultural management practices on the nutrient supply potential of soil organic matter under long-term farming systems. *Soil and Tillage Research* 175, 71 – 81.

Scariot, Aldicir (2013). Land sparing or land sharing: the missing link. *Frontiers in Ecology and the Environment,* vol. 11, pp. 177-178.

Schertz, David L., and Mark A. Nearing (2002). Erosion tolerance/soil loss tolerances. In *Encyclopaedia of Soil Science*, Rattan Lal, ed. New York: Marcel Dekker.

Schmidt B.L., and others (1982). Determinants of soil loss tolerance. In *Proceedings of a Symposium, sponsored by Division S-6 of the Soil Science Society of America.* American Society of Agronomy Special Publication, No 45.

Scholes, Robert J., and Reinette Biggs (2005). A biodiversity intactness index. *Nature,* vol. 434, pp. 45-49.

Scholes, Robert J., and Graham von Maltitz (2006). *Quantifying Tradeoffs between Sustainable Land Management, Global Environmental Concerns and Local Socioeconomic Impacts.* A report prepared for the Global Environmental Facility (GEF) Scientific and Technical Advisory Panel (STAP). Washington, D.C.: Global Environmental Facility.

Searchinger, Tim, and others (2013). The great balancing act. Working Paper, Instalment 1 of Creating a Sustainable Food Future. Washington, D.C.: World Resources Institute. Available from www.worldresourcesreport.org.

Sengeda, AZ, Kahinda, FC, Kashaga, RAL, Semu, E, Mahonga, CP and Mkanda, FX. (2014). Testing of Decision Making Tools for Village Land Use Planning and Natural Resources Management in the Kilimanjaro Region*. Open Journal of Soil Science*, 4, 446-458

Shepherd, Keith D., Tor-Gunnar Vagen, and Thomas Gumbricht (2008). Land degradation surveillance: quantifying and monitoring land degradation. *In Sustainable Land Management Sourcebook*. Washington, D.C.: World Bank.

Shepherd, K.D. and Walsh, M.G. (2007). Infrared spectroscopy—enabling an evidence-based diagnostic surveillance approach to agricultural and environmental management in developing countries. Journal of Near Infrared Spectroscopy, 15(1), pp.1-19.

Shepherd, T.G. (2009) Visual Soil Assessment. Volume 1. Pastoral Grazing and Cropping on Flat to Rolling Country, 2nd edn. Horizons Regional Council, Palmerston North, New Zealand.

Shepherd, T.G., Stagnari, F., Pisante, M. and Benites, J. (2008) Visual Soil Assessment – Field Guide for Annual Crops. FAO, Rome.

Sherwood, S. and Uphoff, N. (2000). Soil health: research, practice and policy for a more regenerative agriculture. *Applied Soil Ecology*, 15(1), pp.85-97.

Sims, Neil; Green, Carly; Newnham, Glenn; England, Jacqui; Held, Alex; Wulder, Michael; Herold, Martin; Cox, Simon; Huete, Alfredo; Kumar, Lalit; Viscarra Rossel, Raphael; Roxburgh, Stephen; McKenzie, Neil. (2017) Good practice guidance. SDG Indicator 15.3.1: Proportion of land that is degraded over total land area. Version 1.0. Bonn, Germany: United Nations Convention to Combat Desertification.

Smetana, S., Mathys, A., Knoch, A. and Heinz, V. (2015)). Meat alternatives: life cycle assessment of most known meat substitutes. *The International Journal of Life Cycle Assessment*, *20*(9), pp.1254-1267.

Smil, Vaclav (1997). Global population and the nitrogen cycle. *Scientific American*, vol. 277, pp. 76-81.

Smith, Cynthia S., Geoffrey T. McDonald, and R.N. Thwaites (2000). TIM: assessing the sustainability of agricultural land management. *Journal of Environmental Management,* vol. 60, pp. 267-288.

Smith, Pete (2008). Land use change and soil organic carbon dynamics. *Nutrient Cycling in Agroecosystems*, vol 81, pp. 169-178.

Smith, P. (2016). Soil carbon sequestration and biochar as negative emission technologies. *Global change biology*, *22*(3), pp.1315-1324.

Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E, …, and Van Vuuren, D.P. (2016). Biophysical and economic limits to negative CO2 emissions. *Nature Climate Change*, 6(1), pp.42-50.

Smith, P., Lutfalla, S., Riley, W. J., Torn, M. S., Schmidt, M. W. I., & Soussana, J. F. (2018). The changing faces of soil organic matter research. *European Journal of Soil Science* 69: 23-30.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C. and Scholes, B., (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 363, pp. 789-813.

Soane, B.D., and others (2012). No-till in northern, western and south-western Europe: a review of problems and opportunities for crop production and the environment. *Soil and Tillage Research,* vol. 118, pp. 66-87.

Soil Survey Staff (1999). A Basic System of Soil Classification for Making and Interpreting Soil Surveys. Second Edition. Agricultural Handbook No 436. Natural Resources Conservation Service. USDA.

Solomon, S., and others (2007). Climate Change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, New York: Cambridge University Press.

Spiertz, J.H.J. (2008). Nitrogen, sustainable agriculture and food security: A review. *Agronomy for Sustainable Development,* vol. 30, pp. 43-55.

Squires, Victor R. (2002). *Desertification, the extent of*. In *Encyclopedia of Soil Science,* Rattan Lal, ed. New York: Marcel Dekker.

Stern, Nicholas (2007). *The Economics of Climate Change.* Cambridge: Cambridge University Press.

Stewart, Bobby A., Xiaobo Hou, and Sanjeev R. Yalla (2013). Facts and myths of feeding the world with organic farming methods. In *Principles of Sustainable Soil Management in Agroecosytems*, Rattan Lal and Bobby A. Stewart, eds. Boca Raton, London, New York: CRC Press, Taylor and Francis Group.

Stocking, Michael A. (2003). Tropical soils and food security: the next 50 years. *Science*, vol. 302, pp. 1356- 1359.

__________ (2008). Sustainable land management and its relation to climate change. Paper presented to CSD 16, Learning Centre Course, New York, May. Available from www.un.org/esa/sustdev/csd/csd16/LC/presentations/stocking.pdf.

Stocking, Michael A., and D. McCormack (1986). Soil potential ratings: II. A test of the method in Zimbabwe. *Soil Survey & Land Evaluation*, vol. 6, pp. 115-122.

Stockmann, Uta, Budaman Minasny, and Alex B. McBratney (2014). How fast does soil grow? *Geoderma*, vol. 216, pp. 48-61.

Stoorvogel, Jetse J., Eric M.A. Smaling, and Boris Jansen (1993). Calculating soil nutrient balances in Africa at different scales: I. Supra-national scale. *Fertilizer Research,* vol. 35, pp**.** 227-235.

Sullivan, Leigh. (2004). Sustainable management of acid sulfate soils (Special Issue). *Australian Journal of Soil Research,* vol. 42, pp. 1.

Taghipour, Marzieh, Shamsollah Ayoubi, and Hossein Khademi (2011). Contribution of lithologic and anthropogenic factors to surface soil heavy metals in Western Iran using multivariate geostatistical analyses. *Soil and Sediment Contamination*, vol. 20, pp. 921-935.

Tan, Zhengxi, Rattan Lal, and Keith D. Wiebe (2005). Global nutrient depletion and yield reduction. *Journal of Sustainable Agriculture,* vol. 26, pp. 123-146.

Tans, Pieter, and Charles D. Keeling (2013). *Trends in atmospheric CO_2 at Mauna Loa, Hawaii*. La Jolla: Earth System Research Laboratory, National Oceanic and Atmospheric Administration and Scripps Institution of Oceanography. Available from www.esrl.noaa.gov/gmd/ccgg/trends/.

Tegen, Ina, and others (2004). Relative importance of climate and land use on soil productivity in determining present and future global dust emission. *Geophysical Research Letters, vol.* 31**:** L05105, doi:10.1029/2003GL109216.

Tengberg, Anna, and Michael Stocking (2001). Land degradation, food security and agro-biodiversity – examining an old problem in a new way. In *Responses to Land Degradation*. Proceedings, second International Conference on Land Degradation and Desertification, E.M. Bridges, and others, eds. Khon Kaen and New Delhi: Oxford Press.

Tettah, Samuel, and others (2010). Levels of mercury, cadmium and zinc in the topsoil of some selected towns in the Wassa West district of the western region of Ghana. *Soil and Sediment Contamination*, vol. 19, 635-643.

Thiele, R. (2002). The bias against agriculture in Sub-Saharan Africa: Has it survived 20 years of structural adjustment programs? Kiel Institute for World Economics, Report Kiel, Germany, 27 pp.

Tighe, M., Muñoz-Robles, C., Reid, N., Wilson, B. and Briggs, S.V. (2012). Hydrological thresholds of soil surface properties identified using conditional inference tree analysis. Earth Surface Processes and Landforms, 37(6), pp.620-632.

Thiombiano, Lamourdia, and Malo Meshack (2009). *Scaling-up Conservation Agriculture in Africa: Strategy and Approaches.* Addis Ababa: The FAO Subregional Office for Eastern Africa.

Tilman, David, and others (2011). Global food demand and the sustainable intensification of agriculture. *PNAS,* vol. 108, pp. 20260-20264.

__________ (2002). Agricultural sustainability and intensive production practices. *Nature*, vol. 418, pp. 671-677.

Tittonell, Pablo, and Ken E. Giller (2013). When yield gaps are poverty traps: the paradigm of ecological intensification in African smallholder agriculture. *Field Crops Research*, vol. 143, pp. 76-90.

Toensmeier, E. (2016). The carbon farming solution: A global toolkit of perennial crops and regenerative agriculture practices for climate change mitigation and food security. Chelsea Green Publishing.

Tongway, David, and Norman Hindley (2004). Landscape function analysis: a system for monitoring rangeland function. *African Journal of Range and Forage Science*, vol. 21**,** pp. 109-113.

Tongway DJ, Ludwig JA. (2005). Heterogeneity in arid and semi-arid lands. In Ecosystem Function in Heterogeneous Landscapes, Lovett GM, Turner MG, Jones CG, Weathers KC (eds). Springer: New York, NY; 189–205.

Troy, Tara J., Chinpihoi Kipgen, and Indrani Pal (2015). The impact of climate extremes and irrigation on US crop yields. *Environmental Research Letters,* vol. 10, pp. 054013.

Tscharntke, Teja, and others (2012). Global food security, biodiversity conservation and the future of agricultural intensification. *Biological Conservation,* vol. 151, pp. 53–59.

Tubiello, Francesco N., Jean-François Soussiana, and S. Mark Howden (2007). Crop and pasture response to climate change. *Proceedings of the National Academy of Sciences,* vol. 104, pp**.** 19686-19690.

Tueller, Paul T. (2002). Desertification. In *Encyclopedia of Soil Science*, Rattan Lal, ed. New York: Marcel Dekker.

United Nations (1987). *Report of the World Commission on Environment and Development*, General Assembly Resolution 42/187, 11 December 1987, New York.

__________(1995). *Chapter 40: Information for Decision-making and Earthwatch*. Commission on Sustainable Development, Economic and Social Council. E/CN.17/1995/7, February, New York.

__________(2007). United Nations Department of Economic and Social Affairs, Population Division. *World Population Prospects: The 2006 Revision.* New York.

__________(2009). *The Millennium Development Goals Report*. New York.

United Nations Convention to Combat Desertification (2011). *Land and soil in the context of a green economy for sustainable development, food security and poverty eradication*. Submission of the UNCCD Secretariat to the Preparatory Process for the Rio+ 20 Conference. Revised Version 18 November 2011. New York.

__________(2016). Report of the Conference of the Parties on its twelfth session, held in Ankara from 12 to 23 October 2015. ICCD/COP(12)/20/Add.1. January 2016. Available from:
https://www2.unccd.int/sites/default/files/sessions/documents/ICCD_COP12_20_Add.1/20add1eng.pdf
(Accessed April 2018).

United Nations Department of Economic and Social Affairs (UNDESA). News. Available from:
https://www.un.org/development/desa/en/news/population/world-population-prospects-2017.html
(Accessed April 2018)

UNEP (2014). Assessing Global Land Use: Balancing Consumption with Sustainable Supply. A Report of the Working Group on Land and Soils of the International Resource Panel. Bringezu S., Schütz H., Pengue W., O´Brien M., Garcia F., Sims R., Howarth R., Kauppi L., Swilling M., and Herrick J.

UNEP. 2016. Unlocking the Sustainable Potential of Land Resources: Evaluation Systems, Strategies and Tools. A Report of the Working Group on Land and Soils of the International Resource Panel. Herrick, J.E., O. Arnalds, B. Bestelmeyer, S. Bringezu, G. Han, M.V. Johnson, D. Kimiti, Yihe Lu, L. Montanarella, W. Pengue, G. Toth, J. Tukahirwa, M. Velayutham, and G. Zhang. United Nations Environment Programme (UNEP), Nairobi. Available online:
http://www.resourcepanel.org/reports/unlocking-sustainable-potential-land-resources

United States Department of Agriculture (2015). National Soil Survey Handbook- Part 622. Interpretive Groups. Technical Handbook 430. Washington, D.C.

Uvin, Peter, Pankaj K. Jain, and L. David Brown (2000). Think large and act small: toward a new paradigm for NGO scaling up. *World Development*, vol. 28, pp. 1409-1419.

Vågen, T.-G., Winowiecki, L.A., Abegaz, A., Hadgu, K.M. (2013). Landsat-based approaches for mapping of land degradation prevalence and soil functional properties in Ethiopia. Remote Sens. Environ. 134, 266–275.

Vågen, TG, Winowiecki, LA, Tondoh, JE, Desta, LT, Gumbricht, T. (2016). Mapping of soil properties and land degradation risk in Africa using MODIS reflectance. Geoderma 263, 216 -225.

van Bussel, Lenny, and others (2015). From field to atlas: upscaling of location-specific yield gap estimates. *Field Crops Research,* vol. 177, pp. 98-108.

Van-Camp, L, Bujarrabal, B, Anna Rita Gentile, AR, Robert J A, Jones, RJA, Montanarella, L, Claudia Olazabal, C, Selvaradjou, SK (eds) (2004). Volume IV. Contamination and Land Management. In Van-Camp. L., Bujarrabal, B., Gentile, A-R., Jones, R.J.A., Montanarella, L., Olazabal, C. and Selvaradjou, S-K. (2004). Reports of the Technical Working Groups Established under the Thematic Strategy for Soil Protection. EUR 21319 EN/4, 872 pp. Office for Official Publications of the European Communities, Luxembourg.

van Ittersum, Martin K., and others (2013). Yield gap analysis with local to global relevance—a review. *Field Crops Research,* vol. 143, pp. 4-17.

van Wart, Justin, and others (2013). Estimating crop yield potential at regional to national scales. *Field Crops Research,* vol. 143, pp. 34-43.

Verheijen, Frank G. A., and others (2005). Organic carbon ranges in arable soils of England and Wales. *Soil Use and Management*, vol. 21, pp. 2-9.

__________(2009). *Biochar Application to Soils – A Critical Scientific Review of Effects on Soil Properties, Processes and Functions*. EUR 24099 EN. Luxembourg: Office for the Official Publications of the European Communities.

Viscarra Rossel, R.A., Lobsey, C.R., Sharman, C., Flick, P. and McLachlan, G. (2017). Novel Proximal Sensing for Monitoring Soil Organic C Stocks and Condition. Environmental Science & Technology, 51(10), pp.5630-5641.

Viscarra Rossel, R.A., Walvoort, D.J.J., McBratney, A.B., Janik, L.J. and Skjemstad, J.O., 2006. Visible, near infrared, mid infrared or combined diffuse reflectance spectroscopy for simultaneous assessment of various soil properties. Geoderma, 131(1), pp.59-75.

Vivien, Franck-Dominique (2008). Sustainable development: an overview of economic proposals. *SAPIENS*, vol. 1, pp. 1-8.

Vlek, Paul L.G., R.F. Kuhne, and Manfred Denich (1997). Nutrient resources for crop production in the tropics. *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 352, pp. 975-985.

Wade, Mark R., Geoff M. Gurr, and Steve D. Wratten (2008). Ecological restoration of farmland: progress and prospects. *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 363, pp. 831-847.

Walter, Christof, and Hartmut Stutzel (2009). A new method for assessing the sustainability of land-use systems I: identifying the relevant issues. *Ecological Economics*, vol. 68, pp. 1275-1287.

Wani, Suhas P., Kanwar Lal SahRawat, and Srinivasa R. Chennamaneni (2008). Integrated nutrient management in the semi-arid tropics. In *Sustainable Land Management Sourcebook*. Washington, D.C.: World Bank.

Weston, P., Hong, R., Kaboré, C. and Kull, C.A. (2015). Farmer-managed natural regeneration enhances rural livelihoods in dryland west Africa. Environmental management, 55(6), pp.1402-1417.

Wheeler, Tim, and Joachim von Braun (2013). Climate change impacts on global food security. *Science*, vol. 341, pp. 508-513.

White, Mark A. (2013). Sustainability: I know it when I see it. *Ecological Economics*, vol. 86, pp. 213-217.

__________ (2000). *Running Down: Water in a Changing Land*. East Roseville, Australia: Kangaroo Press.

Wiebe, Keith (2002). Resources, agricultural productivity and food security. In *Encyclopedia of Soil Science,* Rattan Lal, ed. New York: Marcel Dekker.

__________ (2003). Linking land quality, agricultural productivity, and food security. Agricultural Economic Report No. 823. Washington, D.C.: Resource Economics Division, Economic Research Service, U.S. Department of Agriculture.

Wilson, Brian R., I. Gowns, and J. Lemon (2008). Land use effects on soil properties on the northwestern slopes of New South Wales: implications for soil condition assessment. *Australian Journal of Soil Research*, vol. 46, pp. 359-367.

Winterbottom, R., and others, (2013). Improving land and water management. Working Paper, Instalment 4 of Creating a Sustainable Food Future. Washington, D.C.: World Resources Institute. Available from www.worldresourcesreport.org.

Wood, S.W. and Cowie, A. (2004). A review of greenhouse gas emission factors for fertiliser production. A report to IEA Bioenergy Task 38. Available at : http://task38.org/publications/GHG_Emission_Fertilizer_Production_July2004.pdf

Woomer, Paul L., and others (1998). The biological management of tropical soil fertility: some research and development priorities for Africa. In *Soil Quality and Agricultural Sustainability,* Rattan Lal, ed. Chelsea, Michigan: Ann Arbor Press, Chelsea.

World Bank (undated) Water in agriculture. http://www.worldbank.org/en/topic/water-in-agriculture

World Bank (1998). Land quality indicators and their use in sustainable agriculture and rural development. Proceedings of workshop. Rome: United Nations Development Programme and Food and Agriculture Organization of the United Nations.

__________ (2003). *World Development Report 2003: Sustainable Development in a Dynamic World*. Washington, D.C.: World Bank.

__________(2008). *Sustainable Land Management Sourcebook*. Washington, D.C.: World Bank.

__________(2018). Overview of Urban Development. Available from: http://www.worldbank.org/en/topic/urbandevelopment/overview (Accessed April 2018).

Yengoh, Genesis T. and Jonas Ardö (2014). Crop yield gaps in Cameroon. *Ambio,* vol. 43, pp. 175-190.

Appendix 1 – Forms and processes of land degradation

Nutrient decline

Many current agricultural systems export more nutrients than they return to the soil. This results in a net loss of nutrients from the soil (Hartemink, 2006; Jones *et al*., 2013). Globally, only half of the nutrients taken up by crops are replenished (CAWMA, 2007; Noble, 2012). Over the past decades, it is estimated that net losses of nutrients in sub-Saharan Africa amount to 10 to 20 kg/ha/yr N, 3 to 4 kg/ha/yr P and 15 to 19 kg/ha/yr K (Stoorvogel *et al.,* 1993, Sanchez *et al.,* 1997). Globally, Vlek *et al.* (1997) estimated that 230 million tonnes of nutrients are removed from agricultural soils in crop harvest; fertiliser consumption, however, is only 130 million tonnes, which will deliver less than 130 million tonnes of nutrients. While biological nitrogen fixation closes the gap between nutrients added and exported, it is estimated to contribute 90 million tonnes of N, so there remains a net removal of N from agricultural soils. Tan *et al.* (2005) estimated the global net rates of soil nutrient decline in 2000 as 19 kg/ha of N, 5 kg/ha of P and 39 kg/ha of K after conversion to agriculture.

The potential impacts in many areas of Africa are especially acute because of inadequate fertiliser use and the low levels of inputs in crop lands, especially where incomes are low and landholders are poor (Craswell and Vlek, 2013, Jones *et al*., 2013; Winterbottom *et al.*, 2013). Large areas of agriculture in Africa are also hampered by the predominance of low fertility soils and fragile ecosystems. Such soils have minimal stores of nutrients and so have low resilience to the removal of nutrients. This can make it difficult to implement intensive agriculture without inputs of nutrients from outside sources.

The main soil types on land suitable for agriculture include the Lixisols, Arenosols, Ferrasols, Acrisols, Plinthosols and some of the slightly better Luvisols. Some areas of the more fertile soils such as Nitosols and Vertosols do occur, but of these the Nitosols have very high P-fixing capacity (Jones *et al*., 2013). Based on low-input agricultural systems where irrigation is absent, the use of fertilisers and chemicals for pest and weed control is minimal, and soil management does not include high levels of mechanised equipment. Eswaran *et al.* (1997) estimated that only 16% of the land in Africa had high potential, 13% moderate potential and 16% low potential for this low-input agriculture. These potentials can change if the inputs are increased. Many African soils tend to have naturally low nutrient levels. Therefore, the management of soil organic matter, which holds many nutrients, is potentially a critical part of managing soil nutrients.

Traditionally, land was cleared and cropped for two or several years, and then allowed to return to bush for at least 10 years to rebuild the nutrients. Hand clearing left the trees in place and the use of fire produced ash, which was effective fertiliser (Craswell and Vlek, 2013). The long fallow periods recharged the soil organic matter levels. However, as available land became less abundant, fallow periods were shortened, allowing less time for replenishment of soil organic matter and nutrients. Soil nutrients and soil organic matter declines, and land became susceptible to water and wind erosion, resulting in further losses of nutrients. The nutrient balance can be restored using organic and mineral fertilisers, but these are often not available or unaffordable.

The highest rates of nutrient depletion occur under subsistence agriculture where extra inputs are not affordable. Increasing cropping intensity causes a spiral poverty trap with higher population, pressure for food, shorter fallows, low yields, less food, low income, low inputs, low yield, etc.

The rates of nutrient balance depletion have been estimated at the national scale, and at the farm scale (Craswell and Vlek, 2013). At the national scale, the total nutrient flows are shown for some countries in Table A1.1. These figures are based on average nutrient balances for arable land. It accounts for nutrient losses in crop products, crop residues, erosion and gaseous losses of nutrients, as well as inputs from mineral fertilisers, organic fertilisers, nitrogen fixation and sedimentation. While estimates are approximate, the important result from this table is a general loss of nutrients across all the countries.

In a review of 57 nutrient balance studies at the plot and farm scale, Cobo *et al.* (2010), reported in Craswell and Vlek (2013), concluded the following:

- The studies showing negative balances for nutrients were:
  - 85% for N
  - 56% for P
  - 76% for K
- The studies showing a positive balance for nutrients were:
  - 24 % for N
  - 44% for P
  - 15% for K

While these results do support the general conclusion that nutrients are depleting, there were a significant number of studies of positive nutrient balances, especially for P. These were presumed to be associated with cash crops and wealthier farmers who could afford to add inputs. Cobo *et al.* (2010) pointed out that some of these studies did not link the balance to existing levels of soil nutrient stocks, which limits the interpretation of the data.

The most telling evidence for the potential for nutrient decline is the continuing low fertiliser use in much of Africa over the last 25 years (1982-2008) based on FAO statistics and Craswell and Vlek (2013) and Sanginga and Woomer (2009). Fertiliser use in middle or central Africa is low to negligible without any indication of an upward trend.

Using maps, Jones *et al.* (2013) showed that loss of soil productivity, largely attributed to nutrient decline, is closely linked to increasing levels of hunger and malnutrition in Africa. Ngoze *et al.* (2008) showed loss of nutrients from soil in fields in Kenya where the mineral N, strongly bound P and plant available P decreased by 82%, 31% and 36% after 100 years of cropping. Yields of maize decreased to a low base level of 1.6t/ha after 25 years. The yields were restored by the addition of mineral fertilisers, although the benefit-cost ratios associated with the use of fertilisers needs assessment.

The effects of population pressure on nutrient decline are shown by Drechsel and Penning de Vries (2001) in a study of sub-Saharan Africa. Once the area of available land became less than 4 ha per capita, there was a negative balance for nitrogen because of shorter fallows and less time for the soil to recover after cropping phases. Increasing population pressure begins a cycle of nutrient decline causing yields to fall and possible increases in malnutrition and poverty.

In Nepal, cropping of maize led to a general nutrient deficit; this was due both to removal of nutrients in the crop, and losses of nutrients from erosion in the hill soils (Brown *et al.*, 1999). To counter this, the soils on the flats gained nutrients from deposition and irrigation water. Overall, the nutrient balance resulted in a decline in nutrients in both the hill and flat soils, although the decline was greater in the hill soils. The level of nutrients obtained from compost and organic sources was not sufficient to replenish the nutrients under a three crop rotation.

Biological N fixation is a logical approach for maintaining nitrogen balance in soils. However, this requires strong legume growth, which requires in turn adequate level of P. The supply of P is seen as a critical factor in African soils, especially as many of them have a high P absorption capacity. The supply of P to African soils is seen as a major research and practical problem. The supply of P from local sources of P is a potential solution (Byrnes and Hellums, 1998; Woomer *et al.,* 1998; Sanginga and Woomer, 2009).

Use of N fertilisers and N-fixation by legumes and other plant species results in an increase in active N (e.g. nitrates and nitrous oxides) relative to N_2 in the global N cycle. In turn, this leads to an increase in greenhouse gas levels, predominantly as nitrous oxide (Galloway and Cowling, 2002). This becomes more acute because N_2O has 289 times the greater global warming potential (GWP) relative to CO_2 (Forster *et al*., 2007).

Achieving nutrient balance is a requirement for any land management to be sustainable and, especially, to meet the objectives of food security.

Table A1.1. Average country nutrient balances in selected African countries.

Country	Hanao and Baanante (1999, 2006) N $+P_2O_5$+K_2O kg/ha 1981 - 1985	 2002 - 2004
Benin	-37	-44
Botswana	-1	-47
Cameroon	-25	-44
Ethiopia	-56	-49
Ghana	-32	-58
Kenya	-48	-68
Malawi	-42	-72
Mali	-34	-49
Nigeria	-35	-57
Rwanda	-101	-77
Senegal	-38	-41
Tanzania	-44	-61
Zimbabwe	-12	-53

Note: the US convention is to give the weight of P as P_2O_5 and K as K_2O. This is based on the convention of the Association of American Plant Food Control.

Source: Craswell and Vlek, 2013.

Deforestation

Deforestation is a major problem, especially in Africa, parts of Asia and South America. The net change of the area of forested land has slowed (from 8.3 million ha in 1990-2000 to 5.2 million ha in 2000-2010, FRA, 2010). However, the amount of forest cleared was 13 million ha per year on average since 2000; the difference is made up by regrowth and plantings. The area of primary forests has decreased by 40 million ha since 2000 as the pressure for other land uses increases. Clearing the forested land (especially primary forest) results in loss of biodiversity and carbon emissions and possibly some soil degradation, depending on the land use to which the forest is converted.

The existing forests have a number of uses, including biodiversity conservation; protection of soil and water resources; production for timber; and socio-economic functions such as tourism, education, and cultural and spiritual significance. Threats to forested land include fire, disease, pests, natural disasters and invasive species. Ownership of the forest lands can also be an issue in the conservation and preservation of the forest resources.

Desertification

Desertification is used to describe land degradation "… when there is a reduction or loss of the biological or economic productivity of soils in arid, semi-arid or dry sub-humid areas resulting from a combination of activities, a deterioration of the land to support core ecosystem functions, coupled with a long-term loss of natural vegetation" (Jones *et al.,* 2013). In many parts of Africa, increasing unreliability of rainfall and increasing population demands on vulnerable soils limit the capacity of soils to recover from land use. About 40% of the land surface of Africa is considered to be under threat from desertification. The reduction in productivity of the land becomes a problem as overpopulation, overgrazing, land exhaustion and overexploitation of groundwater creates a deteriorating cycle of increasing poverty and land degradation. Sustainable land management practices to cope with drought and nutrient management of the soils are needed to break the cycle.

Desertification is a threat to lands across Africa, Asia, Australia, North America, South America and small areas of Europe (Squires, 2002). Desertification is not a single land degradation process. In their descriptions of desertification, Le Houerou (2002), Tueller (2002) and Squires (2002) found the distinguishing feature of desertification is a set of recognised land degradation processes. These processes include soil erosion (both wind and water), nutrient decline, compaction and possibly salinization; these must all occur in a difficult arid environment with at least one extended dry season and a high risk of drought.

Some of the effects of desertification were reversible. Tueller acknowledges, however, the effects would be irreversible on some shallower soil types on desert pavements and calcrete; in shallower soils, the loss of topsoil is also difficult to replace. As one key management issue, processes associated with desertification are the same for wind and water erosion, nutrient decline, loss of vegetation cover and sometimes salinization.

Soil organic matter decline

Increasing soil organic matter will increase soil functionality and soil health (Wilson *et al.*, 2008; Koch *et al.,* 2013; Stockman *et al.,* 2013; McBratney *et al.,* 2014; Murphy, 2015). Soil organic matter is made up of decomposed plant and animal materials, as well as microbial organisms and is approximately 58% carbon (Baldock and Skjemstad, 1999).

Key functions of soil organic matter are listed in Section 5.3.2. There is evidence to support these individual functions of soil organic matter (Murphy, 2015). However, due to complex and interacting processes, the relationship between soil organic matter and crop yields will vary from year to year depending on seasons. It is also complicated because it is possible to overcome some limitations by additional inputs or management operations. Ringrose-Voase *et al.* (1997) examined gross margins across a cropping area in the wheat belt of south-eastern Australia and found a positive relationship between soil carbon level and gross margin over a five-year period. On a Red Lixisol, they detected that in the range of soil organic carbon from 0.9 to 1.9 g/100 g, an increase in the soil carbon level by

1.0 g/100 g was worth about $35 with a 95% confidence interval of $25. The reasons suggested for this increase included nutrient cycling (where soil organic matter can supply nutrients to the crops and pastures), but also the reduced fuel use in cultivation and sowing attributed to enhanced friability of the soils. The enhanced friability also gave better seedbeds under direct drill. Using results from 34 farmer trials, Carsky *et al.* (1998) showed a diminishing yield response to fertilisers as soil organic carbon increased from 0.5% to 2.0%; this confirmed the capacity of soil organic matter to act as a nutrient supply.

The loss of soil organic matter can have a significant effect on soil function and soil health. Furthermore, it influences a range of ecosystem services (Govers *et al*., 2013):

- The maintenance of soil organic matter (SOM) is linked to the maintenance of productivity on existing crop lands, and thus strongly linked to food security.
- As a major source of energy for soil biota, SOM is strongly related to soil biodiversity.
- SOM helps manage greenhouse gas emissions through the sequestration of carbon. Preserving soil carbon already stored in soils is important for maintaining soil organic matter levels. Past losses of SOC due to changes in land use imply there is potential to reduce atmospheric carbon dioxide levels through targeted land management practices such as no-till, agroforestry, management of peat lands, forestry. However, increasing soil carbon levels should not involve land management changes that result in increased emission of other greenhouse gases.
    - A significant opportunity for soil carbon sequestration is in restoring degraded lands that have lost large amounts of carbon.
- Soil OM can also have an impact on international waters through two main processes.
    - Sequestration of C to reduce carbon dioxide levels in the atmosphere and reduce the rates of acidification of waters in the ocean.
    - Increasing SOM to reduce water erosion and the amount of siltation in streams and reservoirs and subsequent pollution with nutrients. Increasing SOM can also reduce wind erosion and the severity of dust storms.
- Soils are an important reservoir of persistent organic pollutants (POPs) and their capacity to store and retain POPs depends greatly on the level and type of soil organic matter. However, the ability of SOM to retain and react with chemicals included under POPs varies. Therefore, the overall effectiveness of SOM to mitigate the movement and pollution potential of POPs will vary with individual chemicals. The capacity of the microbial communities in the soils to degrade pollutants will also vary.

Soil organic carbon is a useful indicator of land degradation and soil health (Wilson *et al.,* 2008; Koch *et al*., 2013; McBratney *et al.,* 2014) because of the central role it plays in many soil functions.

In conclusion, the management of soil carbon is a key factor in sustainable land management; increasing soil organic carbon can be an effective land management strategy for several of the focal areas of the GEF.

Water erosion

Water erosion is a land degradation problem globally and can have the following impacts:

- Water erosion can affect the long-term soil health and capacity of soils to maintain crop production levels on existing crop lands. Much depends on the depth of useable or productive soil; water erosion can have an immediate effect on functionality of shallow soils (see Tengberg and Stocking, 2001; Stocking, 2003).
- Water erosion can remove SOM from a given point in the landscape. Even if it redistributes SOM at another location, the loss of SOM at the point of erosion is linked to an overall trend for degradation. From the climate change perspective, the fate of soil carbon in sediments moved during water erosion is uncertain (ODG, 2006); a large proportion may be stabilised where it is deposited. Lal (2003) estimates about 20% of the soil organic carbon is decomposed before being redeposited, depending on soil texture, aggregation and the nature of the soil organic matter.
- Water erosion can have an impact on international waters, streams and reservoirs through off-site impacts of sediment, siltation, eutrophication and possibly pollution if nutrients and chemicals or POPs are attached to the sediment.
- If water erosion results in soil degradation, it is likely to have an adverse effect on biodiversity at the site through the loss of fertility and removal of the more biodiverse topsoil layer. Off-site, the effects of erosion on biodiversity can be through sedimentation and eutrophication of water courses, lakes and other water bodies and the spread of weed propagules.

Soil formation rates are usually much slower than erosion rates in many areas. The soil formation rates on bedrock are less than 0.1 to 4 t/ha or 0.001 to 0.250 mm/yr (Stockmann *et al.,* 2014). In a study of tombstones reported in Jenny (1941), a range of limestones took 240 to 500 years to show weathering to a depth of 1 inch (2.5 cm). Sandstones weathered more quickly and porphyry much more slowly. This would indicate rates of soil formation (from rock) of less than 1 tonne/ha/yr. A tolerable soil loss was estimated for Australia using measured and estimated erosion rates as 0.21 t/ha (Bui *et al.* 2010). The rates of soil formation in unconsolidated sediments and on exposed subsoils or B horizons are much higher than those on bedrock. However, the reformed soil materials do not necessarily have the same productivity as the original soil materials (see Greene and Wilson, 1989; Read *et al*., 2012).

Soil loss tolerance values have been used to estimate the balance between soil loss rates and soil formation rates. Though not universally accepted (Critchley *et al.,* 2001), they do provide some indication of whether soil loss rates are sustainable in the long term. The use of soil loss tolerance values (T values) has not been considered necessary because of the capacity to overcome the loss of topsoil through soil management strategies, including fertilisers and tillage operations and soil ameliorants (Schertz and Nearing, 2002). More recently, the move to long-term sustainability and concern about the level of resources needed to overcome the effects of erosion losses has renewed interest in the soil loss tolerance values.

In low input, resource-poor environments and agricultural systems, there is also a case for considering the use of T values. Schertz and Nearing (2002) suggest the only way to make T values viable is to make them much more responsive to site-specific conditions and improve knowledge of soil formation rates and levels of erosion that affect off-site impacts. Pretorius and Cook (1989) advocate different T values for different soil types in Africa. The purpose for this discussion is not to recommend the wide-scale application of T values, but to draw attention to the real threat that soil erosion can pose to sustainability and long-term productivity on particular soil types.

Wind erosion

Wind erosion, which is driven by different factors than water erosion, is generally associated with drier lands and sandier soils. The Arenosols of the African Sahel are a typical soil that can be susceptible to wind erosion (Jones *et al.,* 2013). Dust storms are a consequence of severe wind erosion that can have global significance (ODG, 2006). It has been suggested that only 10% of the dust associated with dust storms from central Africa has an anthropogenic origin (Tegen *et al.* 2004; ODG, 2006); this may increase, however, if land degradation increases. At the local scale, anthropogenic sources of dust can be significant. However, many dust storms in other parts of the world may be related to land use. Wind erosion and dust storms generate several effects, as noted below.

- Wind erosion can devastate soils by removing the most useful fine fraction of the soil. This includes the soil organic matter and the clay and silt fraction, leaving predominately the sand fraction behind. This is one of the effects of desertification. The capacity of the soil to maintain crop and animal production levels can be severely affected, and there is a potential effect on long-term food security. The dust may be deposited elsewhere and add to soil formation in other areas.
- The soil degradation can adversely affect soil biodiversity.
- The climatic effects of wind erosion include:
    - potential loss of soil carbon because the capacity of the soil to replenish the lost soil carbon is diminished
    - effects of dust absorbing and scattering incident solar radiation; results can be increased or decreased temperatures depending on location, reduced marine productivity, cooler oceans, and changes to rainfall through changing convection patterns and cloud formation (Goudie and Middleton, 2001; ODG, 2006).
- Land degradation is often associated with losses of soil organic carbon. As with water erosion, wind erosion can remove soil carbon from a given point in the landscape. Even if it redistributes at another location, there is a loss of soil carbon at the point of erosion.
- Wind erosion tends to winnow out the clay, silt and organic fractions from the soil; its removal from the site results in nutrient decline (Leys, 2002). Inorganic fertilisers can replace this loss of nutrients, but at a cost. As a secondary effect, nutrients are enriched in the wind-eroded sediment. The degree of enrichment depends on the distance from the original eroded site (Leys, 2002). For sediments deposited nearby, the enrichment values are about 1.20 to 1.25, but for sediments transported large distances the enrichment values can be 7 for N and 3 for P. Enrichment values up to 5 were recorded for soil organic carbon 2 m above an eroding soil. This wind-blown material is then rich in nutrients and can be a potential pollutant for water bodies.
- Soils are an important reservoir of persistent organic pollutants (POPs). Dust storms can transport these chemicals and nutrients to other locations.

Soil acidification

Although not generally considered a major land degradation problem, soil acidification is a potentially long-term problem under agriculture. Acidification under agriculture is a consequence of the following processes:

- removing bases or cations in the agricultural produce taken from the landscape
- leaching of nitrate, which is formed in the soil after additions of N to the soil from two main sources; N from mineral fertiliser, and N from the conversion of N_2 to $2NH_4^+$ by N fixation usually as a symbiotic processes associated with legumes and other N-fixing plant species (Fenton and Helyar, 2007).

Acidification of agricultural soils is likely to occur on most soils that do not have large reserves of bases or cations and have a low cation exchange capacity (Fenton and Helyar, 2007). The depth of acidification is an important management consideration; if acidification is confined to the surface, it can be readily treated with additions of lime, provided lime is available and affordable. Where acidification affects deeper layers in the soil, it is more costly and difficult to ameliorate.

Noble *et al.* (2001) reported soil acidification as a problem in Thailand. In addition, Jayakody (2001) and Rahman *et al.* (2001) report soil acidification through agricultural production in Sri Lanka and Bangladesh respectively. They also identify soil acidification associated with the drainage of acid sulphate coastal soils as a land degradation problem in these two countries, which involves a different set of processes and land management approaches than acidification from agriculture. In acid sulfate soils, acidification is a consequence of the oxidation of pyrite minerals in the soil when the soils are drained. The programs for the management of acid soils in Africa and Asia are described in Craswell (2001).

In Africa, the use of sulphur dust to control powdery mildew in cashew nuts in south eastern Tanzania has led to the acidification of soils with low buffering capacity (Ngatunga *et al.,* 2003).

Sanchez *et al.* (2003) estimated that acidification could affect as much as 32% of soils in the tropics, which results in high aluminium levels. Some soils are naturally acidic and others have acidity induced by agriculture. While aluminium toxicity is rare in most smallholder farming in sub-humid and semi-arid Africa, it can occur in parts of Rwanda, Burundi, northern Zambia, southern Congo, KwaZulu Natal province in South Africa and in some sandy soils of Zimbabwe. It is most common on soil types such as Oxisols and Ultisols from Soil Taxonomy or Ferralsols, Acrisols and Lixisols from the World Reference Base (IUSS, 2015). The high aluminium toxicity need not be a limitation if aluminium-tolerant plant species are grown (Sanchez *et al.,* 2003).

Another form of acidification is associated with acid sulfate soils with high levels of oxidizable sulphur minerals such as pyrite (Dent and Pons, 1995; Sullivan, 2004). The sulphur often has its origin from sea water, which has substantial amounts of sulfate; this becomes reduced under waterlogged conditions such as tidal flats to form oxidizable sulphur. The tidal flats can become exposed over time because of geomorphological processes, removal of peat or the changing of river flow regimes (Dent and Pons, 1995). Once exposed these soils are often used for agriculture. However, draining the soils can also result in the oxidation of the sulphur minerals and the formation of sulphuric acid. This can severely affect the soils and the waters and infrastructure surrounding the soils.

Soil salinization

Salinization is a process where salt accumulates in the soil to levels that can limit plant growth. The location of the salinity in the soil profile is critical for plant growth: under some hydrological conditions, when there is an upward flow of water or poor drainage, salt from the deeper profile can be brought to the surface. This is a potential problem in some irrigation areas. A further problem is the salinity and sodium levels (sodium adsorption ratio) of the irrigation waters; water too high in salt and sodium can cause salt and/or sodium to accumulate if not managed carefully (Kijne and Kuper, 1998; Sanchez *et al.,* 2003; Jones *et al*., 2013). Increased sodium levels in the soil can cause serious soil structural problems such as surface sealing and low hydraulic conductivity and aeration. Without drainage, plants leave behind the salt in the soil after evapotranspiration, which builds up salt in these irrigated soils. Where there is an existing salt store deep in the soil, excessive irrigation can raise the water table and bring the salts from the deep salt store to the surface. Irrigation without growing plants may be required to flush salts from the soil (Ayers and Westcott, 1994).

Replacing vegetation that has high transpiration rates with land use that has lower potential for transpiration alters catchment hydrology, and this can cause salinization in susceptible catchments (Charman and Wooldridge, 2007). The original water use by the vegetation is reduced; therefore, the volume of groundwater increases, resulting in rising water tables. When the water table is high enough, the water can move to the soil surface under capillary action. This creates a movement of salts (if they are present) from deeper in the soil to the surface where the water evaporates, leaving the salt behind.

Toxicity and heavy metal pollution

The pollution of landscapes and streams by mining operations can take global significance because of its potentially devastating impact on local populations. Pollution from heavy metals or reagents used in mining operations is a real threat for significant areas in developing countries. For example, in Mozambique, artisanal mining of gold deposits and placer gold has resulted in environmental degradation and considerable health risks from mercury pollution (Dondeyne *et al.,* 2009); there are similar examples throughout the developing world. Similar potential contamination with mercury was recorded in the western region of Ghana (Tetteh *et al.,* 2010). Useful information can be gained by identifying the likely sources of heavy metals and potential pollutants where natural sources may result in relatively high levels of metals such as arsenic, lead and chromium in the environment. (Lado *et al*., 2008, Liu *et al.,* 2011; Taghipour *et al*., 2011).

In Iran, some areas have high cadmium (Cd) levels in the bedrock. The Cd can also be introduced with phosphate fertilisers (Qishlaqi *et al.,* 2010). Cd contamination of phosphate fertilisers is a problem, particularly in sandy or acidic soils, where sorption capacity is low, so Cd is readily taken up by plants. While Cd does not affect plant growth, soils contaminated with high levels of Cd pose a threat to animal and human health, due to impact on kidney function.

Major forms of land degradation in Africa

The major forms of degradation recorded in Africa (Jones *et al.,* 2013):

- Nutrient decline – This is exacerbated by the high percentage of low fertility soils under cultivation and agriculture. Many of the soils are the typical low fertility soils including Lixisols, highly weathered Ferrisols, Planosols, Plinthosols and Arenosols. Although some of these soils have significant clay contents, the clay minerals tend to be the kaolinites of low fertility. There is also very low use of mineral fertilisers in Africa. The decline in fertility has decreased yields and per capita food production. The increase in malnutrition in parts of Africa is closely linked to areas of declining fertility.

- Wind and water erosion – An estimated 14 million km^2 are affected by erosion in one form or another. Water erosion is especially a problem in Burkina Faso, Burundi, Madagascar, Lesotho, Morocco and Rwanda. Wind erosion is more of a problem in the Sahel area where rainfall is less than 600 mm per annum and the dry season lasts more than six months. While often the initial effect of erosion is seen as slight or low impact, the long-term effects of continuous erosion will depend on the depth of soil, the productive top soil in particular and on the capacity of parent material to form new soil.
- Decline in soil biodiversity – There is little specific information on this for Africa.
- Loss of agricultural land to urbanization (soil sealing) – Land is covered by infrastructure-related seals such as buildings, concrete, roads and other developments. This process is essentially irreversible and is made more significant because many urban areas were initially established on some of the most fertile agricultural lands. In such cases, any urban expansion tends to occupy more fertile land.
- Soil contamination – This is associated with mining and urban land practices such as waste disposal. The contaminants may include metals, hydrocarbons and other organic pollutants, pathogens and other substances harmful to human health. Contamination can deter future use of an area of land, increasing pressure on other land.
- Salinization – Human intervention can increase the salt levels in soils through irrigation or by changing the hydrology of catchments by deforestation or land clearing. Elevated salt levels are a considerable threat to sustainable land use.
- Soil compaction – Soil compaction can occur in the surface or in the subsoil. Surface compaction is associated with stock trampling of wet soils, while subsoil compaction is more associated with the passage of heavy machinery. Soil compaction is a noted problem in the Sahel, South Africa and Zambia. Compaction can lead to loss of biological activity, nutrient uptake and permeability. It can reduce infiltration and increase water erosion.
- Landslides – Landslides occur most frequently in areas of steep slopes, deep highly erodible soils, weathered and jointed bedrock, usually after periods of intense and prolonged rainfall. They can be triggered by earthquakes. Human activities such as deforestation, removal of vegetation cover and undercutting during infrastructure development can exacerbate the occurrence of landslides.
- Desertification – In areas of lower rainfall ($<$ 600mm per annum) where there is nutrient decline along with wind and water erosion, soils have reduced capacity to provide ecosystem services such as production of food and fibre. In areas of lower rainfall, soils are very susceptible to degradation, especially if they can no longer support the growth of vegetation. There is a long-term loss of native vegetation. When soils become degraded in this way, it is considered desertification. The process of desertification is thought to affect 40% of African land, and much of this is located on the margins of deserts and includes the Sahel.

Figure 17 Loss of ground cover through overgrazing has led to loss of topsoil, exposing infertile subsoil, Kenya Photo: A. Cowie

Figure 18 Erosion gully, Kenya Photo: A. Cowie

Appendix 2 –Check list of field, plant and land management criteria for assessing soil health in an integrated soil fertility management program for sustainable land management

Category	Indicators
Landscape criteria	Proportion of exposed soil Severity of soil erosion Presence of contour structures Protection of riparian strips Surface water clarity
Nutrient deficiency symptoms	Basal leaf chlorosis Purpling of lower leaves Marginal leaf necrosis Apical chlorosis or tip distortion Interveinal chlorosis
Chemical and physical criteria	Soil acidity
Biological criteria	Legume root nodulation Nodule interior colour Soil macrofauna Stem/plant infestations Root disease Root galls
Farm management criteria	Crop residue management Composting Manure management Mineral fertilisers, lime, gypsum Timing and method of application of fertilisers

Source: Adapted from Sanginga and Woomer, 2009.

Figure 19 Saline outbreak where saline seepage has resulted in tree death, reduced ground cover and scalding in lower slopes and depressions. The catchment has a significant salt store in the bedrock, soils and groundwater that has been mobilised by excessive clearing of trees, reducing evapotranspiration rates. Photo: B. Murphy.