2 Enhancing Soil Security for Smallholder Agriculture

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2.1 INTRODUCTION

2.1.1 Broader Picture

Four-fifths of the developing world's food is produced on about half a billion small farms, supporting more than at least one billion people (International Fund for Agricultural Development [IFAD] 2012). Smallholder farmers live and earn their livelihoods in the world's most ecologically and climatically vulnerable landscapes—hillsides, drylands, and floodplains—and rely on weather-dependent natural resources. They are at the forefront of the world's efforts to deal with climate change and environmental degradation. These women, men, and young people face enormous difficulties. Yet they are themselves among the poorest and least food-secure people on Earth. In developed countries, smallholder farmers cannot compete with large commercial farms producing bulk products and have to focus on "niches" in the urban market, increasingly being framed in terms of ecosystem services that go beyond the production of food.

The term "smallholder agriculture" covers a wide variety of farming systems in different parts of the world. In many developing countries, small farms are often less than a few hectares in size, supporting only the farming family. Only somewhat larger farms may be able to grow a limited amount of cash crops for the local market. In many developed countries, farm sizes have increased strongly during the last decades owing to mechanization and rationalization of production; however, many small farms still exist and increasingly service "niche" markets aimed at urban consumers. Recent reviews (e.g., IFAD 2012) emphasize the enormous diversity of small farming systems in developing countries, requiring a focus on local conditions when formulating desirable future developments, as generalizations may be meaningless. The same diversity applies to small farms in developed countries. Smallholder agriculture will be illustrated in the following by a number of case studies, and their selection has therefore a somewhat arbitrary, subjective character.

Farmers everywhere face three stark challenges over the next four decades. They must (i) contribute to fulfilling an estimated 60% increase in demand for agricultural production by 2050 to feed a growing, more urbanized population; (ii) do so facing growing water scarcity, climate change, and the likelihood that the available area of arable land will hardly increase. At the same time, soil degradation is proceeding in many areas, and they must (iii) ensure that developments are sustainable, continuing to provide a range of ecosystem services to future generations.

Problems and the future potential of smallholder agriculture have been widely analyzed, also considering the future challenges of climate change, water availability, and biodiversity loss (e.g., InterAcademy Council [IAC] 2004; Dorward and Chirwa 2011; IFAD 2012; Food and Agriculture Organization [FAO] 2008, 2009, 2010, 2011; Ncube et al. 2009; Garvelink et al. 2012; Herrero et al. 2014; and many others). The major and well-recognized factors inhibiting future development of smallholder agriculture in developing countries are (i) declining productivity, (ii) insecure land tenure, (iii) insufficient infrastructure, (iv) inadequate education and training, (v) lack of new seeds and technologies, and (vi) inadequate financial services. In addition, many institutional barriers retard development of smallholder practices (e.g., Jiggins

2012). Increasing food production therefore does not only present major technical but also socioeconomic challenges. The Sustainable Livelihoods Approach, inspired by the economist Amartya Sen, reverses the usual reasoning by starting with a basic human right to be fed, followed by exploring various means to realize this right in practice (e.g., Morse et al. 2009). When focusing on the role of soils in smallholder agriculture, the broader socioeconomic and ethical context of the problem should never be ignored. However, to assess the role of soils within this broad context is still relevant because soils are a key resource for farmers everywhere. This broader context is also expressed by the nine planetary boundaries, defining a "safe operating space for humanity" (Rockstrom et al. 2009). One important boundary defines land use, and the authors conclude that resource-poor smallholder agriculture will never be able to feed the demanding inhabitants of the urbanized world of the future where the majority of the 9 billion people in 2050 will live in megacities. Nor can smallholder agriculture provide an adequate income, except, perhaps, when specific "niches" for the urban market can be explored. Upscaling of agricultural enterprises to large, technologically advanced but still sustainable production entities is taking place in many developed countries. This development, which is also bound to occur in developing countries, requires major societal changes if only in terms of providing sufficient employment for unemployed countryside workers. Substantial transition periods are needed, and in the meantime, current conditions need to be improved as much as possible. However, the degree of necessary upscaling is still the object of debate. Recognizing the call for larger, more efficient agricultural production entities, a plea will be made later in this chapter to also consider enterprises of intermediate size, where farming families can still make a living and where the potential for providing a wide range of ecosystem services (thereby increasing soil security) may be larger than in highly industrialized megaproduction facilities that are disconnected from the ecosystems in which they occur.

2.1.2 Role of Soils

The role of soil is not covered specifically in current policy reports on smallholder agriculture, except indirectly when mentioning the importance of conservation agriculture, use of fertilizers, and irrigation, where soils are acknowledged to play a key role (e.g., IFAD 2012). The soil fertility literature is quite extensive but often only considers static chemical data from the topsoil, ignoring the dynamic physical behavior of the entire soil (as described in pedology), which is important in understanding plant growth. Soils will not be considered here as an object, as such, but in terms of soil security, which is defined as "the maintenance or improvement of the world's soil resource so it can provide sufficient food and fiber, fresh water, contribute to energy sustainability and climate stability, maintain biodiversity and overall environmental protection and ecosystem services" (Soil Carbon Initiative 2011, p. 4). As most of the mentioned aspects are covered by the concept of ecosystem services (Millennium Ecosystem Assessment [MA] 2005), the definition can be simplified to "the maintenance or improvement of the world's soil resource so it can continue to contribute to important ecosystem services." Ecosystem services are defined as

"benefits people obtain from ecosystems" (MA 2005). Linking soils with soil security and ecosystem services is important as it avoids an inward-looking approach that tends to be common in many disciplines, soil science not excluded, and supports the views of Robinson et al. (2012).

In summary, the objective of this chapter is to (i) describe soil conditions in some selected smallholder farms in both developed and developing countries, expressed in terms of ecosystem services provided and, in turn, soil security, and (ii) explore ways in which soil security can be maintained or increased in the future, focusing in the context of this chapter on use of fertilizers, as mentioned by IFAD (2012) as one of three soil-related measures to alleviate problems of small-scale agriculture.

2.2 MATERIALS AND METHODS

2.2.1 Soil Security Concept

Soil security has been defined in analogy with food security, which aims at the long-term sustainable production of sufficient quantities of food, providing a permanent feeling of security to world citizens. This implies, however, much more than striving for a higher production as such, as many socioeconomic, institutional, and ethical aspects also play a key role. The World Health Organization defines three aspects of food security: food availability, food access, and food use. Food availability refers to having available sufficient quantities of food. Food access refers to having sufficient resources, both economic and physical, to obtain appropriate food for a nutritious diet. Food use is the appropriate use based on knowledge of basic nutrition and care. These elements are also visible in the 1996 World Food Summit definition: "Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life."

The security concept is more complicated when applied to soils. Rather than relate to a sustainable, daily need in terms of food intake, soil security relates to what might happen if soils degrade to the extent that sufficient food production is not feasible anymore. Soil degradation is a long-term process, very much related to varying socioeconomic conditions. Except for erosion, its effects are often gradual and difficult to communicate and translate into environmental and economic values. However, when soils degrade to the extent that they cannot anymore provide certain ecosystem services, of which food production is only one provisioning service, the consequences for society are devastating. To mitigate degraded soils is very difficult and even impossible when soil has been removed by erosion. The challenge, therefore, is to create early awareness about the dangers of soil degradation that may, in the end, terminate many ecosystem services the soil can provide (e.g., Vlek et al. 2008; Desire project, www.desire-project.eu).

Considering the relevance of soils only in broad terms of soil conservation practices, fertilization and irrigation (IFAD 2012) ignores the inherent properties and potentials of any given type of soil, which are different in different parts of the world. For example, a relatively nutrient-rich clayey Nitosol in Africa has a higher potential to provide soil-related ecosystem services than a nutrient-poor Ferralsol, let alone a

drought sensitive, nutrient-poor Lixisol or Arenosol. The same is true for, for example, poorly drained versus well-drained soils. When discussing existing and potential soil conditions for smallholder agriculture and the associated ecosystem services, attention will therefore be focused on the soil types that occur that may allow extrapolation of results to other sites where the same soils occur. This represents the traditional procedure of soil survey interpretation and land evaluation, where soil types are used as "carriers of information" functioning as class-pedotransfer functions (e.g., Bouma 1989; Bouma et al. 2012). However, a focus on soil type alone is not enough as it is based on permanent properties of soils formed by the soil-forming factors over periods of thousands of years or longer. However, for practical applications, emphasis should also be on soil behavior in terms of the effects of different forms of soil management on the functioning of a given soil type, resulting in a series of characteristic phenoforms. Genoforms are genetic soil types, as distinguished in soil classification systems based on pedogenetic principles that are represented on soil maps, while phenoforms describe different properties as a function of different types of management applied to that particular soil type. A series of phenoforms of a given genoform defines its functionality, not only reflecting its potential but also its limitations and resilience. Each soil type (genoform) has a characteristic range of phenoforms, and extrapolation of data obtained for specific phenoforms is particularly relevant for land evaluation. The phenoform analysis has been made for two major soil series in the Netherlands (Droogers and Bouma 1997; Pulleman et al. 2000; Sonneveld et al. 2002). Thus far, standard soil survey procedures do not include a phenoform analysis but soil surveyors are advised to do so in the future expressing the specific effects of soil management rather than only a focus on static, inherent soil properties.

2.2.2 Ecosystem Services: Role of Soils

2.2.2.1 Introduction

The benefits people obtain from ecosystems are described in terms of ecosystem services, a concept that has proved to be effective as a communication tool (MA 2005). Sixteen services are defined for four categories: supporting, provisioning, regulating, and cultural services. Of these, all have a clear connection with soils. To avoid overly complicated schemes with partly overlapping subcategories, a link can be proposed between ecosystem services and soil functions, as defined by the European Union (EU) Soil Protection Strategy of 2006 (Commission of the European Community [CEC] 2006). Each of these functions represents a soil-provided ecosystem service in terms of producing (i) food and fiber (a provisioning service); (ii) fresh water by its filtering action (a provisioning and regulating service); (iii) biodiversity (a supporting service); (iv) a physical and cultural environment for human activities (a cultural service); (v) raw materials (a provisioning service); (vi) a pool for carbon (a regulating service); and (vii) an archive, expressing our common geological and archeological heritage (a cultural service). In turn, these seven ecosystem services are reflected in the soil security concept because when they are considered to be adequate now and in the future, maintenance and improvement of the soil resource is assured, providing the desired security. Of course, the question as to what is "adequate" has to be

defined, representing a major research challenge. Smallholder agriculture represents a very wide range of conditions in different countries. Defining general guidelines for "adequacy" is therefore unrealistic and undesirable. Attention should be focused on local conditions, as presented in this chapter.

2.2.2.2 Selection of Case Studies Focusing on "Use of Fertilizers"

In the limited context of this chapter, a number of case studies have been selected to illustrate the use of fertilizers as mentioned by IFAD (2012) as one of three soil-related means to overcome problems in small-scale agriculture, achieving or maintaining soil security as expressed by the ecosystem services provided. Attention is focused on particular soil types, to allow extrapolation of data obtained, if possible. Case studies will not be restricted to developing countries in Africa but will also include two examples from the Netherlands, demonstrating the universal and unifying power of the soil-related ecosystem services concept.

"Use of fertilizers" is a very broad statement that needs to be specified to become operational both in terms of defining optimal application rates and institutional settings, which will now be discussed.

Determining optimal fertilizer needs of crops is, after pedology, one of the oldest activities in soil science research, and procedures have evolved over time during the past century, summarized as follows:

1. A large number of relatively small plots on experimental stations are fertilized with increasing quantities of chemical fertilizer (N, P, and K), and yields are determined. Soil samples are only taken of the surface soil (e.g., 0–20 cm). Statistical procedures are used to relate application rates to yields, thereby defining optimal rates for farmers. Experiments over many years allow expressions of different weather conditions; however, much scatter is obtained in graphs relating yields to fertilization rates and the soils being used are often not or only broadly characterized in terms of sand, clay, silt, and peat. Nutrient analyses are restricted to surface soil. Still, such graphs are the basis for most current fertilizer recommendations and are the source of the spectacular development of production agriculture in the 20th century (see the two Dutch case studies to be discussed later).
2. In a variant of 1, fertilization rates are adjusted to what is locally feasible (see later examples of Kenya). This relates to the proposal by Tittonell and Giller (2012) to focus on the difference between the actual yields (Ya) and the locally attainable yield (Yl), rather than on the often used difference between Ya and Yw, where Yw is the theoretical water-limited yield where the assumption applies that all growth factors are optimized, except for available water that corresponds to local availability. Yw is beyond reach when soil fertility is as limiting as it often is in smallholder agriculture in developing countries.
3. Considering the major differences between conditions on farm fields and experimental plots on experimental stations, experiments are focused on farmer's fields as part of Farming Systems Research. This involves active participation by farmers and joint learning in interaction with researchers (e.g., Adjei-Nsiah et al. 2008; Sonneveld et al. 2008). Results obtained

are relevant for the particular farms considered but are sometimes difficult to extrapolate because of the peculiarities of the individual farmer's management. This procedure not only includes characterization of existing conditions, as in the Zimbabwe Arenosol case study, but may also involve experimentation with applied manure or inclusion of legumes. This on-farm approach offers opportunities to discover "lighthouse" examples of farmer innovations. When applying organic fertilizers, e.g., manure, it is important to recognize that nutrients are delivered beyond the year of application. This supports the idea that land use history should be taken into account when developing appropriate fertilization strategies within a farm context.

4. Awareness about the possible impact of fertilization on environmental quality has, starting in the 1980s, resulted in a broad system analysis by modeling and monitoring that not only considers nutrient uptake by plants and resulting plant growth, but also leaching of excess nutrients to groundwater and surface waters and production of various gases adversely affecting environmental quality (e.g., Sonneveld et al. 2008). Now, the dynamics of the entire soil are characterized rather than a static fertility sample for surface soil only. This procedure also includes innovative, modern methods to measure soil conditions with, e.g., in situ or proximal sensors.
5. A development of approach 4 is precision agriculture where fertilization in a given farmer's field is "fine-tuned" by applying it differently in space and time, depending on different soil conditions in the field and changing weather and crop demand during the growing season. Dynamic modeling of crop growth, based on the nutrient regime of the soil and weather conditions, allows fine-tuning of fertilization rates and times. A field study in the Netherlands showed that precision procedures resulted in a 30% reduction of fertilizer use as compared with the traditional procedures, while yields did not decrease. This not only represented a considerable savings for the farmer but also a more efficient use of natural resources (Van Alphen and Stoorvogel 2001; Van Alphen 2002; Bouma et al. 2012). Note that only dynamic modeling can provide signals of soil nutrient stocks in the rootzone becoming critically low. The highly promoted use of remote sensing for precision agriculture can indicate nitrogen shortage in crop leaves; however, this signal comes too late as crop growth retardation has already occurred. This is avoided by the dynamic modeling approach. Precision agriculture is the procedure of the future anywhere in the world as it most closely matches the needs of the plants, on the one hand, and fertilizer applications, on the other, taking into account solute fluxes in the soil–plant–atmosphere system. Thus, ecological intensification becomes more feasible, also in developing countries (e.g., Cassman 1999; Tittonell and Giller 2012).

Institutional arrangements have, for a long time, been rather top–down, where fertilizer rates, as determined on experimental stations, were communicated to farmers through extension services. This has been quite successful in both developed and developing countries as long as the focus was on production. As attention shifted since the 1980s to sustainable development and environmental concerns in

terms of water and air pollution, knowledge transfer from the research community to practitioners became less effective in the developed world, the more so as extension services were privatized in many countries. Now we see that farmers everywhere become more knowledgeable, certainly as the information revolution proceeds. Also, researchers realize the advantages of involving farmers in a joint learning approach (e.g., Ncube et al. 2007; Adjei-Nsiah et al. 2008; Sonneveld et al. 2008; Bouma et al. 2008, 2011; Rusinamhodzi et al. 2013). This results in a fundamentally different relationship between scientists and users of their information (as will be illustrated in the Northern Frisian Woods [NFW] case study) and this will most likely increasingly apply to developing countries as well, requiring not only an interdisciplinary but also a transdisciplinary research approach (e.g., Bouma et al. 2011). The soil science profession is not quite prepared yet to face this challenge. When describing interdisciplinarity in the *Handbook of Soil Science* (e.g., Levy 2012), attention is focused on technical aspects of soils, ignoring the social sciences while transdisciplinarity is not being covered at all.

An innovative approach to achieving progress in development is being followed in the so-called Millennium Villages by supplying large quantities of improved seeds and fertilizers to allow a "jump-start" of the agricultural production system (www.millenniumvillages.com). Denning et al. (2009) and Dorward and Chirwa (2011) report positive results for Malawi, illustrating that direct assistance to farmers works better than top–down national programs, although long-duration strategic and institutional support at national policy level is crucial.

2.2.2.3 Risk of Gloom

Barriers, as cited above, to raising smallholder agriculture to sustainable levels providing a stable range of ecosystem services are severe. Rather than trying to solve all problems at once, every scientific discipline would be well advised to first explore the potential of its possible contributions to solving the immense problems at hand. As stated, we will therefore first focus on soil-related ecosystem services, expecting that they are quite relevant in an essential broader analysis at a later date, including socioeconomic, institutional, and ethical aspects and consideration of the planetary boundaries of Rockstrom et al. (2009).

Also, rather than being discouraged about all barriers, there are also favorable and encouraging developments that deserve to be recognized as "lighthouses" forming a source of inspiration (IFAD 2012). Worldwide, farmers are demonstrating the benefits of managing natural assets sustainably and in harmony with local ecosystems. They, and their farmers' organizations, developed succesful enterprises in areas where common wisdom considered this to be impossible. The research community would be well advised to be more on the lookout for such succes stories rather than being restricted by classical experimentation. For example, IFAD (2012) reports research on rice intensification undertaken by >100 farmers in Cambodia, resulting in yields increasing by 60% while use of inorganic fertilizers decreased by >70%. In India, the Mahatma Gandhi National Rural Employment Guarantee Act guarantees 100 days of work creating durable assets to help farmers improve productivity more sustainably, such as water harvesting structures. On a broader scale, Brazilian farmers have implemented minimum-till agriculture on 60% of the country's cultivable

land. The government of the Philippines has stopped its fertilizer subsidy program, replacing it with a balanced policy that promotes location-specific combinations of organic and inorganic fertilizers. Turkey has tripled agricultural productivity in the past 8 years using sustainable methods. In addition, extension workers are being deployed to live in villages alongside the farmers who need their services. Thus far, with 7500 technicians hired, 80% of the country's 35,000 villages are covered. Open-channel irrigation is being converted to drip or sprinkler irrigation systems through interest-free loans and 50% grants to farmers. Subsidies for fertilizer are conditioned on soil analysis. Once the soil is analyzed and the farmer knows what nutrients it needs, the government pays for the soil analysis and for a certain amount of fertilizer.

Looking for innovative farmers and the "lighthouses" they create, and linking their results to the type of soil where they work, is a key element of the analysis provided in this chapter. The International Union of Soil Sciences World Reference Base (IUSS-WRB 2007) system of soil classification will be used throughout to define soil types being analyzed. Soil classifications are often not provided in the soil fertility literature, and soil types in this chapter are therefore characterized at the highest level of classification, the Reference Soil Groups (RSG). Only when possible are qualifiers added, such as in the Dutch case studies.

2.3 RESULTS

2.3.1 Semiarid Arenosols and Lixisols in Zimbabwe

Ncube at al. (2009) described farming systems in semiarid (av. 590 mm/yr rainfall) southwest Zimbabwe. The soils were Ferralitic Arenosols, locally interspersed by Aridic Arenosols. Farm sizes were 5 ha and smaller. Three types of farmers were distinguished: better, medium, and poorly resourced. Drought-resistant pearl millet (*Pennisetum glaucum*) was grown on 80% of the land. This 3-year study showed that all farmers could, on average, not satisfy the nutritional demands of their households. Total cereal production varied widely as a function of precipitation. All nutrient balances were strongly negative. Clearly, adequate ecosystem services are not delivered: the food and fiber service is inadequate, while negative nutrient balances illustrate worsening future conditions. Soil security is not assured, a conclusion also implicitly presented by Tittonell and Giller (2012) in a broad review of smallholder agriculture in Africa, stating that successful ecological intensification is only feasible when soil nutrient stocks would be strongly increased. Current socioeconomic and institutional conditions are not favorable to achieve this. Incorporation of legumes in the cropping system can increase production levels (Giller and Cadisch 1995), particularly when P is added as well. However, additional input by manure and chemical fertilizer is indispensable (Adjei-Nsiah et al. [2008] working on Lixisols in Ghana, Ojiem et al. [2007] working in West Kenya without mentioning the type of soil they covered, and Rusinamhodzi et al. [2012, 2013] working on Lixisols and Luvisols in Mozambique). Ncube et al. (2007) suggest improving current conditions by applying a series of small doses of manure and fertilizers rather than a single application or double applications. Also, concentrating the little manure and fertilizer there is on fields near

the farmstead could produce satisfying yields on at least a small part of the farm. This method has been widely used in Europe before the arrival of chemical fertilizers. Mtambanengwe and Mapfumo (2005) illustrate this approach, based on 120 farm field sites in Zimbabwe, reporting that manifestation of within-field soil fertility gradients on Lixisols and Arenosols under smallholder agriculture is primarily a function of differential capacities by farmers to manage organic matter, which, in turn, is driven by their resource endowment. Designated rich fields consistently contain higher levels of organic matter than corresponding poor fields (or field sections), apparently owing to cumulative effects of applying substantial amounts of organic matter to such specific areas on a regular basis (e.g., Rusinamhodzi et al. 2013). This has conceivably resulted in the formation of specific soil phenoforms that could act as a "lighthouse"; however, no attention was paid to this type of interpretation. Tittonell and Giller (2012) reach comparable conclusions when stating that differential management of the various fields of the farm led to the establishment of gradients of soil fertility, notably decreasing with distance from the homestead. Farmers tended to allocate their scarce nutrient and labor resources in the fields they perceived as most fertile or less risky, or in fields around the homestead where high value crops were better protected from marauding livestock or theft. A close interaction was also found between soil fertility gradients and topography in these highly dissected landscapes, with homesteads located on the upper positions of the slope. Such interactions between inherent soil–landscape variability, historical and current management, nutrient balances, and current soil fertility were documented for smallholder systems in different parts of Africa, e.g., on Lixisols and Luvisols in Zimbabwe (Zingore et al. 2008; Rusinamhodzi et al. 2013), where significantly different yields were obtained between the two types of soil with comparable fertilization rates, and Lixisols in Ghana (Adjei-Nsiah et al. 2008). Zingore et al. (2011) reported for highly degraded Lixisols in Zimbabwe that restoring soil fertility required the application of 10 tons of manure per hectare for 10 years before a maintenance rate of 5 tons/ha could sustain productivity. This illustrates the major investment needed to reestablish soil fertility of highly degraded soils.

2.3.2 Nitosols and Vertisols in the Central Highlands of Ethiopia

This case study is based on an experiment at Holetta Research Centre in the tropical highlands of central Ethiopia (Assefa and Ledin 2001). The study serves to show that, again, the soil type, fertilizer application, and crop variety are factors that determine the yield and quality of the produce. The site is located at an elevation of 2390 m above sea level; the mean air minimum is 6.1°C and the maximum is 21.9°C. Mean annual rainfall is 1100 mm. Trials were conducted on a red Nitosol and a black Vertisol. Nitosols comprise among the most inherently productive tropical soils owing to their high nutrient status and deep, permeable structure, whereas Vertisols show marked shrinking-and-swelling upon drying–wetting and poor physical properties, such as impeded drainage and poor workability when wet (Bridges et al. 1998).

Three oats varieties (*Avena sativa* L.) and two vetch species (*Vicia villosa* and *Vicia dasycarpa*) were sown in monoculture and in mixtures in a randomized

complete block under two fertilizer regimes (F1 = 18 kg N and 46 kg Pe_2O_5 and 23 kg N ha^{-1} at tillering; F0 = without application of fertilizer) with three replications. The fertilizer levels considered here reflect conditions in Ethiopia (Assefa and Ledin 2001).

Significantly higher average dry matter forage yields of mixtures, pure oats, and pure vetch were obtained on the red Nitosol (9.7, 9.4, and 4.5 tons/ha, respectively) than on the black Vertisol (5.6, 5.5, and 2.8 tons/ha, respectively). The example illustrates differences in yield for two different soil types that have a similar soil reaction (pH [1:1 H_2O] of 4.6–5.0), organic carbon content (1.8%–2.5%), and % clay (51%–65%) in the study area, yet with markedly different clay mineralogy. The reported experiments were made under controlled conditions, which are likely to differ on farms in the area. Be that as it may, crop yields on the Nitosols are above subsistence level and provided that the amount of fertilizer can again be applied every year, ecosystem service 1 (biomass production) is marginally assured, providing a certain degree of soil security. The picture is different for the Vertisol, for which production levels were approximately 40% lower, leading to lower soil security.

2.3.3 Ferralsols in Mozambique

Materechera and Mkhabela (2001) reported changes in the properties of strongly weathered Ferralsols under conditions of low external input farming systems associated with differences in land use and management practices. Their study was conducted on a small farm at Malindza, Swaziland. The area falls under the eastern part of the low veld ("bushveld"). The 5-ha farm is on a gently undulating terrain at an altitude of about 700 m. The climate is subtropical with a mean annual rainfall of 760 mm (range, 650–1050 mm). For over a decade before 1987, the whole farm was under natural vegetation and used for grazing by about 100 head of cattle. A kraal and holding pen for handling the animals was located on a 0.5-ha piece of land in the center of the farm next to the homestead. In 1987, all animals were removed from the farm and crop production was introduced. Three treatments were compared: (i) "kraal" areas where before 1987 the cattle used to stay during the night had the highest maize yields, followed by (ii) fallow fields after clearing and (iii) by continuous maize. The latter two had negative nutrient balances and yields below subsistence levels. If former "kraal" areas are not fertilized, they are bound to degrade in time.

2.3.4 Nitosols, Ferralsols, and Acrisols in Western Kenya

The highlands of western Kenya support one of the densest rural populations in the world, with >1500 inhabitants/km^2 in the Vihiga district with fertile soils. Population growth, however, has gradually led to depletion of nutrients through crop harvest removal, leaching, and soil erosion. Farmers have largely been unable to compensate such losses via crop residues, manure, and mineral fertilizers (Shepherd and Soule 1998), adversely affecting ecosystem services and soil security. The observed patterns of soil deterioration are spatially heterogeneous in the area. Spatial and temporal niches for targeting soil fertility management and technologies were studied by Tittonnell et al. (2005). The dominant soil types are Humic Ferralsols, Dystric and

Humic Nitosols, and Orthic Acrisols. Sixty farms, located in the three sublocations, were selected by Tittonell et al. (2005). Together, they represent much of the biophysical and socioeconomic variability observed in the highlands of western Kenya where cultural backgrounds differ widely (e.g., tribes). This led to the differentiation of five farm types, referred to here as T1 to T5, where T1 farms have the highest assets and T5 the lowest. A consistent trend of decreasing input use from farm types T1 to T5 was generally observed by Tittonell et al. (2005); however, nutrient resources and land management practices (e.g., fallow) differed markedly between sublocations. Maize (*Zea mays* L.) yields on Nitisols were slightly higher than those on Acrisols and Ferralsols; however, nutrient balances were dominantly negative and self-sufficiency in maize production was achieved by <40% of farmers in all sublocations—ecosystem service 1, thus, is only partially met in the area.

The case for western Kenya and the earlier cases reviewed here illustrate the very high variability in soil fertility management that is associated with the "soilscape," such as the location of land along hillslopes, and with differences in soil fertility management as a function of household wealth. This will be reflected in different gradations of achievable soil security; however, usually, soil security is low. Many studies report a high variability of fertility within farmer's fields, which is based on samples for chemical analyses of surface soil. However, variability of soil types within farms is usually much smaller as they are correlated with landscape position, and this is one reason to use soil type classifications as "carriers" of information.

2.3.5 Sapric Histosols in the Western Part of the Netherlands

Sapric Histosols, located in the lower reaches of the European Rhine–Meuse Delta, contain large amounts of nitrogen (N), and peat decomposition is a substantial contributor to the mineral N supply of crops. For grasslands on nonfertilized poorly drained peat soils in the Netherlands, an average N uptake of 252 kg/ha was reported (Vellinga and André 1999). Despite the large supply of N from the soil, application of fertilizer N was about 205 kg N/ha per year for dairy farms on peat soils in the west of the Netherlands in the 1990s (Reijneveld et al. 2000). This largely corresponded with common fertilizer guidelines: 195–230 kg N/ha per year for well-drained and 235–275 kg N/ha per year for poorly drained peat soils. Together with relatively large inputs from concentrates (102 kg N/ha per year on average) and relatively low exports of N through milk (68 kg N/ha per year) and animals (13 kg N/ha per year), this resulted in N surpluses at farm level of 270 kg N/ha per year on average for a dairy farm on peat soil at the end of the 1990s (Reijneveld et al. 2000). These surpluses are distributed over various environmental fluxes, such as gaseous losses to the atmosphere, because of denitrification and export of N to surface waters (Van Beek et al. 2004).

Following EU Directives, environmental policies were introduced to reduce N losses and increase farm nutrient efficiencies. One farmer in the area, owning a farm of 37 ha, was able to remain economically viable without the input of fertilizer N (Sonneveld et al. 2008) by large and long-term inputs of organic N sources, such as dung, ditch sludge, farmyard manure, cow slurry, and nonharvested herbage. Thus, average N uptake under nonfertilized conditions increased to 342 kg/ha, with only

a limited part being derived from peat mineralization and with small losses to the environment (Sonneveld and Lantinga 2011). The example of this pioneering farmer acted as a "lighthouse," inspiring other farmers and scientists. Procedures resulted in the formation of an anthropogenic A horizon in these Histosols, which may be regarded as a separate phenoform. Soil security has improved following this form of innovative management that had a positive effect on several ecosystem functions. Ecosystem services 1 and 3 have improved. Reducing the N surplus has reduced N flow into surface waters and has thus improved service 2. The landscape in which this particular farm is located is the National Landscape "Green Hart" of Holland, which is highly valued for its historic reclamation patterns and dominance of dairy farming. Maintaining farming in this area, which is enhanced by the described innovative new approach to management, contributes to services 4 and 7. Yet, a continuous problem is land subsidence because of drainage, resulting in net carbon loss, giving problems with ecosystem service 6 although the organic matter content of surface soil has increased following innovative management.

2.3.6 Gleyic Podzols in the Netherlands

Gleyic Podzols are the most common sandy soils in the Netherlands. The official fertilizer recommendations for these soils were relatively high at the end of the 1980s, up to 400 kg N/ha per year. They decreased thereafter; however, a group of 100 dairy farmers in the National Landscape Northern Frisian Woodlands reported in 1995 an average N fertilizer use of 290 kg N/ha, ranging from 150 to 478 kg N/ha (Verhoeven et al. 2003). As a result, N surpluses at farm level ranged from 162 kg N/ha per year to 560 kg N/ha per year, with a mean farm N surplus of 326 kg N/ha per year. These high environmental losses resulted in a poor environmental quality, for example, reflected in high levels of nitrate in the upper groundwater (Sonneveld and Bouma 2003).

Ecosystem services 2 and 3 were not satisfied and services 4 and 7 were threatened because rationalization of dairy farming called for large fields and cutting hedgerows, which are considered to be a key quality of the landscape. Concerned farmers organized into an environmental cooperative to improve conditions, taking a proactive approach that also attracted researchers. Thus, a "lighthouse" was created that has received continued national and international attention. An intensive participatory research program from 1997 to 2003, focused on increasing nutrient use efficiencies, resulted in a reduction of fertilizer input to 136 kg N/ha per year in 2001/2002 and a corresponding decrease of N surpluses to 172 kg N/ha on average. More emphasis was placed on organic manuring. Farm N uptake efficiencies increased from 21% in 1997/1998 to 33% in 2001/2002, and organic matter contents of surface soils increased significantly forming a recognizable phenoform: old grassland (Sonneveld et al. 2002). In addition, this study defined two other phenoforms of the genoform Gleyic Podzols: reseeded grassland and continuous maize cropping. After studying 40 fields on different farms, these forms of management could be related to soil C contents:

$$\%C = 3.40 - (1.54 \times \text{Maize}) + (0.19 \times \text{Old}) + (0.55 \times \text{GWC}) (r^2 = 0.75)$$

where Maize = 1 for continuous maize cropping and 0 otherwise; Old = 1 for old grassland and 0 otherwise; and GWC describes groundwater levels with value 1 for class V and 0 otherwise.

Thus, organic matter contents of a given genoform are predicted as a function of past management based on field data. Additionally, the phenoform approach provided farmers with a more holistic view on soil functioning as compared with standard chemical soil analyses. Up until 2000, soil samples for acquiring fertilizer guidelines were taken from the upper 0–5 cm of the soil, which increased to 0–10 cm from 2000 onward, although topsoil depth for Gleyic Podzols is always 30 cm at a minimum. More important, the Gleyic prefix of the genoform indicates shallow groundwater, which has a major effect on plant growth by upward capillary flow of water that is, of course, not expressed by the chemical analyses of surface soil. Six of the seven ecosystem services, with the exception of providing raw materials, therefore had a positive value, thus contributing to soil security. But how about the future?

A group of farmers was not yet satisfied, and they proceeded to refine management to a form of cradle-to-cradle dairy farming, further reducing the amount of chemical fertilizers, increasing organic manuring, and restricting input from outside feed sources and contractors. They were generally more extensive and smaller in size, as compared with other conventional dairy farms in the region. The proportion of arable crops on the farm (silage maize) was significantly lower and farmers were reluctant to apply grassland renovation since this has a negative impact on soil organic matter contents. Application of a life cycle analysis showed that they significantly increased the organic matter content of the soil as compared with comparable farms on sandy soils, thereby increasing the biomass production potential, the filtering capacity of the soil, and its biodiversity (ecosystem services 1, 2, and 3). Energy use was reduced, while the specific character of the landscape was maintained, supporting services 4 and 7 (Dolman et al. 2013). Looking at the future, soil security was not only maintained here, but it is being improved significantly. Note that farmers were the driving force in pursuing these developments, in close cooperation with soil scientists, illustrating a favorable modern tendency for participatory approaches and joint learning.

2.4 MESSAGE FROM DUTCH FARMERS TO SMALLHOLDERS OF DEVELOPING COUNTRIES

Farmers in both National Landscapes in the Netherlands, discussed here, do not qualify as smallholders as distinguished in developing countries, as their farms have an average size of approximately 50 ha. Only one hundred years ago, farm sizes in the Netherlands were as small as they are now in many developing countries. Industrial development and growth of cities providing employment to former agricultural workers has allowed farms to increase in size, making them commercially viable. The same development is likely in developing countries; however, sufficient time should be allowed to transform existing socioeconomic and institutional conditions. The farmers in the two Dutch case studies perform important services to society that go way beyond producing food and fiber (ecosystem service 1). They also have a message for farmers in developing countries by showing that modern agricultural development does not necessarily imply the exclusive need to establish

dairy megafarms with 1000 cattle or more or arable farms of thousands of hectares with monocultures. Intermediate sizes of family farms represent, next to megafarms, a viable business proposition for the future that is particularly suitable to satisfy most recognized ecosystem services and that, therefore, presents a major contribution to soil security in the future. Whether such security can also be assured when implementing impersonal and highly industrialized megafarms remains to be seen and should be considered by Rockstrom et al. (2009) when further developing the important planetary boundaries paradigm.

2.5 DISCUSSION

2.5.1 Smallholder Agriculture and the Planetary Boundary of Land Use

Rockstrom et al. (2009) have defined land use as one of nine planetary boundaries and conclude, in a fascinating long-term vision, that feeding 9 billion people in 2050 will require a drastic increase of agricultural production, in roughly the same area that is currently used. Enlarging the area is not only impossible because of lack of suitable land but also undesirable because it would imply a corresponding decrease of nature areas. The reviewed case studies in this chapter, covering smallholder agriculture in Zimbabwe, Kenya, Uganda, Mozambique, Swaziland, and Ghana, show that production levels on small farms of just a few hectares are, in many cases, too low to even support farming families, let alone provide food for fellow citizens. The ecosystem service of producing food and biomass is therefore inadequate and so is therefore soil security, which declines because of continued nutrient depletion. However, experiments show that yields can be improved with proper fertilization practices, preferably to be combined with legumes, although socioeconomic and institutional barriers remain severe. Rockstrom et al. (2009) express a long-term need for establishing larger production units near megacities of the future, using modern management techniques that combine relatively high yields with proper environmental stewardship. This transformation has been and is taking place in the developed world during the past 100 years, and it is hard to see why a similar development would not occur in the developing world. But how large is large? Such transformation should be gradual, avoiding social disruption, and this can be achieved by creating job opportunities in an urban environment. In the short term, the case studies show that smallholder agriculture and soil security can and should be improved. The two Dutch examples intend to show that developing very large industrial megafarms may not be the only future option and that intermediate-sized family farms may offer an additional possibility that could be particularly attractive to ensure future soil security.

2.5.2 Role of Soil Science

The case studies presented in this chapter, focusing on use of fertilizers, show that different soil types have different potentials requiring different management measures to achieve them. Results obtained on Nitosols and Luvisols were significantly better than those on Arenosols, Lixisols, Acrisols, and Ferralsols. Taking this into account when extrapolating favorable results (acting as "lighthouses") to identical

soil types elsewhere will improve the transfer of knowledge and may, thus, in principle, contribute to higher soil security. The case studies show that researchers are increasingly investigating conditions on real-life farms in close interaction with farmers and are on the lookout for "lighthouse" examples where inventive farmers have achieved successes on a particular soil type, sometimes to be identified as distinct phenoforms. This clearly happened in the two Dutch case studies.

The soil type, formed by a unique set of interacting soil-forming factors, is represented by mapping units on soil maps, and such units have traditionally been used as "carriers" of information for land evaluation purposes, extrapolating experiences obtained (Bouma et al. 2012). Bouma et al. (1998) and Bouma (2002) illustrated in this context the significantly different behavior of seven soil types from China, Zambia, Nigeria, Colombia, and Indonesia in terms of their Yw values (the water limited yield). If, however, soil mapping units that are, according to the legend of the soil map, supposed to contain certain soil types are quite heterogenous or ill defined, the procedure is questionable and, indeed, many questions have been raised about this procedure. Recent attempts to use sensors to directly obtain soil data (such as the organic matter content, the cation exchange capacity, and pH of surface horizons) (e.g., Kweon 2012) without using soil maps is potentially valuable but cannot explain dynamic physical, chemical, and biological soil behavior the way a well-characterized soil type can, be it in an often qualitative manner. Extrapolation of soil behavior from one well-characterized location to a new location on the basis of CEC, organic matter content, and pH of surface horizons is, of course, impossible. Such sensing data would therefore be most useful when coupled with the type of soil being observed.

Also, when only data obtained at the soil surface are available, important subsurface properties that are essential for soil behavior remain unknown. Soil chemical analyses used in the African case studies, reviewed in this chapter, were made in samples from 0 to 20 cm depth. However, plant roots always go much deeper. Also, many soils have subsurface horizons that strongly affect soil behavior: Lixisols have, for example, a clayey subsoil in contrast to Arenosols. The clay layer often ponds water, causing anaerobic conditions that strongly impair root development and crop growth. This is not observed when only a sample of surface soil is taken for chemical analyses. Soil type data therefore provide a valuable context for separate chemical, physical, and biological measurements.

2.5.3 Other Factors Determining Soil Security

Aside from a set of socioeconomic, institutional, and ethical challenges for smallholder agriculture as mentioned in Section 2.1, IFAD (2012) distinguishes three important soil-related issues: use of fertilizers, conservation agriculture, and irrigation. The restricted size of this chapter only allowed discussion of the soil fertility issue. However, recent reviews of conservation agriculture (e.g., Vlek et al. 2008 and the Desire project, www.desire-project.eu) show that problems are severe but that efforts in many countries to combat soil degradation and erosion are succesful, particularly when approached comprehensively in large-scale watersheds, requiring cooperation among farmers and effective institutional arrangements. Dealing with

individual smallholders is much more difficult. Some agronomists, however, challenge the potential of conservation agriculture if only because of the limited amount of crop residues left on the land (e.g., Giller et al. 2009). When applied correctly, irrigation can also strongly improve yields (e.g., IAC 2004). However, it requires a relatively high level of technical expertise that can be applied most effectively in larger irrigation schemes. Again, introducing irrigation on 2-acre fields has little potential. This supports the long-range vision of Rockstrom et al. (2009) that large and modern production systems are needed to satisfy the needs of an ever-wealthier population in the decades to come. The Dutch case studies suggest that there may also be local potential for intermediate-size family farms.

2.6 CONCLUSIONS

Five major conclusions are derived from this study:

1. Soil security is expressed in terms of the degree to which ecosystem services can be provided. The sixteen ecosystem services defined by MA (2005) can, for simplicity, be related to the seven basic soil functions defined by CEC (2006). Large differences among smallholder conditions in different countries, as reviewed in this chapter, make unified expressions of soil security less meaningful and require a local approach taking into account socioeconomic and institutional issues.
2. Recent reports on smallholder agriculture pay little attention to soils. IFAD (2012) mentions conservation agriculture, use of fertilizers, and irrigation as possible soil-related activities that may improve ecosystem services and, in turn, soil security. In this chapter, the very general term "use of fertilizers" is explored by analyzing the various ways in which optimal use of fertilizers has been investigated during the last hundred years, as well as ways in which this knowledge has been communicated to farmers. The traditional top–down approach is now being replaced by interactive joint learning in both developed and developing countries.
3. Case studies in Zimbabwe (Arenosols) and Kenya (Vertisols) demonstrate conditions where ecosystem services are inadequate, as production levels remain below that required by the farming families to meet their food need. This applies to studies in several other countries. Current socioeconomic and institutional conditions do not offer obvious future perspectives for improvement. However, Nitosols in Kenya and Luvisols in Zimbabwe presented an adequate, be it marginal, level of ecosystem services. Rather than only perform classical soil fertility experiments, focusing on surface soil, the suggestion is made to (i) also consider subsoil conditions as defined in soil classification in terms of genoforms, and (ii) look for "lighthouse" examples where farmers, working with a given soil type, have achieved unexpected success. Then, genoforms can be used as a "carriers" of valuable management information.
4. A study on Gleyic Podzols and Sapric Histosols in the Netherlands demonstrated bottom–up actions of farmers applying cradle-to-cradle techniques that resulted in six clearly improved ecosystem services and thus improved

soil security. This improved soil management resulted in distinctly different phenoforms of the given genoform, associated with different forms of management. Distinction of phenoforms offers a more specific possibility to extrapolate management expertise to nonstudied locations with the same soil type: the classic procedure in land evaluation.

5. Smallholder agriculture has to be considered in a broad societal context, with a focus to the future. Rockstrom et al. (2009) have defined planetary boundaries for nine issues, among them land use. Feeding 9 billion people in 2050 will require a 50% increase of agricultural production. The marginal character of many smallholders at this time does not allow such an increase, although case studies reviewed show that significant improvements can be made by improving management practices. Larger production units, using modern production techniques, are needed and this development occurs in the developed world. The two Dutch case studies show the potential of intermediate sizes of farms, providing satisfactory incomes and a range of ecosystem services, creating soil security.

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