11 System productivity and natural resource integrity in smallholder farming

Friends or foes?

Bernard Vanlauwe, Edmundo Barrios, Timothy Robinson, Piet Van Asten, Shamie Zingore and Bruno Gérard

Introduction

In sub-Saharan Africa (SSA), increases in yields of the major crops in smallholder farming systems have failed to match population growth, with increased production resulting rather from agricultural area expansion (Worldbank, 2007), very often at the expense of the natural resource base, such as carbon-rich and biodiverse forest land (e.g. Gockowski and Sonwa, 2011). Intensification of smallholder agriculture is a must under high population densities but also desirable in less populated areas in order to protect natural ecosystems. Smallholder farming communities and systems in SSA are heterogeneous, both at the community and farm level, driven by varying and often limited access for production resources (land, labour, capital) (Tittonell et al., 2010). At the community level, variable resource endowments and production objectives are often conceptualized through the construction of farm typologies. At farm level, preferential management of specific plots within a farm has resulted in within-farm soil fertility gradients, often with soils of higher fertility near the homestead, and more degraded soils towards the outer limits of the farm. For many households and regions, agriculture alone will not be able to provide rural populations with adequate livelihoods due to limited farm size and access to land (Harris and Orr, 2014; Jayne et al., 2014). Besides heterogeneity at farm and community level, enabling conditions for intensification, often expressed as access to agro-inputs, markets, and credit, quality of rural infrastructure, or conducive policies, also vary considerably. Intensification of smallholder farming systems will thus require co-learning among research, development, and private sector actors for the tailored integration of both technical and institutional innovations (Giller et al., 2011; Coe et al., 2014).

Sustainable Intensification (SI), though ill-defined, encompasses the need to enhance productivity, whilst maintaining or improving ecosystem services and system resilience. Although the discourse on what constitutes SI and how it relates to other intensification paradigms is very active nowadays (e.g., van Noordwijk and Brussaard, 2014; Petersen and Snapp, 2015; Wezel et al., 2015), advancing this discourse is beyond the scope of the current paper. In this chapter, the productivity dimension of SI refers to total farm productivity, using the unit of land as the denominator for areas with high population densities and limited smallholder access to land. Total farm productivity can be expressed in various ways, partly related to the objectives of why such data are collected. Summing up dry matter yields over various crops does not really make sense since crops such as cassava (with up to 25 ton dry matter ha^{-1} $year^{-1}$) have a much higher yield potential than others such as cowpea (with up to 2 seasons of 3 ton ha^{-1} or 6 ton ha^{-1} $year^{-1}$). Farm-level productivity can be aggregated based on total value generated (in USD $farm^{-1}$), total energy (kJ $farm^{-1}$), protein (kg $farm^{-1}$), or other nutritional components generated (energy (kJ $farm^{-1}$), protein (kg $farm^{-1}$)), or total biomass produced (in kg dry matter $farm^{-1}$). While the first indicator is important in the context of income generation, the second set of indicators is relevant in relation to the food and nutrition security discourse while the latter indicator is relevant when focussing on carbon and nutrient stocks and flows that affect natural resource integrity.

Ecosystem services that require maintenance under SI are many and are regulated at different scales. Following TEEB (2010), ecosystem services are classified as provisioning, regulating, habitat, and cultural services, whereby (i) provisioning services refer mainly to goods that can be directly consumed, and include food, water, raw materials, such as fibre and biofuel, and genetic, medicinal, and ornamental resources; (ii) regulating services comprise regulation of climate, air quality, nutrient cycles, and water flows; moderation of extreme events; treatment of waste; preventing erosion; maintaining soil fertility; pollination; and biological controls of pests and diseases; (iii) habitat services are those that maintain the life cycles of species or maintain genetic diversity; and (iv) cultural services refer to the aesthetic, recreational and tourism, inspirational, spiritual, cognitive development, and mental health services provided by ecosystems.

In the context of this chapter, we focus on plot/farm level intensification and provisioning services are covered by the enhanced productivity dimension of SI. Only regulating services operating at plot/farm level are considered and these include regulation of climate, regulation of nutrient cycles and water flows, preventing erosion, and maintaining soil fertility. All of these can be positively affected by increased soil organic carbon (SOC) contents. For instance, (i) increased SOC contents enhance climate change mitigation; (ii) SOC interacts positively with the biological (e.g., provision of energy for biological activity), chemical (e.g., exchange capacity for nutrient retention), and physical dimensions (e.g., enhanced aggregate stability) of soil fertility; and (iii) application of mulch and increased aggregate stability reduce soil erosion and increase water infiltration. For the remainder of the chapter, SOC or soil fertility status is used as an indicator of ecosystem service maintenance, thereby recognizing that

SOC contains several distinct pools or fractions, each with their own functions and consequent contributions to specific ecosystem services (Lehmann and Kleber, 2015). We also recognize that beyond biophysical dimensions, social, economic, and human dimensions are critical for SI (e.g., Loos et al., 2014), but these are outside the scope of this chapter.

The objectives of this paper are (i) to conceptualize the yield reduction and soil fertility degradation processes and how these interact; (ii) to conceptualize and provide evidence from long-term soil management trails for potential rehabilitation trajectories as proposed by various intensification paradigms; and (iii) to evaluate the potential impact on yield and SOC of those paradigms in response to the question posed in the title of this chapter: can SI interventions simultaneously address the need for more produce and the delivery of other soil-based ecosystem services, or are trade-offs in space and time inevitable?

Soil degradation and yield decline

After conversion of natural fallows to agricultural land (Figure 11.1a), it has been frequently observed that in the absence of the use of external nutrients, crop yields decline over time as do soil fertility conditions, often expressed as SOC content. In the short-term, the first degradation process that is commonly initiated is nutrient mining, resulting in deficiencies of those nutrients of which removal by a crop quickly exceeds the nutrient replenishment potential of the soil (Stoorvogel et al., 1993). In most cases in cereal-based systems, these nutrients are N and P (e.g., Sanchez et al., 2001). Note that under specific circumstances, other degradation processes can also be immediately initiated, e.g., soil erosion on fields with steep slopes and lack of surface cover. As a result, not only crop yields decline but also the amount of crop residues produced that can either be retained in the plot or recycled through livestock feeding systems. Consequently, declining crop yields are accompanied by declining soil fertility conditions, with both processes reinforcing each other. In the initial stages of land conversion (e.g., the first 5–10 years, depending on the soil type), solutions to these trends can be found in the application of those nutrients that are limiting crop growth, with N, P (and K) fertilizer being the most commonly available. Application of these nutrients can help rehabilitate crop yields, and the provision of crop-residue-related biomass, thereby contributing to reduce the rate of SOC loss.

Where the soil degradation process is not addressed and thus allowed to proceed, several other degradation processes gradually take effect reducing the effectiveness of nutrient applications, ultimately resulting in non-responsive soils (Vanlauwe et al., 2010) (Figure 11.1b). Such degradation processes include acidification caused by the removal of crop residues (Van Breemen et al., 1983), soil erosion due to a reduced surface cover (Valentin et al., 2004), or the generation of nutrient imbalances causing secondary and micronutrient deficiencies (Turmel et al., 2015). Other degradation processes that can trigger non-responsiveness include soil crusting reducing infiltration and germination

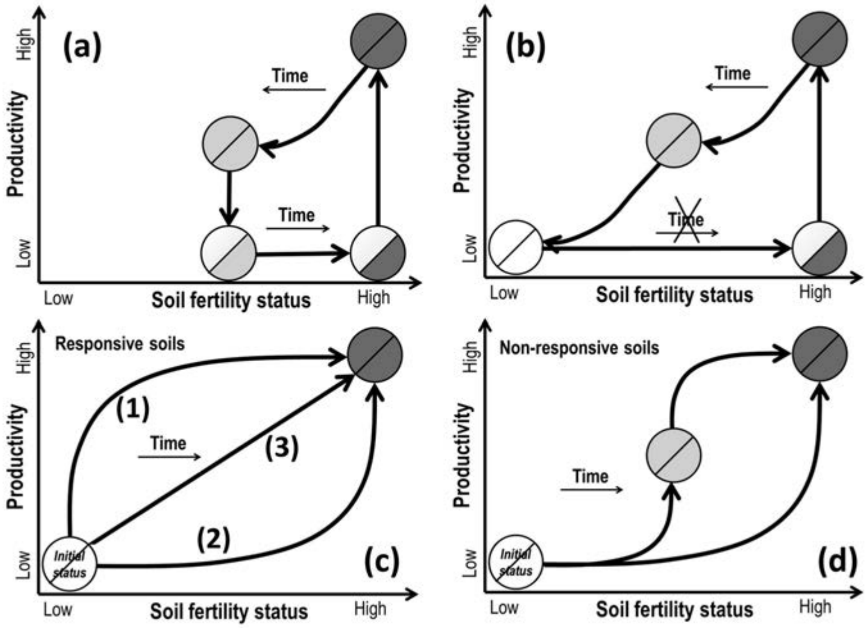

Figure 11.1 Conceptual depiction of the slash-and-burn cycle whereby (a) land is left to return to fallow after a certain period with continuous yield and soil fertility decline, and (b) how an extension of the cropping cycle with increasing population density can generate fields with low yields and severely degraded soils. The conceptual pathways from a current situation (degraded soil with low productivity; lower left circle) to a SI situation (healthy soil and high productivity; upper right circle) are described by two possible situations: (c) where limitations to crop growth can be readily addressed (e.g., application of N fertilizer on N-deficient soils, application of lime on acid soils), and (d) where soil rehabilitation will require more complex and longer-term investments (e.g., soils with multiple chemical, biological, and/or physical deficiencies). The upper left half of each circle refers to the status of productivity and the lower right half to soil fertility conditions with darker (half)circles indicating better conditions

(Rouw and Rajot, 2004) or hardpan formation reducing rooting depth (Lahmar et al., 2012). In such conditions, soil fertility rehabilitation is a pre-condition for inducing increased crop growth and the nature of the degradation status should determine whether it still makes economic sense to rehabilitate certain soils, especially in the absence of specific incentive schemes such as food-for-work programmes aiming at establishing physical and/or biological erosion control measures.

Sustainable Intensification (SI) could be placed in the top right circle in Figure 11.1b. A substantial acreage of cropland in densely populated areas of SSA, characterized by low crop productivity and poor soil health due to long-term nutrient mining and SOC decline, can be situated within or near the conceptual 'initial status' circle of Figure 11.1c. That said, as described above, within each farm, various fields can be positioned at different locations within the two-dimensional space. While homestead plots commonly have good yields and better soil fertility conditions, and are often reserved for high-value crops, degraded outfields can often be mapped at the lower left of this space and reserved for other uses, e.g., woodlots.

Pathways towards SI and potential entry points

Sustainable Intensification requires increases in productivity and maintenance/restoration of ecosystem services, and in this chapter we focus on field-based ecosystem services that are regulated by soil conditions. Various pathways can be followed to turn the 'lower left' situation of Figure 11.1b back to a 'top right' situation. Path (1) of Figure 11.1c depicts a pathway focussing primarily on increases in crop productivity, thus assuming that this will not only result in higher yields but also in higher amounts of biomass in the form of crop residues which can then be re-invested in rehabilitating soil fertility conditions. Integrated Soil Fertility Management (ISFM) (Vanlauwe et al., 2010) follows this logic, using fertilizer as entry point towards the SI of smallholder agriculture. ISFM also recognizes that non-responsive conditions require other entry points (Vanlauwe et al., 2010, Vanlauwe et al., 2015), including the application of lime on acid soils, or the use of high rates of farmyard manure (Zingore et al., 2008). Zingore et al. (2005), for instance, demonstrated that on clayey soils, commercial farmers were able to retain substantially higher SOC contents when using high yielding maize varieties and fertilizer in comparison with communal farmers who were practicing low input agriculture on the same soils.

On the other hand, path (2) follows a logic whereby investments in improved soil fertility conditions will gradually improve crop yields and thus move towards SI. Some agroforestry practices fit this logic since tree establishment can take some years before these deliver their full benefits to productivity and soil fertility (e.g., Garrity et al., 2010). Nevertheless, other agroforestry practices like improved fallows (Barrios et al., 1998; Chirwa et al., 2003), as well as those which rely on existing tree cover, like farmer-managed natural regeneration (Dossa et al., 2012) and the Quesungual agroforestry system (Fonte et al., 2010), have a more rapid impact and can contribute more quickly to enhancing crop productivity, as do other paradigms, such as conservation agriculture (e.g., Kassam et al., 2009), 'push–pull' intercropping (e.g., Khan et al., 2000), or crop–livestock integration (e.g., Achard and Banoin, 2003), which likely follow intermediate paths (3). Note that for severely degraded soils with multiple deficiencies, path (1) is not an option and rehabilitation of soil fertility, e.g., through the application of large amounts of manure for several years (Zingore et al., 2008), may be required to restore the responsiveness of soils to standard fertilizer and other amendments. For instance, in southern Benin Republic, deep-rooting *Senna siamea* trees were able to access the relatively fertile subsoil of a site with severe topsoil degradation and thus restore crop productivity (Aihou et al., 1998). More details on the above paradigms are given in relation to their potential impact on yield and soil fertility conditions in Table 11.1. Recognizing the strong demand for crop residue as livestock feed in West-African smallholder systems, Lahmar et al. (2012), based on CA (Conservation Agriculture) principles, explored the option to use prunings of native evergreen multipurpose woody shrubs to provide field permanent soil cover and rehabilitate degraded land through an aggradation than a conservation phase. The work of Fatondji et al. (2009) demonstrated the potential of significantly increasing cereal yields on degraded land using the Zai technology, whereby crops are grown in planting pits for harvesting water and spot-placing organic inputs and fertilizer. However, to our knowledge, there is no published research on the long-term management after the initial labour-demanding rehabilitation of degraded land through Zai.

Yield and SOC data from long-term trials in support of potential entry points

Besides restoring crop productivity and rehabilitating degraded soils, it is equally important to ensure that yields and soil fertility conditions are maintained on fields with favourable conditions ('top right' situations in Figure 11.1c). Data from two long-term trials (Figure 11.2), established on sites that had been cleared from natural fallows with supposedly favourable soil fertility conditions at their establishment, provide some insight into how this could be achieved. Data from a long-term agroforestry trial in Ibadan (Figure 11.2a) demonstrate that only the treatment with *Senna siamea* alley cropping and fertilizer application succeeds in retaining yield and relative SOC within the vicinity of the data at trial establishment, although some decline in yields is obvious. Without fertilizer, both yields and SOC decline in the Senna alley cropping treatment. Yields in the no-input control treatment decline very rapidly to values near zero while SOC decline takes more time. With fertilizer application, the decline in yield and SOC was reduced but did reach unacceptably low levels after 20 years (Figure 11.2a). This decline in SOC with fertilizer application contradicts what was earlier observed in Zimbabwe (Zingore et al., 2005), which is very likely related to the fact that maize yields in Nigeria were less than half those of Zimbabwe, with consequent lower inputs of maize crop residues and the lighter texture of the soil in Nigeria, thus providing less physical protection for applied organic C (Six et al., 2002). In a conservation agriculture trial in Zambia (Figure 11.2b), standard practices tend to result in decreasing yields and SOC, especially since maize residues were removed in this treatment (Thierfelder et al., 2013). Only the treatment with inclusion of cotton and sum hemp appears to retain yields at original levels (though SOC contents did not appear to decrease under all treatments with direct seeding and residue retention).

While both trials in Figure 11.2 started from relatively good soil fertility conditions, experiments in Figure 11.3 started on degraded and non-degraded

Table 11.1 Selected content of currently promoted intensification paradigms

Paradigm	*Major principles*	*Potential impact on yield*	*Potential impact on soil fertility status*
Integrated Soil Fertility Management	1. Integrate improved varieties, fertilizer, organic resources, and other soil amendments 2. Target resources in relation to soil fertility gradients, resource endowments, and status of enabling conditions	1. Immediate increases in yield if the right inputs are applied to the right field type (e.g., the use of improved germplasm and improved varieties on responsive soils) 2. Rehabilitation of non-responsive soils will be required before increased yields can be expected on such soils	1. Enhanced crop yields also generate a larger amount of crop residues that can be recycled either directly or as manure after feeding to livestock thus potentially increasing SOC[1] stocks 2. Integration of organic resource production systems (e.g., dual purpose legumes) can further enhance the availability of (higher quality) organic inputs
Conservation Agriculture	1. Reduce tillage 2. Keep soil covered 3. Diversify cropping systems, e.g., with rotations 4. Apply fertilizer (or other sources of nutrients)[2]	1. The impact of CA on crop yields is usually expressed after 2–3 years 2. Sufficient nutrient inputs are required to produce the required amount of crop residues for mulch otherwise yields can decrease; reduced/no tillage without mulch application reduces crop yields 3. Mulch commonly improves soil moisture conditions and thus resilience of crops to drought stress	1. CA can enhance soil fertility conditions through reduced soil disturbance although care needs to be taken to manage degradation processes that are alleviated by tillage (e.g., soil crusting) 2. The impact of CA on SOC stocks varies between negative and positive, depending on many factors affecting C mineralization and stabilization
Crop–livestock integration	1. Integrate fodder options (e.g., fodder legumes) in cropping systems 2. Integrate appropriate feed and manure management systems 3. Store, compost, and recycle farmyard manure	1. Enhanced availability of livestock feed of appropriate quality improves livestock weight gains and manure production 2. Manure recycled to crops after proper composting/storage can create immediate increases in crop productivity 3. Competition for organic resources of high quality (e.g., legumes) can negatively affect crop yields especially if manure is not recycled	1. Manure is shown to retain more of its C in the SOC pool, probably related to C stabilization processes during manure production 2. Removal of crop residues for feed can negatively impact on SOC status, especially if the manure produced is not recycled in the same plot 3. Much of the potential benefits of manure depends on the way feeding regime of the livestock and the way in which the manure is managed and recycled

(*Continued*)

Table 11.1 (Continued)

Paradigm	*Major principles*	*Potential impact on yield*	*Potential impact on soil fertility status*
Agroforestry	1. Integrate perennials in cropping systems	1. Crop yield increases in 2–3 years in N-limited soils as a result of organic inputs from fast-growing N-fixing trees (e.g., *Gliricidia sepium*) 2. Selective slash and mulch management of existing tree cover increases yields in 1–3 years 3. Planting of trees and crops with compatible attributes to generate multi-strata agroforestry systems generates yield increases and a variety of products in the longer term	1. Above ground and below ground contributions of N-rich biomass increases soil organic N stocks and N availability to crops 2. Significant biomass additions, commonly greater than amounts added as crop residues, contribute to permanent soil cover, erosion control, increased SOC, greater soil water-holding capacity and nutrient availability, creation of habitats for beneficial soil organisms
'Push–pull' intercropping systems	1. Plant maize in the live intercropped Desmodium mulch 2. Harvest Desmodium fodder at least 3 times per year	1. Desmodium takes one year to establish so yield effects will take at least one year to appear 2. Once Desmodium is fully established and managed well, maize yields are substantially higher in comparison with current practices	1. In comparison with current practices, the larger amounts of maize stover and Desmodium above and below ground biomass can increase SOC stocks 2. N stocks can be enhanced due to the N added to the soil through biological N fixation 3. The Desmodium live mulch protects the soil from erosion and improves soil moisture conditions

[1] SOC means 'Soil organic carbon'.

[2] In recent publications, the need for external nutrient inputs to ensure a sufficient quantity of crop residues to keep at least 30% of the soil covered was proposed as an additional principle, first by Vanlauwe et al. (2014), and later confirmed by Lal (2015).

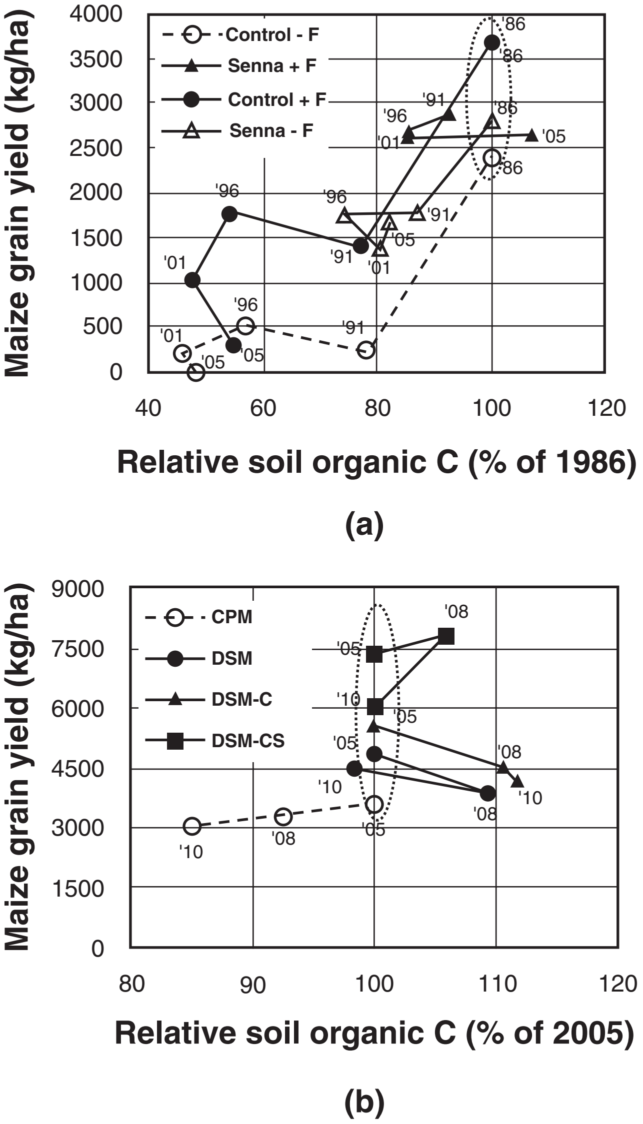

Figure 11.2 Trends in yields and relative soil organic carbon (SOC) contents for (a) a long-term (1986–2005) agroforestry trial in Nigeria, and (b) a long-term (2005–2010) conservation agriculture trial in Zambia. In (a) SOC data from 1991 were interpolated between those of 1986 and 1996. In (b) 'CPM' means 'conventional ploughing, residue removal, sole maize', 'DSM' means 'animal traction direct seeding, residue retention, sole maize', 'DSM-C' means 'animal traction direct seeding, residue retention, maize-cotton rotation', and 'DSM-CS' means 'animal traction direct seeding, residue retention, maize-cotton-sun hemp rotation'. Fertilizer was applied in all treatments. Dashed oval shapes indicate yields and SOC data at the start of the trials

Source: (a) Diels et al., 2004; Vanlauwe et al., 2005; Vanlauwe et al., 2012; (b) Thierfelder et al., 2013.

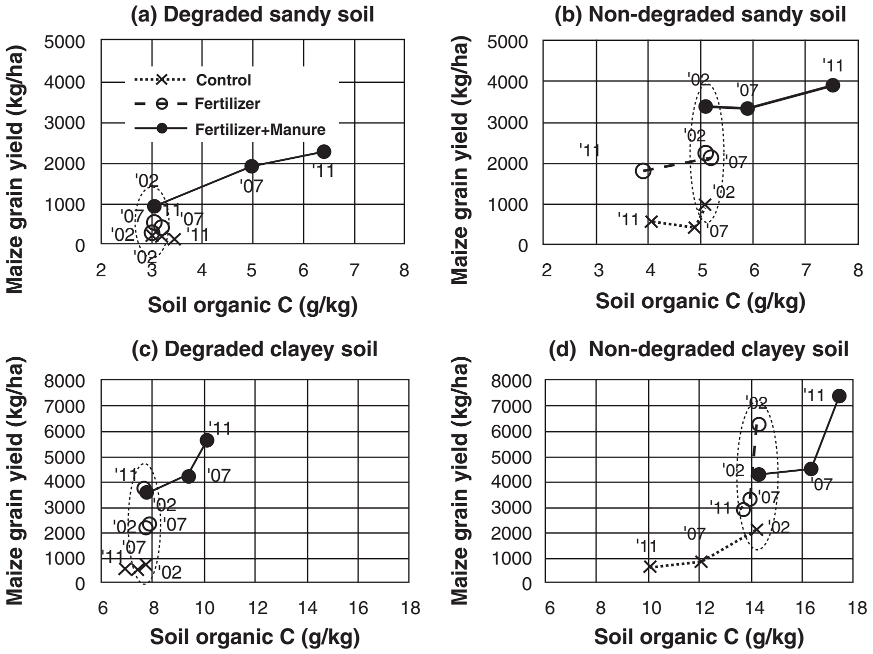

Figure 11.3 Trends in yields and relative soil organic carbon (SOC) contents for a set of long-term (2002–2011) trials established in Zimbabwe on (a) a degraded or (b) non-degraded sandy soil, and (c) on a degraded or (d) non-degraded clayey soil. Fertilizer application in the sole fertilizer treatment consisted of 100 kg N ha^{-1} and 30 kg P ha^{-1}, applied annually, while in the mixed treatment, 100 kg N ha^{-1} was applied as fertilizer in combination with 15 ton farmyard manure ha^{-1}, applied annually. Dashed oval shapes indicate yields and SOC data at the start of the trials

Source: Rusinamhodzi et al., 2013.

sites with sandy and clayey soils in Zimbabwe (Rusinamhodzi et al., 2013). In situations where crop residues are removed from the field, only the treatments with high application of manure managed to increase yields and SOC contents; however, fertilizer application doubled yields in 2011 on the clayey soil (Figure 11.3). As expected, yields and SOC declined on both non-degraded soils without the application of fertilizer and/or manure. Again, only in the treatment with application of manure do SOC contents increase substantially while yields in the fertilizer-only treatment are marginally lower than those in the combined treatment on the clayey soil (Figure 11.3). As for the data presented in Figure 11.2a, recycling maize crop residues does not appear sufficient to increase SOC contents.

Similar long-term data assessing the status of yields and SOC (and other ecosystem services) are required to make objective inferences about the SI nature of various soil management paradigms and are unfortunately in short supply, especially for sub-Saharan Africa.

Productivity and natural resource integrity: Friends or foes?

System productivity and natural resource integrity are inherently foes since opening up natural ecosystems for agriculture consistently reduces their C stocks, above as well as below ground, and agriculture results in a net removal of nutrients from available soil stocks, thus initiating nutrient mining and a consequent suite of degradation processes. In addition, conversion from natural to agricultural land can strongly reduce ecosystem diversity. Traditional systems under low intensification levels succeeded in managing trade-offs between agriculture and nature by limiting the agricultural phase to a relatively short period allowing nature to regenerate during relatively long fallow periods. Although in many situations such a model is no longer feasible and/or desirable, continuous agriculture without inputs of nutrients and organic matter either through fertilizer, biomass transfer, or integration of trees extracting nutrients below the crop root zone consistently leads to yield declines and soil degradation (Figures 11.2 and 11.3). In the short-term, more crop residues can be removed, e.g., to feed livestock, or crops having a higher yield and nutrient extraction rate can be chosen, but in the long-term, these practices cannot be sustained, unless organic resources are imported from outside the plot/farm, at the expense of other plots or natural lands. Some researchers suggest that an increase in livestock should be part of the solution, but Bekunda and Woomer (1996) and Sseguya et al. (1999) have shown that the use of cattle manure is closely related to farm size and that the latter is continuously shrinking under increasing land pressure. Unless cattle feed is imported from outside the farm, the use of fodder and crop residues for feeding zero-grazing cattle generally decreases nutrient replenishment at the plot level. The collapse of traditional 'nutrient transfer systems' under current population growth has also been demonstrated by Baijukya et al. (2005).

The main question then is how farmers can move from current, degraded, and low productivity conditions to SI and thereby ensure that improvement in either productivity or natural resource integrity does not occur at the expense of further degradation of the other. Considering the plot level, based on the data from the long-term trials, to maintain productivity and SOC conditions at the initial, relatively high levels (Figures 11.2a, 11.2b, 11.3b, 11.3d), under most conditions, simultaneous interventions are needed that address both crop productivity and SOC status. While fertilizer alone resulted in yield declines over time, except when maize yields were really high (Figure 11.3d), applying fertilizer in combination with tree prunings (Figure 11.2a), high biomass intercrops (Figure 11.2b), or farmyard manure (Figure 11.3b, 11.3d) allowed yields and SOC conditions to stabilize (Figures 11.2a, 11.2b), or further increase (Figures 11.3b, 11.3d). For degraded conditions (Figures 11.3a and 11.3c), while application of fertilizer results in gradual increases in crop yield for the clayey soil, the co-application of fertilizer and manure increases both yields and SOC contents.

Notwithstanding the continuing reference in literature to thresholds for SOC, it will remain hard or impossible to derive these for various soil and climatic conditions since SOC regulates various functions that will probably require different levels of SOC. For instance, Diels et al. (2002) noted that to increase the amount of plant-extractable water in the topsoil, an increase of 8 to 13 g kg^{-1} SOC would store an extra 1 mm of water in the top 15 cm of soil while the cation exchange capacity (CEC) function of SOC is only relevant for soils of which the CEC of the mineral fraction is less than 2 $cmol_c$ kg^{-1} (e.g., Arenosols or coarse-textured Ferralsols). On the other hand, plant-available N supply from the soil organic matter pool is known to commonly increase with higher SOC content. Studies on sandy soils in Zimbabwe showed that non-responsiveness was associated with SOC contents less than 4 g kg^{-1} (Mtambanengwe and Mapfumo, 2005; Zingore et al., 2008), although the SOC functions that influence crop response in these cases were complex and not clearly understood (Zingore et al., 2008). Interventions addressing crop productivity are 'friends' of natural resource integrity mainly when crop yields are high and crop residues recycled, while interventions addressing SOC can have a positive effect on crop yield only if substantial amounts of organic inputs with the right quality characteristics (e.g., high N content, low lignin, and soluble polyphenol contents) are applied (Palm et al., 2001).

Pathways towards SI can be considered as consisting of consecutive phases. An initial phase focussed on increasing productivity and thus in-situ biomass accumulation (ISFM paradigm) followed by a stabilization phase in which other paradigms take over. For instance, agroforestry, after some time, can facilitate SI by addressing the challenge of optimizing crop productivity while maintaining the provision of other ecosystem services (Barrios et al., 2012). Vanlauwe et al. (2014) argued that fertilizer is needed to kick-start CA since at low crop yields insufficient crop residue biomass is produced to keep the soil covered.

At farm level, farmers can make decisions on where to apply inputs and organic resources within their heterogeneous farms. Such decisions affect the productivity and natural integrity status of individual fields and the total farm whereby it is common for farmers to degrade certain plots (e.g., outfields furthest from the homestead) in favour of others (e.g., homestead plots), very often through the transport of crop residues for livestock feed and the consequent recycling of farmyard manure produced. Rowe et al. (2006) observed that regular applications of manure to only part of a farm, common on farms with limited manure availability, rapidly led to large gradients in crop yield while spreading manure evenly at a lower rate would give greater whole-farm yields. Fertilizer should be applied only on fields where grain yield is responsive to higher nutrient inputs, and not on infields which are nutrient-saturated or on degraded outfields. Of course, to improve the relevance of fertilizer and manure recommendations, it is necessary to consider resource limitations and production at the farm scale, and the effects of applying nutrient resources not only on current crop yield but also on the development of soil fertility of different fields. In highland conditions, with farms covering steep gradients, larger applications of nutrients in the uphill end of the farm, combined with live barriers following contour lines, may favour greater whole-farm yields given the natural redistribution of nutrients in steep terrain as a result of leaching and soil erosion which favours higher fertility soils downslope.

In reality, trade-offs in time and/or space between productivity and soil fertility rehabilitation will be the rule rather than the exception since not all the required inputs, amendments, and implements will be available to most smallholder farmers at the required time for the required space. Most smallholder farmers are resource-constrained and the earlier-mentioned soil fertility gradients are a manifestation of spatial trade-offs between productivity on homestead fields at the cost of degradation of outfields, mostly via biomass transfer to livestock feed and manure recycling strategies. Indeed, one can expect that crop-livestock farmers favour feeding their livestock, which contribute to multiple livelihood functions, to the detriment of long-term maintenance of their SOC status. Moreover, since decisions made by farmers on resource allocations in time and space will depend on their production objectives, resource endowments, and/or attitudes towards farming, assisting farmers with decision support tools that can facilitate decision-making is likely to have more impact in the route towards SI than providing 'best' recommendations for all.

The current chapter focussed on two important dimensions of SI of smallholder agriculture, thereby recognizing that achievement of SI will require institutional, economic, and social dimensions to be aligned. While agro-input and output market forces can provide the necessary incentives to invest in enhanced productivity, investing in natural resource rehabilitation that is independent of immediate benefits generated through improved productivity will require other incentives such as subsidy or payment for ecosystem service schemes and changes in land tenure systems with land ownership being a major driver for long-term investments in improving soil fertility and land quality. Moving towards SI requires investments from farmers and farming communities in terms of capital and labour and where many households are trapped in poverty and lack the necessary resources to invest (Tittonell and Giller, 2013), the move towards SI at scale will require substantial support and facilitation. Without this, the issue of 'friends or foes' is irrelevant.

Conclusions

In many cases, after clearing natural fallows, nutrient mining is the first degradation process kick-starting a number of other degradation processes, if not contained in time. Declining soil fertility drives crop yields down and triggers a mutually reinforcing vicious cycle of resource degradation which can often be reverted at early stages with the application of nutrient inputs. After years of soil degradation, soils can become non-responsive to fertilizer applications and must be rehabilitated before becoming productive again. Different SI trajectories, and land management paradigms associated with such trajectories, are discussed, and their potential impact on productivity increases and soil fertility conditions are evaluated. This is supported by yield and SOC data from ISFM, CA, and agroforestry trials, established on sandy to clayey soils.

The question of whether system productivity and natural resource integrity in smallholder farming are friends or foes does not have a simple answer. When population pressure over land is low, the potential for 'friendship' is high because there is often room to manage negative interactions and trade-offs through changes in the temporal and spatial arrangements across fields. As population pressure on land increases, and the flexibility for land use arrangements is limited or not possible, soil degradation is invariably initiated in the absence of nutrient inputs. External nutrient inputs are thus needed to prime farming systems, thus breaking the downward spiral of soil degradation. The biophysical context (e.g., non-responsive soils), however, can determine which nutrient input type would be effective (e.g., manure) under such circumstances. To make ends meet, poor smallholder families often curtail their investment horizons, resulting in a bias towards short-term returns which might jeopardize long-term land productivity.

Lastly, more long-term trials related to various intensification options are needed to guide meaningful inferences on the SI nature of those options, including aspects of resilience to biophysical stresses.

Acknowledgements

The authors gratefully acknowledge the many donors that have supported natural resources management R4D for the past decades and, more specifically, the Bill and Melinda Gates Foundation (BMGF), the Directorate General for Development (Belgium), the International Fund for Agricultural Development (IFAD), and the United States Agency for International Development (USAID). Partial support to produce this chapter was provided by the Humidtropics, the Forest, Trees, and Agroforestry (FTA), and the MAIZE CGIAR Research Programs.

References

Achard, F. and Banoin, M. (2003) 'Fallows, forage production and nutrient transfers by livestock in niger', *Nutrient Cycling in Agroecosystems*, vol 65, pp. 183–189.

Aihou, K., Sanginga, N., Vanlauwe, B., Lyasse, O., Diels, J. and Merckx, R. (1998) 'Alley cropping in the moist savanna of West-Africa: I. Restoration and maintenance of soil fertility on'terre de barre 'soils in Bénin Republic', *Agroforestry Systems*, vol 42, pp. 213–227.

Baijukya, F.P., de Ridder, N., Masuki, K.F. and Giller, K.E. (2005), 'Dynamics of banana-based farming systems in Bukoba district, Tanzania: changes in land use, cropping and cattle keeping', *Agriculture, Ecosystems and Environment*, vol 106, pp. 395–406.

Barrios, E., Kwesiga, F., Buresh, R.J., Coe, R. and Sprent, J.I. (1998) 'Relating preseason soil nitrogen to maize yield in tree legume-maize rotations', *Soil Science Society of America Journal*, vol 62, pp. 1604–1609.

Barrios, E., Sileshi, G.W., Shepherd, K. and Sinclair, F. (2012) 'Agroforestry and soil health: Linking trees, soil biota and ecosystem services' in D.H. Wall, R.D. Bardgett, V. Behan-Pelletier, J.E. Herrick, T.H. Jones, K. Ritz, J. Six, D.R. Strong and W. van der Putten (eds) *Soil Ecology and Ecosystem Services*, Oxford University Press, Oxford, pp. 315–330.

Bekunda, M.A. and Woomer, P.L. (1996), 'Organic resource management in banana-based cropping systems of the Lake Victoria Basin, Uganda', *Agriculture, Ecosystems and Environment*, vol 59, pp. 171–180.

Chirwa, T.S., Mafongoya, P.L. and Chintu, R. (2003) 'Mixed planted-fallows using coppicing and non-coppicing tree species for degraded acrisols in eastern zambia', *Agroforestry systems*, vol 59, pp. 243–251.

Coe, R., Sinclair, F. and Barrios, E. (2014) 'Scaling up agroforestry requires research 'in' rather than 'for' development', *Current Opinion in Environmental Sustainability*, vol 6, pp. 73–77.

Diels, J., Aihou, K., Iwuafor, E.N.O., Merckx, R., Lyasse, O., Sanginga, N, Vanlauwe, B. and Deckers, J. (2002) 'Options for soil organic carbon maintenance under intensive cropping in the West-African Savanna' in B. Vanlauwe, J. Diels, N. Sanginga and R. Merckx (eds) *Integrated Plant Nutrient Management in sub-Saharan Africa: From Concept to Practice*, CABI, Wallingford, UK, pp. 299–312.

Diels, J., Vanlauwe, B., Van der Meersch, M.K., Sanginga, N. and Merckx, R. (2004) 'Long-term soil organic carbon dynamics in a subhumid tropical climate: 13 C data in mixed C 3/C 4 cropping and modeling with ROTHC', *Soil Biology and Biochemistry*, vol 36, pp. 1739–1750.

Dossa, E.L., Diedhiou, I., Khouma, M., Sene, M., Lufafa, A., Kizito, F., Samba, S.A.N., Badiane, A.N., Diedhiou, S., Dick, R.P. (2012) 'Crop productivity and nutrient dynamics in a shrub (*Guiera senegalensis*)–based Farming System of the Sahel', *Agronomy Journal*, vol 104, pp. 1255–1264.

Fatondji, D., Martius, C., Zougmore, R., Vlek, P.L.G., Bielders, C.L. and Koala, S. (2009) 'Decomposition of organic amendment and nutrient release under the zai technique in the Sahel,' *Nutrient Cycling in Agroecosystems*, Springer, vol 85, no 3, pp. 225–239.

Fonte, S.J., Barrios, E. and Six, J. (2010) 'Earthworms, soil fertility and aggregate-associated soil organic matter dynamics in the Quesungual agroforestry system', *Geoderma*, vol 155, pp. 320–328.

Garrity, D.P., Akinnifesi, F.K., Ajayi, O.C., Weldesemayat, S.G., Mowo, J.G., Kalinganire, A., Larwanou, M. and Bayala, J. (2010) 'Evergreen agriculture: a robust approach to sustainable food security in Africa', *Food Security*, vol 2, pp. 197–214.

Giller, K.E., Tittonell, P., Rufino, M.C., van Wijk, M.T., Zingore, S., Mapfumo, P., Adjei-Nsiah, S., Herrero, M., Chikowo, R., Corbeels, M., Rowe, E.C., Baijukya, F., Mwijage, A., Smith, J., Yeboah, E., van der Burg, W.J., Sanogo, O.M., Misiko, M., de Ridder, N., Karanja, S., Kaizzi, L., K'ungu, J., Mwale, M., Nwaga, D., Pacini, C. and Vanlauwe, B. (2011) 'Communicating complexity: integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development', *Agricultural Systems*, vol 104, pp. 191–203.

Gockowski, J. and Sonwa, D. (2011) 'Cocoa intensification scenarios and their predicted impact on CO_2 emissions, biodiversity conservation, and rural livelihoods in the Guinea rain forest of West Africa', *Environmental Management*, vol 48, pp. 307–321.

Harris, D. and Orr, A. (2014) 'Is rainfed agriculture really a pathway from poverty?', *Agricultural Systems*, vol 123, pp. 84–96.

Jayne, T.S., Chamberlin, J. and Headey, D.D. (2014) 'Land pressures, the evolution of farming systems, and development strategies in Africa: a synthesis', *Food Policy*, vol 48, pp. 1–17.

Kassam, A., Friedrich, T., Shaxson, F. and Pretty, J. (2009) 'The spread of conservation agriculture: justification, sustainability and uptake', *International Journal of Agricultural Sustainability*, vol 7, pp. 292–320.

Khan, Z.R., Pickett, J.A., Berg, J. van den, Wadhams, L.J. and Woodcock, C.M. (2000) 'Exploiting chemical ecology and species diversity: stem borer and striga control for maize and sorghum in Africa', *Pest Management Science*, vol 56, pp. 957–962.

Lahmar, R., Bationo, B.A., Lamso, N.D., Guéro, Y. and Tittonell, P. (2012) 'Tailoring conservation agriculture technologies to West Africa semi-arid zones: building on traditional local practices for soil restoration', *Field Crops Research*, vol 132, pp. 158–167.

Lal, R. (2015) 'Sequestering carbon and increasing productivity by conservation agriculture', *Journal of Soil and Water Conservation*, vol 70, pp. 55A–62A.

Lehmann, J. and Kleber, M. (2015) 'The contentious nature of soil organic matter', *Nature*, vol 528, pp. 60–68.

Loos, J., Abson, D.J., Chappell, M.J., Hanspach, J., Mikulcak, F., Tichit, M. and Fischer, J. (2014) 'Putting meaning back into sustainable intensification'. *Frontiers in Ecology and the Environment*, vol 12, pp. 356–361.

Mtambanengwe, F. and Mapfumo, P. (2005), 'Organic matter management as an underlying cause for soil fertility gradients on smallholder farms in Zimbabwe', *Nutrient Cycling in Agroecosystems*, vol 73, pp. 227–243.

Palm, C.A., Gachengo, C.N., Delve, R.J., Cadisch, G. and Giller, K.E. (2001), 'Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database', *Agriculture, Ecosystems and Environment*, vol 83, pp. 27–42.

Petersen, B. and Snapp, S. (2015), 'What is sustainable intensification? Views from experts', *Land Use Policy*, vol 46, pp. 1–10.

Rouw, A. De and Rajot, J. (2004) 'Soil organic matter, surface crusting and erosion in Sahelian farming systems based on manuring or fallowing', *Environment*, vol 104, pp. 263–276.

Rowe, E.C., van Wijk, M.T., de Ridder, N. and Giller, K.E. (2006), 'Nutrient allocation strategies across a simplified heterogeneous African smallholder farm', *Agriculture, Ecosystems and Environment*, vol 116, pp. 60–71.

Rusinamhodzi, L., Corbeels, M., Zingore, S., Nyamangara, J. and Giller, K.E. (2013) 'Pushing the envelope? Maize production intensification and the role of cattle manure in recovery of degraded soils in smallholder farming areas of Zimbabwe', *Field Crops Research*, vol 147, pp. 40–53.

Sanchez, P.A., Jama, B.A., Vanlauwe, B., Diels, J., Sanginga, N. and Merckx, R. (2001) 'Soil fertility replenishment takes off in East and Southern Africa' in B. Vanlauwe, J. Diels, N. Sanginga and R Merckx (eds), *Integrated Plant Nutrient Management in Sub-Saharan Africa: From Concept to Practice*, CABI, Wallingford, UK, pp. 23–45.

Six, J., Conant, R.T., Paul, E.A. and Paustian, K. (2002) 'Stabilization mechanisms of soil organic matter: implications for C-saturation of soils', *Plant and Soil*, vol 241, pp. 155–176.

Sseguya, H., Semana, A.R. and Bekunda, M.A. (1999), 'Soil fertility management in the banana-based agriculture of central Uganda: farmers constraints and opinions', *African Crop Science Journal*, vol 7, pp. 559–567.

Stoorvogel, J.J., Smaling, E.A. and Janssen, B.H. (1993) 'Calculating soil nutrient balances in Africa at different scales', *Fertilizer Research*, vol 35, pp. 227–235.

TEEB (The Economics of Ecosystems and Biodiversity) (2010) *Ecological and Economic Foundations*, Earthscan, London.

Thierfelder, C., Mwila, M. and Rusinamhodzi, L. (2013) 'Conservation agriculture in eastern and southern provinces of Zambia: long-term effects on soil quality and maize productivity', *Soil and Tillage Research*, vol 126, pp. 246–258.

Tittonell, P. and Giller, K.E. (2013), 'When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture', *Field Crops Research*, vol 143, pp. 76–90.

Tittonell, P., Muriuki, A., Shepherd, K.D., Mugendi, D., Kaizzi, K.C., Okeyo, J., Verchot, L., Coe, R. and Vanlauwe, B. (2010), 'The diversity of rural livelihoods and their influence on soil fertility in agricultural systems of East Africa – a typology of smallholder farms', *Agricultural Systems*, vol 103, pp. 83–97.

Turmel, M.-S., Speratti, A., Baudron, F., Verhulst, N. and Govaerts, B. (2015) 'Crop residue management and soil health: a systems analysis', *Agricultural Systems*, vol 134, pp. 6–16.

Valentin, C., Rajot, J.-L. and Mitja, D. (2004) 'Responses of soil crusting, runoff and erosion to fallowing in the sub-humid and semi-arid regions of West Africa', *Agriculture, Ecosystems & Environment*, vol 104, pp. 287–302.

van Breemen, N., Mulder, J. and Driscoll, C.T. (1983) 'Acidification and alkalinization of soils', *Plant and Soil*, vol 75, pp. 283–308.

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K.E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K.D., Smaling, E.M.A., Woomer, P.L. and Sanginga, N. (2010) 'Integrated soil fertility management operational definition and consequences for implementation and dissemination', *Outlook on Agriculture*, vol 39, pp. 17–24.

Vanlauwe, B., Descheemaeker, K., Giller, K.E., Huising, J., Merckx, R., Nziguheba, G., Wendt, J. and Zingore, S. (2015) 'Integrated soil fertility management in Sub-Saharan Africa: unravelling local adaptation', *Soil*, vol 1, pp. 491–508.

Vanlauwe, B., Diels, J., Sanginga, N. and Merckx, R. (2005) 'Long-term integrated soil fertility management in south-western Nigeria: crop performance and impact on the soil fertility status', *Plant and Soil*, vol 273, pp. 337–354.

Vanlauwe, B., Nziguheba, G., Nwoke, O.C., Diels, J., Sanginga, N., Merckx, R. (2012) 'Long-term integrated soil fertility management in south-western Nigeria: crop performance and impact on the soil fertility status' in A. Bationo, B. Waswa, J. Kihara, I. Adolwa, B. Vanlauwe and K. Saidou (eds), *Lessons Learned from Long-Term Soil Fertility Management Experiments in Africa*, Springer, Dordrecht, the Netherlands, pp. 175–200.

Vanlauwe, B., Wendt, J., Giller, K.E., Corbeels, M., Gerard, B. and Nolte, C. (2014) 'A fourth principle is required to define conservation agriculture in sub-Saharan Africa: the appropriate use of fertilizer to enhance crop productivity', *Field Crops Research*, vol 155, pp. 10–13.

van Noordwijk, M. and Brussaard, L. (2014), 'Minimizing the ecological footprint of food: closing yield and efficiency gaps simultaneously?' *Current Opinion in Environmental Sustainability*, vol 8, pp. 62–70.

Wezel, A., Soboksa, G., McClelland, S., Delespesse, F. and Boissau, A. (2015), 'The blurred boundaries of ecological, sustainable, and agroecological intensification: a review', *Agronomy for Sustainable Development*, vol 35, pp. 1283–1295.

Worldbank (2007) *World Development Report 2008: Agriculture for Development*, The International Bank for Reconstruction and Development, Washington, DC.

Zingore, S., Delve, R.J., Nyamangara, J. and Giller, K.E. (2008) 'Multiple benefits of manure: the key to maintenance of soil fertility and restoration of depleted sandy soils on African smallholder farms', *Nutrient Cycling in Agroecosystems*, vol 80, pp. 267–282.

Zingore, S., Manyame, C., Nyamugafata, P. and Giller, K.E. (2005) 'Long-term changes in organic matter of woodland soils cleared for arable cropping in Zimbabwe', *European Journal of Soil Science*, vol 56, pp. 727–736.