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THE SUSTAINABILITY OF THE WORLD'S SOILS

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Introduction

Agriculture and food production are predominantly soil-based, with only marginal portions based on hydroponics or the use of only biomass as a substrate. In this chapter, the factors affecting sustainable soil use will be elaborated. This is defined as factors that:

- maintain or improve soil biological, chemical, and physical properties;
- maintain an input:output (harvest) ratio greater than one for all macronutrients;
- use nutrient inputs, preferably but not exclusively from renewable rather than non-renewable sources that seek to complement natural nutrient cycling; and
- permit the system to recover from the disturbances caused by cultivation and harvest (adapted after Schaller 1993).

To address and apply these themes, the attention of this chapter rests predominately on the situation in sub-Saharan Africa. There are good reasons for this geographical focus. In the twentieth century, the green revolution in Asia demonstrated that dramatic yield increases are possible in the poorer tropical regions, achieved by combining fertilizer inputs, better agronomy, improved pest management, soil water management and crop varieties (Huang et al. 2002). These, coupled with development of rural infrastructure, have sustained input supply lines and marketing and value chains. However, sub-Saharan Africa has neither experienced a green revolution nor has it the rural infrastructure or NARES to support agriculture to even keep pace with the food demands of the growing population. According to FAO (2012), sub-Saharan Africa is the only region with an increasing number of people suffering undernourishment, often with more than 25 per cent of the total population thus classified (FAO 2011). Sub-Saharan Africa has the world's lowest fertilizer application rates (Morris 2007) and one of the lowest percentages of irrigated agricultural land (FAO 2011). Thus the region is the most reliant on the nutrient and water-providing functions of soil, given the lack of replacement of nutrients by external inputs and the absence of irrigation at scale. Furthermore, this region has the highest food crop yield gaps globally as well as the lowest growth in the agricultural sector. Coelli and Rao (2005) conducted a study of 93 countries and demonstrated that those African countries had the lowest growth in total factor productivity (TFP) in agriculture between 1980 and 2000, however, certain individual countries, notably Nigeria had higher growth in TFP (FAO 2011), yet increasing food demand. While some other parts of the world have serious threats to soil sustainability because of over-fertilization and consequent pollution or high levels of soil erosion due to excessive mechanization, we shall focus our discussion mainly on sub-Saharan Africa or areas with similar agro-eco zones.

Background to traditional cropping systems

In sub-Saharan Africa, there are two core tropical agro-eco regions for agricultural cultivation: the savannah zones with mono-modal rainfall and a relatively short rainy season of no longer than six months and the humid forest zones with either mono- or bi-modal rainfall, yet with dry seasons no longer than four months. This chapter will first outline the traditional shifting cultivation system, and then describe systems with shortened fallows, replacement of natural fallows with managed or planted fallows, and those where fallow is no longer possible and continuous cultivation is necessary.

Still existing early forms of tropical agriculture used land in an extensive way by selectively removing vegetation by slashing, followed by burning, yet conserving part of the original vegetation. This ensures that after the cropping phase, fallow re-establishment is rapid. In many parts of West and Central Africa, such practices are enshrined in traditional laws affecting land use rights. For example, in southern Cameroon, *mvut* (*Trichoscypha acuminata*) and *tom* (*Pachypodanthium staudtii*) trees have to be conserved during clearing to gain exclusive control of the land (Diaw 1997). Likewise, it is forbidden to cut down *Garcinia kola* trees and thus they feature commonly in food crop fields (Fondoun and Tiki Manga 2000). In such fields, relatively shade-tolerant crops such as plantain (*Musa* spp. AAB), the cocoyams tannia (*Xanthosoma sagittifolium*) and taro (*Colocasia esculenta*) are grown. In the savannah, with fewer trees, light-demanding crops such as sorghum, millet and cowpea are dominant. In the past, crops such as African yam bean (*Sphenostylis stenocarpa*), bambara groundnut (*Vigna subterranea*) and various species of melon were more important. These systems were predominant at low human population densities and are still deemed sustainable. However, here it is important to distinguish between sustainability and productivity. The traditional systems were sustainable, meaning they were reliably producing crops sufficient to sustain farming households year after year. Systems relied upon long fallow phases during which soil chemical fertility was restored, weeds were smothered, pests and diseases were reduced or eliminated, and soil macrofaunal populations reestablished under the permanent shade (Hauser 1993). These processes stabilized soil physical and chemical properties. Soil macrofauna produce large biopores with high continuity, allowing rapid water infiltration during heavy rainstorms, thus avoiding or reducing soil erosion.

The total factor productivity of these systems is difficult to assess but is considered low. However, labour productivity was relatively high as the slash and burn system requires less labour over the crop cycle. From Latin America it has been reported that labour-intensive systems were abandoned in favour of shifting cultivation due to decreasing population densities.

The traditional system was used throughout the tropics, yet research on optimizing the trade-off between fallow length and productivity is rare and largely restricted to the Congo region. Laudelout (1990) summarized fallow research work conducted at Yangambi, during the first half of the twentieth century and calculated that at 20 people km^2 and a minimum fallow period of 12 years, the system is sustainable and these criteria are likely to apply to the larger part of the Congo Basin. In West Africa, Nye and Greenland (1960) related sustainability of shifting cultivation systems directly to population density and estimated the limit to be 7.8 people km^2. In contrast, an earlier report from south west Nigeria indicated that land was cropped for 3–4 years then left fallow for 3 years at most and soil fertility maintenance was reported to be due to the activity of *Siphonogaster* earthworms (Millson 1891), although the predominantly Alfisol soils of this area are of relatively high fertility. The large difference in estimates indicates that there may be strong effects of site and climate and the dominant crops. However, these issues have not been sufficiently researched.

Population densities have exceeded these thresholds across most of the tropics. The most common response has been that smallholders have shortened the fallow length: for example, Van Vliet et al. (2012) conducted a recent global review of shifting cultivation systems and found that more than 80 per cent of studies reported declining fallow lengths. Following the principle proposed by Guillemin (1956) of declining soil fertility replenishment with shortened fallow length, the food production per unit area should start to decline over several crop/fallow cycles. Yet, there is little evidence for real yield declines due to reduced fallow length. For example, Mertz (2002) did not find a significant relationship between previous fallow length and crop yields. The yield declines experienced by farmers are most likely due to the number of crop/fallow cycles the land has undergone and the declining fallow occupation time to crop occupation time ratio. For more detailed information on slash and burn systems, farmers' reasons to use it, options to intensify and stabilize and their effects on the ecosystem and productivity consult: Jurion and Henry (1969); Nyerges (1989); Peters and Neuenschwander (1988); Thurston (1992); and Hauser and Norgrove (2013).

Factors and processes affecting soil sustainability

Soil inherent factors affecting sustainability

Soils in the tropics developed from various parent materials, which affect the soil quality and the susceptibility to degrading processes. In West Africa, most soils are basement complex soils developed on the parent materials granite or gneiss, rocks of low nutrient status and thus producing poor soils. There are a few areas with basaltic parent materials producing more fertile soils and even fewer areas are covered with younger volcanic (basaltic) ashes. Although the same parent materials are present in Asia and South America, these regions have larger proportions of soils from basaltic parent materials (Vertisols in India) and volcanic ashes (islands of Java, Bali and others of the Indonesian archipelago) and a larger portion of soils are not as old as the SSA region.

The age and rainfall regime are two important factors determining soil quality. The older and the more exposed to rainfall, the more weathered the soils. Excess rainfall leaches minerals and nutrients from the topsoil into deeper layers inaccessible to plant roots. West and Central African soils are predominantly old, up to 200 million years, and have been exposed to high rainfall for most of that development time. Accordingly, many soils are highly weathered and inherently nutrient poor, with a dominance of kaolinitic clay minerals, which have very low cation exchange capacity, thus lacking a major prerequisite to retain nutrients in the soil.

Erosion, run-off, leaching and compaction

The principles of soil erosion control are well understood and measures have been developed to reduce or avoid erosion. In Ethiopia, erosion control using stone bunds is effective yet was not widely adopted due to the high labour requirements of construction. In urban vicinities of eastern DR Congo, cropping on steep slopes without any measures to prevent erosion has caused almost complete loss of the topsoil, rendering the land unsuitable for any crop, yet there is no response to reduce or stop the practice. Important here is to mention, that all other measures to retain fertility and crop productivity rely on the topsoil being preserved.

Run-off is the removal of dissolved substances, such as fertilizer, through the horizontal flow of surface water without the removal of soil. Usually run-off precedes soil physical erosion and both contribute to soil organic matter and nutrient losses. Avoiding run-off can be attained by the same measures as to control erosion. However, the contribution of run-off to nutrient loss is pronounced in systems where fertilizer is used and under conditions of high rainfall intensity.

Leaching – the transfer of dissolved materials through the soil matrix into deeper soil layers from which food crops and fallow species cannot recover nutrients – is a process leading to soil degradation. Long-term (geological time frame) leaching is responsible for soil development and the loss of minerals leaving only the most resilient materials. Short-term leaching is currently a major process leading to nutrient losses from inputs. Farmers have practically no means to control such losses as they depend on rainfall amounts and intensity.

Compaction of soils occurs when natural vegetation cover is removed and the soil is exposed to direct impact of rain. This process is not directly contributing to nutrient losses but can increase losses through run-off and erosion, particularly when soil porosity and pore continuity are low and so do not allow rain to penetrate the soil but lead to ponding water at the soil surface. Compacted soil hampers growth of most crops and thus has other negative effects such as reduced plant biomass production, delayed canopy cover, fewer roots to break up compacted soil and higher human labour requirements for tillage and harvesting of root and tuber crops.

Fallow length and vegetation management

The traditional shifting cultivation system removes biomass by burning, thus retaining only the ash and some charcoal residues. In most systems, the soil is clean and friable after the burn and does not require tillage to plant crops such as cooking bananas, plantain, cocoyam, cassava, maize, upland rice or melon. Weed control is achieved as the burning of large quantities of biomass heats the soil surface to lethal temperatures, killing most weed seeds and small stumps of shrubs and trees. Thus, labour requirements to maintain fields after planting are low and fertility due to the large amounts of ash and the high soil organic matter (SOM) levels was sufficient to supply crops, while pest and disease pressure is low due to the long-term absence of crops serving as hosts.

With fallow length being shortened, the effects of these factors change. Vegetation does not recover to the same type and species composition and certain species may not appear in the fallow any longer. The amount of biomass will be lower and specifically the amount of woody biomass may be reduced. Thus the burn will be less intensive and weed control less efficient. Furthermore, weed seeds may survive the shorter fallow and a weed seed bank may build up, contributing to more severe weed infestation. Less biomass will contain less ash and thus return lower amounts of nutrients, specifically potassium, magnesium, calcium and phosphorus to the soil. This is combined with less SOM accumulated and thus lower levels of soil fertility. However, retention of the biomass as mulch is not a realistic option because the material is mostly of such a structure that it will hinder planting, seeding and weeding operations.

Soil management and tillage

Smallholders respond to these less favourable soil properties by introducing tillage. Tillage may be primarily related to crops, such as groundnut, that require the mixing of ash into the soil and loose topsoil yet retains the flat surface. Other forms of tillage, such as mounding or ridging concentrate richer topsoil around the crops yet shape a new surface on which water flow is directed. In many regions farmers ridge up and down the slope thereby creating channels that may lead to more run-off than ridging perpendicular to the slope. Another effect of tillage is that it acts as an early weed control measure. As land use frequency increases more weeds survive the fallow phase and the reason for tillage shifts more towards weed control which becomes more important as soil fertility declines and nutrients need to be 'reserved' for crops by early removal of weeds. However, tillage reduces aggregation, reduces pore continuity and exposes the soil to physical degradation, primarily to erosion, run-off, compaction, and waterlogging, depending on slope and soil texture.

Crop growth, canopy closure and soil protection

Crops grow relatively slowly in the early stages, leaving the soil for a long phase unprotected against impact of rain and thus erosion and run-off (see the discussion above). It is often the weed flora that contributes to soil protection before the crop canopy is sufficient to cover the soil. However, weed infestation indicates competition, leading to yield losses even if the weeds are controlled later. Crops such as cassava, often planted at low densities (<10000 ha^{-1}) may take three months for canopy closure. Weed infestation during the first three months has been shown to be detrimental and thus early weeding is recommended. Most smallholders weed manually and remove weed residues from the field, thus increasing soil exposure to rain and creating a high risk of erosion, depending on slope and soil type. In many areas, specifically where rainfall is high and frequent weeds are removed from fields to avoid them recovering and growing, thus biomass that could serve as mulch and SOM and nutrient source is removed, exposing the soil. Intercropping a fast with a slow growing crop is frequently practiced and this, inadvertently, can protect the soil as well as achieving higher overall system productivity. This, in turn, will often lead to higher biomass production and thus more crop residues and future mulch. Crop residue retention or mulching with biomass from external sources (cut & carry) has been shown to be highly effective in soil protection to physical degradation and in producing higher crop yields as long as a minimum amount of biomass (5–7 Mg ha^{-1}) was applied.

Crop nutrient uptake and export

Improved varieties of food crops, specifically those with high harvest indices (HI) and those with several plant organs or parts being regularly harvested and removed from fields, result in large quantities of nutrients exported from the field. The same applies to cropping systems that allow for several crops per year such as irrigated rice. Cassava (*Manihot esculenta*) attains a root HI of >50 per cent, on a fresh mass basis, and stems are also removed to provide new planting material. In southern Cameroon, cassava exported five times more K than maize, and 10 times more than groundnut on a per hectare basis. Cassava exports of P, Mg and Ca also exceeded those of maize and groundnut (Hauser, unpublished). Total K uptake into these three crops was similarly high, indicating that nutrient retention and cycling is better in maize and groundnut and that cassava is likely to exhaust the exchangeable K reserves more rapidly than other crops. Such exports may require fertilizer application to balance losses, specifically in situations where there is little nutrient return to fields through manure, as is the case in most of the humid forest zone across the tropics.

Improving food security will rely on increasing yields and thus improved germplasm, yet the consequences of increased nutrient export need to be considered and measures taken to avoid deficiencies that will compromise future food production. While it is possible to add N through legumes and symbiotic N_2 fixation, all other elements need to be retained or replenished either through tightening nutrient cycling or imported through use of biological materials or mineral fertilizer.

Legume integration: how beneficial is N_2 fixation?

Legumes that nodulate and fix N_2 may benefit the N balance of a soil. There has been much research on N_2 fixation in grain legumes, yet less in cover crops or green manure legumes. These two legume types have different purposes and thus potentially different effects on soil N, fertility and on following crops and system sustainability. Most studies on N_2 fixation in grain legumes show that the largest portion of the fixed N is exported with the grains, leaving little or no positive N balance. This is very different in green manure or cover crop legumes, which are not harvested but retained on the land and thus return the entire amount of fixed N_2 to the soil. A commonly used cover crop, *Mucuna pruriens*, may fix between 40 (Houngnandan et al. 2000) and 250 kg ha^{-1} of N (Sanginga et al. 1996). The lower of these estimates is approximately the same as the amount that less fertile soils naturally supply (Hauser and Nolte 2002). More fertile soils may supply up to 90 kg ha^{-1} N from soil sources (Grove 1979). Thus the higher estimates of fixed N by cover crops exceed N supply from the soil and uptake of most annual crops, thus could contribute to soil N accumulation if N losses are limited. However, although benefits may be realized through leguminous cover crops the time they occupy the land without making a contribution to food production and revenue generation has to be considered a cost. Furthermore, despite their benefits, adoption of cover crops remains low in SSA and SE Asia with most farmers arguing that the effort to establish cover crops is not remunerated directly. Livestock integration and use of cover crops as feedstock may improve such lack of revenue, yet there has been no research on the consequences of browsing on biomass production and N_2 fixation and long-term effects on the soil in cover crop systems.

Soil maintenance in shortened fallow cycles

Here some of the major consequences of shortened fallows and measures taken to counter the lack of soil fertility replenishment will be discussed.

Consequences of vegetation shifts

The use of shorter fallows may cause shifts in vegetation composition. With less time available, certain species are not able to establish and reach reproductive stages, thus they disappear over a number of cycles from the fallow. The number of species affected increases as fallows progressively shorten and can ultimately lead to arrested succession and the permanent establishment of grassland on previously forested land. At the same time, the absence of plant cover permits invasive species to establish in the cropping phase. Such species would be eliminated in long fallows yet may survive short fallows, such as in the case of *Chromolaena odorata* that took over vast swathes of fallow vegetation across most of humid West and Central Africa. Generally, as fallows are shortened, they become less effective as weed breaks, as the fallow time may no longer exceed the maximum longevity of the weed seed bank. Thus weeds may be present at the start of a cropping phase, causing higher weed pressure and demanding more intensive or frequent weeding. Biomass management practices still rely on burning as it is labour efficient. While burning could potentially prevent the immobilization of N in fallows dominated by vegetation with a high C:N ratio, it can have the opposite effect. For example, the low-N grass *Imperata cylindrica* can dominate fallows across the tropics, yet it is selected for by repeated burning because it can resprout from underground rhizomes and, being light sensitive, will grow faster on exposed soils.

Planted fallows

To allow for shorter fallow phases yet attain soil fertility restoration, planted fallow systems were developed that were expected to recover soil fertility faster than natural fallows. Such systems use trees or shrubs to form the fallow vegetation which are cut back during cropping phases yet are retained alive to allow rapid growth at the end of the cropping phase. Other systems use herbaceous cover crops, often legumes such as *Mucuna pruriens*, *Pueraria phaseoloides* or *Stylosathes* spp., to replace natural fallow or invasive species. For cover crops, live and dead mulch systems were tested in which the cover crop was maintained through or killed before cropping phases, respectively.

In South America various types of the maize/mucuna system are common and widely adopted as they keep maize production at reasonably high levels at relatively low input, with mucuna smothering weeds as an added benefit. In SSA, research has shown the potential of these systems to maintain crop yields in short fallow/crop cycles and to attain higher crop yields than natural fallows of the same length (Hauser et al. 2006). Despite such potential, none of these systems has been adopted at scale, as labour requirements exceed those of the natural fallow and farmers have not chosen to invest in labour for the potential yield gains. Even a system in which a short-term crop, such as maize, that can be grown every year, using the remaining time to fallow with cover crops (Hauser et al. 2002) has not been adopted.

Tree-based planted fallow systems using *Leucaena* and *Gliricidia* were developed and used a long time ago in high population areas of Java. The tree rows stabilized soils on slopes, produced mulch, browse and firewood and the interrow space was used for crops. The transfer of the system to SSA, however, failed although the positive effects on soil fertility and structure could be shown. However, the yield increments of the alley cropping system on Alfisols and Ultisols were too low and labour requirements were too high. Indigenous soil management systems in SSA were found in south eastern Nigeria with planted *Dactyladenia barteri* trees (Stamp 1938) presumably to replenish fertility and control weeds and in north west Cameroon with *Tephrosia vogelii* to control erosion on steep slopes and add fertility.

In South America *Inga*, *Erythrina* and other species are used to replenish soil fertility and protect the soil surface.

Crop: fallow type compatibility

Certain fallow types favour specific crops. Cassava has been reported to respond negatively to cover crops, on the contrary, significant yield increases of maize have been achieved when grown after cover crops. In most of the West and Central African humid zone, plantain (*Musa* spp. AAB) is preferably grown after clearing forest or old bush fallow. Planting plantain after short bush fallow leads to drastic yield losses. For other crops farmers noted that bush fallow was beneficial. One such example is from Cameroon, where farmers prefer *Chromolaena odorata* dominated fallow for their most common field type, a groundnut, maize, cassava intercrop (Büttner and Hauser, 2003).

Ensuring crop–fallow compatibility is particularly important when planted fallow species are introduced. When *Sesbania sesban* was introduced into the western Kenyan bean/maize rotation, it caused major problems as it propagated *Meloidogyne* nematodes that caused yield losses in the bean crops (Desaeger and Rao 1999). Although little is known about the biophysical sustainability of such systems, it is clear that farmers assess these systems more by their ability and reliability to produce adequate crop yields against the amount of labour that is required to clear and maintain crops in such fields.

Livestock integration, nutrient cycling and fallow use efficiency

Recent surveys and stakeholder consultations across East, Central and West African countries revealed a strong interest of smallholders in integrating livestock into their farming systems. Although the reasons for such requests may vary, manure is a valuable source of organic matter and nutrients. Livestock integration is a measure to increase and potentially tighten nutrient cycles as well as accessing nutrient sources that would otherwise not become available for crop fields. Depending on the animal and its feed requirements, materials such as crop residues, weeds, unused fallow and 'waste land' vegetation are being used and returned as manure. The manner in which livestock is kept is decisive for the quantity and efficiency of nutrient cycling. Well-managed and corralled livestock would reduce losses to cropland and potentially increase nutrient stock depending on the proportion of feed foraged from outside the cropped area. Livestock may be a critical component to overcome problems of adoption of planted fallow systems (see the section in this chapter on *Planted fallows*) if the fallow can be used as forage specifically in phases when natural vegetation is short such as in dry seasons and short before the start of a cropping cycle. Corralling livestock on cover crop fields would ensure conversion to and retention of manure to improve soil quality and potentially reduce labour for land clearing and preparation before planting. Animals would improve food security, nutritional quality and income generation. However, a major constraint to their use in West and Central Africa include the presence of tsetse flies limiting the area suitable for cattle.

Complementing nutrient cycling and organic sources with fertilizer

In shortened fallow systems, the soil regenerating processes still contribute to the maintenance of the ability of the soils to provide nutrients to crops. However, depending on soil type and fallow length, some specific elements may be deficient and limit yields in certain crops. Under such conditions, application of fertilizer of a particular composition, such as NPK 15:15:15, may not supply sufficient amount of the most limiting nutrient and relatively oversupply other elements. Considering the high risk farmers take when investing capital, it is likely that in many cases the fertilizer available in the market cannot profitably provide the nutrients required. Further, crops may need different elements at different times in different quantities, fixed fertilizer compositions cannot cater to such changing demands. Single nutrient fertilizers, except for urea, are uncommon in SSA. More fertilizer blends for specific crops and sites are required to improve fertilizer use efficiency and profitability and thereby their use and positive impact on soils. From the savannahs of West Africa, it is known that a crop like soybean requires mainly P supplements to attain high yields (provided effective rhizobia are present). Often, rather small quantities are required to balance a deficiency leading to profitable yield increases (Chiezey 2013). However, research still has to catch up on assessing nutrient deficiencies at scale and develop site-specific fertilizer recommendations. Only if farmers see the profits reaped from investing in fertilizer will it be possible to produce more food and more crop residue. While food crop sales permit reinvesting in soil fertility, more crop residues are directly contributing to soil quality as long as they are retained. Fertilizer companies are yet to join research to develop a wider range of fertilizer blends to suit the varying demands of crops and soils.

Soil maintenance in continuous cropping systems

With increasing population densities and increasing demand for food, fiber, fuel and other agricultural products it is to be expected that more land will be cropped continuously and that the strain on the soils' natural resources will increase. Sustainable intensification measures are needed as population pressure increases. Through improved soil fertility management comprising the application of manure or fertilizer, integration of legume crops and the use of soil amendments such as biochar, the positive effects of fallow may be replaced. If smallholders do not use inputs either due to poor access or lack of capital, continuous cropping leads to soil depletion, declining yields (Vanlauwe et al. 2014), and thus lower incomes and may lead to marginalization.

Obviously under such conditions, smallholders may not be able to address all constraints adequately and thus may need to prioritize which constraint is the most threatening. It appears that smallholders do not or cannot sufficiently invest in retaining their production base even if land use intensity allows no longer for fallow.

Fertilizer use

Fertilizer use is the easiest measure to balance nutrient deficiencies and maintain yields at sufficiently high levels. However, not all crops respond sufficiently positively to fertilizer and with increasing energy costs, and increasing scarcity of fertilizers such as phosphates, projected to be depleted within 100 years (Cordell et al. 2009), fertilizer will become more expensive, increasing smallholders' risk of not recovering their investment. In the Nigerian savannah zone, maize production is today heavily reliant on timely supply of fertilizer and past research on fertilizer use enabled farmers to attain grain yields of 4–5 Mg ha^{-1}. However, according to members of a large farmer association, these high yields could not be maintained and have dropped to around 3 Mg ha^{-1}. Continuous cropping and the use of only NPK fertilizer have apparently led to deficiencies of other elements or SOM decline and poor nutrient retention in the soil. Fertilizer suppliers are not sufficiently involved in research to modify their blends to balance for such deficiencies and many farmers' response was to increase NPK application, thereby taking a higher risk of economic shortfalls. Application of Mg and Zn increased yields by around 10 per cent (Hauser, unpublished) at the standard recommended NPK rate. Thus fertilizer, as it is available in the market, should not be considered a sustainable measure to maintain crop yields and soil nutrient balances but should be looked upon as a tool that requires constant adjustment in composition and quantity to supply all essential nutrients as it is to be assumed that in continuous cropping the contribution from soil resources becomes marginal.

Most recent approaches on fertilizer recommendations move away from 'blanket application' and use site-specific information to estimate fertilizer rates according to soil properties, yield targets and farmers' resource endowment. However, these nutrient management systems are not yet available for most sites and many crops.

Manure and other organic nutrient sources

Crop residues are commonly used in intensified systems to return SOM and nutrients to the soil, yet often biomass production is low. Furthermore, several competing uses of biomass (mainly crop residues) limit their use as mulch, which has several purposes such as protecting the soil surface from impact of rain, fostering soil faunal activity and through decomposition providing nutrients to crops. If biomass is used as livestock feed, the benefits of mulch are lost and the impact of biomass recycling is reduced to SOM and nutrient return through manure. The optimum use of biomass will be context-specific.

Livestock manure is a valuable SOM and nutrient source. However, livestock keeping and feeding poses severe problems in many areas as uncontrolled livestock browsing in crop fields can cause damage and crop loss while keeping animals in enclosures requires hauling feed to the paddock and thus labour. The impact of manure versus mulch or other biomass uses, such as biochar (see below), on soil fertility and sustainable crop production as well as overall livelihoods is difficult to determine and dependent on local conditions.

Biochar

In regions where dominant soil types comprise those of low activity clays, with limited cation exchange capacity, the role of mineral fertilizers is limited. The discovery of anthropogenic dark earths in South America and West Africa has triggered research on biochar. Biochar is the carbon-rich solid formed by heating organic materials in the absence of air (pyrolysis) and can be used as a soil amendment (Woolf et al. 2010). Biochar application to soils with low CEC and low SOC can increase the nutrient holding capacity of such soils and thus can increase crop yields or reverse yield declines (Kimetu et al. 2008). However, the magnitude of effects is soil-dependent. A meta-analysis by Jeffery et al. (2011) found that the greatest positive effects were found on acidic to neutral soils with a coarse or medium texture. They deduced that positive yield effects were due to a soil liming effect and an improvement in water-holding capacity, as well as increased nutrient availability. However, the production of biochar requires biomass, which is usually in short supply in areas with dominantly continuous cropping. Biochar has various effects on soils and is in itself of such structure that nutrient retention may be increased. However, it remains to be determined what quantities of biochar are required to attain sustained yield advantages.

Indicators of soil sustainability

Measuring the sustainability of soils remains a challenge due to the large number, the wide range and the lack of information on the ranking of parameters that play a role in sustaining soils' ability to support crop growth. In addition, while the biophysical sustainability may be considered most important as the basis of future food production, the economic and social aspects of sustainable soil use may not be neglected as they may be major obstacles to the implementation of soil protecting and fertility conserving or rehabilitating measures.

Crop yields

Crop yields have been used as simple and highly relevant indicators of soil quality. However, with changes in land use, crop management and specifically nutrient inputs, it becomes difficult to assess which factors contribute which portion to the crop yield. Further, changes of crop varieties, specifically when pest or disease problems are tackled through tolerant or resistant germplasm, may contribute to large yield increases without a major contribution from the soil. Declines in soil quality that would appear as declining yields when varieties are not changed may be masked, at least temporarily, by better performing varieties. At the same time, better performing varieties may be able to acquire more nutrients from the soil and thus accelerate soil degradation. Thus crop yields may not be suitable long-term indicators.

Erosion and run-off

The absence of erosion and run-off is a good indicator of sustainability. Although erosion is often easily recognized, it is difficult to quantify and also to assess the degree of run-off and the nutrient load removed from fields, which can be highly variable where fertilizer is applied. Run-off with high nutrient loads is not only a loss to the soil and crops but can have severe negative off-site effects if water bodies or groundwater is polluted. As such, it has to be considered that sustaining soils makes a potentially important contribution to the sustainability and 'health' of entire catchments. Although acceptable and critical levels of erosion have been proposed, it is not known if at such levels the soils' sustainability is ensured.

Soil chemical properties

Soil chemical properties appear to be easily determined through standard analysis for the essential nutrients and the SOM. Although this is regarded and accepted as a straightforward approach, concentrations of nutrients in a particular soil layer alone do not constitute a good measure for the amount of nutrients available to a crop. As sustainability needs to be evaluated or quantified over time, changes in the soil mass considered in the chemical analysis can bias results. Many results on changes over time in soil chemical properties have been obtained by the simple multiplication of nutrient concentration with the bulk density of the analysed soil layer, without considering that changes in bulk density cause over- or under-estimation of the changes depending on increases or decreases in bulk density. Wendt and Hauser (2013) demonstrated for organic carbon (OC) that 'this method systematically overestimates OC stocks in treatments with greater bulk densities such as minimum tillage, exaggerating their benefits. Its use has compromised estimates of OC change where bulk densities differed between treatments or over time periods' (Wendt and Hauser 2013). Thus, in addition to selecting suitable indicators, the analytical methodology needs revision and new standards need to be agreed upon before reliable data on soil sustainability can be obtained.

Conclusion

The ability of soils to support crop growth is threatened in much of the tropics by erosion, run-off, compaction, nutrient depletion, loss of soil organic matter and a decline in soil faunal activity. Land use frequency and intensity are increasing and accelerating soil degrading processes. For erosion and run-off, control measures are well known. Yet, affordable, simple, farmer-friendly implementation approaches are missing. More applied and farmer community participatory research is required to overcome these problems.

Nutrient deficiencies are commonplace in much of the tropics. Fertilizer application could provide a solution, yet the infrastructure of supplying fertilizers, and knowledge on the type (elemental composition), quantity and timing of fertilizer use needs major improvement to convince policy makers to promote its use and farmers to invest in fertilizer. New approaches, such as site- and crop-specific decision support systems should be the foci of future research, thus maximizing fertilizer use efficiency while avoiding any negative impact on soils and the environment.

Higher level system integration by combining crop production, livestock and optimized crop residue, manure and biological refuse use, should receive more research attention. So should the expansion of precision agricultural techniques to poorer tropical countries, allowing the optimization of fertilizer application to combat soil nutrient heterogeneity. Change and growth in other sectors is also essential as the lack of industrial development and consequent dearth of job opportunities maintains the general labour value at such a low level that it is not economically

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efficient for farmers to substitute labour for technology. Farmers' willingness to invest in soil quality is thus apparently low as they need to eke a living out of limited resources, thus only measures with immediate effect on food security and income appear likely to be adopted.

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