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SLU Global

Review of interventions and technologies for sustainable intensification of smallholder crop production in sub-humid sub-Saharan Africa

– with an assessment of effectiveness of selected options on differently endowed case study farms

A working paper

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Review of interventions and technologies for sustainable intensification of smallholder crop production in sub-humid sub-Saharan Africa

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Abstract

Besides low soil fertility, climate variability has often been identified as the major constraint to agricultural productivity in Sub-Saharan Africa (SSA), with rainfall variability (both within and across seasons) being the most critical. Traditionally, reasonable yields could be achieved in spite of constant or smaller resource inputs by expanding the cropped area, but this is no longer a viable option. Crop production intensification is required to produce more food per unit of input and land, while maintaining or rebuilding soil fertility. However, most smallholder farmers lack access to resources such cash, fertiliser and technological expertise to address constraints caused by the biophysical environments in which they operate. The objective of this review was to collate and appraise the range of crop production intensification options that have been developed for smallholder farmers in SSA. A case study from central Mozambique was included to illustrate the impact and relevance of locally feasible options to farmers who own different resources. The study has revealed that sustainable intensification of crop production requires that multiple constraints are addressed simultaneously, in this case primarily soil fertility/plant nutrient supply and weed management. Success of crop intensification options will also depend on proper targeting to different farm types as well as field soil fertility gradients. Although smallholder farmers in SSA have limited assets, the case study revealed the occurrence of local opportunities to increase current crop productivity which in some cases do not need substantial capital inputs by the farmers, but more efficient use and targeting.

Contents

1. Introduction

Agricultural production needs to be increased to meet the food needs of a growing population in many Sub-Saharan African (SSA) countries where smallholder farms are dominant. Food security on these smallholder farms remains elusive due to the problems of high rainfall variability, soil fertility decline, rising prices or unavailability of fertilizers, compounded by limited availability of key resources such as land, cash and labour, high rates of rural poverty and inappropriate solutions being prescribed (Fig. 1; Giller et al., 2006; Giller et al., 2009; Sanginga and Woomer, 2009). This situation is exacerbated by a rising population pressure which demands the production of more food using fewer inputs on smaller pieces of land (Koning and van Ittersum, 2009), making agricultural systems such as shifting cultivation which are still prevalent in some areas in SSA unsustainable and irrelevant. Increasing population pressure leads to changes such as decreasing farm size and increasing urbanisation. Intensification of farming systems is thus required to meet current and future food demands of rural as well as urban populations. At the farm level there is need to produce surplus that can be sold to bring income. Such intensification can be achieved by increasing yields per unit area and input, increasing the number of crops (i.e. two or more crops) per unit area, and changing land use from low-value to higher-value produce (Pretty et al., 2011). To achieve ecological sustainability, crop production systems need to be developed that use nutrients, water and other resources more efficiently and have positive biophysical and socio-economic externalities. A particular challenge for improving agricultural productivity in SSA is to build and maintain soil fertility despite low incomes and land and labour constraints faced by smallholder farmers (Kumwenda et al., 1997).

African smallholder farming systems are complex, dynamic systems with many interacting biophysical components along a wide range of soil, climatic and socio-economic conditions (Tittonell et al., 2005a; Tittonell et al., 2005b; Zingore et al., 2007a). Under these circumstances, there is need for an understanding of the interactions of the components that are unique to each farming systems in order to identify appropriate resource management strategies for improved crop production and system sustainability. Modelling and simulation tools help in identifying opportunities in smallholder farming systems and identifying options for improved resources management. Modelling tools to predict the longer-term effects of suggested interventions and technologies may be used to enhance the ex-ante understanding of their impact and to enable more efficient use of resources. It is important that these modelling tools have a balanced description of the socio-economic and biophysical components of the system and are applicable in many situations (Tittonell et al., 2007a). One such tool developed in the context of African smallholder farmers is the integrated crop-livestock model NUANCES-FARMSIM (van Wijk et al., 2009). With the aid of this tool, the effects of allocation of limited resources such as organic matter, plant nutrients and labour within the farm can be explored.

In this paper, we review interventions and farm technologies suggested for sustainable intensification of crop production in the sub-humid areas of SSA. Focus will be on farmers´ opportunities to strategically allocate the limited local resources available as well as external interventions for increased crop productivity and soil fertility improvement. Although enhanced integration of animal and crop production has potential to improve overall farm productivity, in this report we do not focus on animal production per se but we highlight its importance where necessary e.g. the direct influence livestock manure or fodder crops on soil fertility and crop productivity. Current knowledge is reviewed and scenarios developed using identified best fit options for increased productivity. Long-term effects of selected options on crop productivity and soil fertility are analysed and explored using the NUANCES framework and farm resource flow data for three case study farms with different resource-endowment in central Mozambique. Multiple goals, conflicts and trade-offs are discussed and possible solutions are suggested where possible.

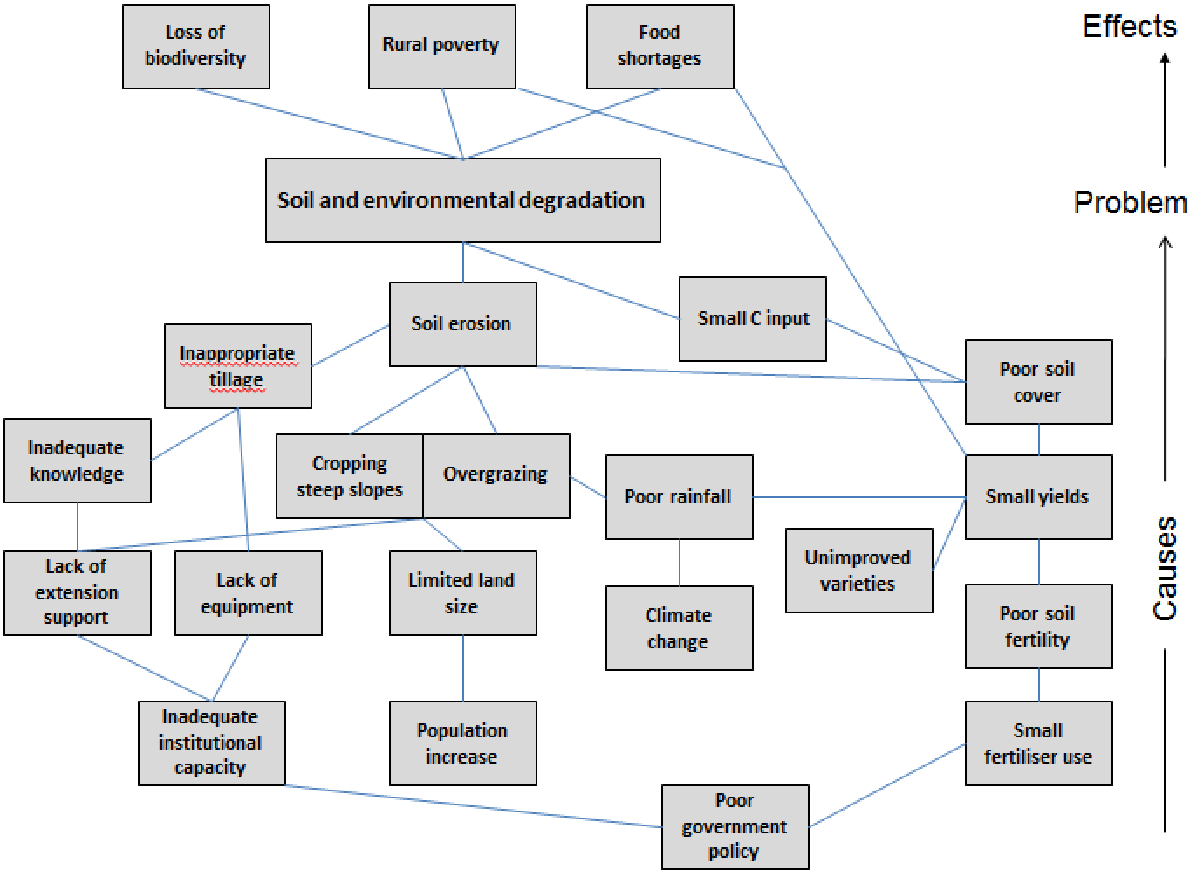

Figure 1. The linkages and relationships between some of the causes of soil and environmental degradation which leads to poor crop productivity, rural poverty and loss of bio-diversity on many smallholder SSA farms.

2. Background

Poor soil fertility status and limited options to address it are perennial challenges in most African smallholder farming systems. The situation is exacerbated by the fact that most soils in SSA are developed from very old bedrock (Jones et al., 2013). As much of the land surface has been geologically stable for millions of years, time has allowed development of deeply weathered soils with low inherent fertility. Also large areas of soils developed from relatively recent sediments, such as the wind-blown Kalahari sands, are characterised by low fertility in spite of being younger. There are, however, also some areas with more fertile soils developed from younger and relatively base-rich bedrock, e.g. in parts of the Rift Valley.

The sub-humid zones of SSA are dominated by mixed crop-livestock systems based on maize (*Zea mays* (L.)) and cereal-root crop mixed farming system (Dixon et al., 2001). Traditionally, slash and burn systems have existed in large areas with long-term fallowing used for soil fertility regeneration. However, fallowing periods are becoming increasingly shorter and the systems are frequently unsustainable (Raintree and Warner, 1986). Farmers have pursued different paths to overcome the limitations posed by decreasing soil fertility and climatic volatility. In spite of extension services advocating different routes to intensification and diversification, a historically common approach has been to expand the cultivated area without using nutrient inputs leading to labour intensive systems. In such situations, labour may become very limiting, and ploughing, sowing, weeding and harvesting may not be carried out to a sufficient intensity or at the correct time.

Despite the large variability between individual farmers and farm households, smallholder farming households in SSA can be successfully grouped into different farm types reflecting their overall resource endowment and livelihood strategies (Tittonell et al., 2005a; Tittonell et al., 2010a). Such farm typologies in a chosen physical location provide a starting point for formulating informed recommendations. Generally, two typology development pathways are distinguished: (a) structural household typologies - grouping of households using wealth indicators, which are often used when farmers classify themselves through participatory wealth rankings (e.g. Mango, 1999), and (b) functional typologies - that also consider the dynamics of production orientations and livelihood strategies, which may improve the categorization of households (e.g. Tittonell et al., 2010a). Important variables for creating typologies include characteristics of the household, labour availability, main source of income, farm land use patterns, market participation, use of agricultural inputs, food security, livestock ownership, and production orientation. The typologies range from relatively wealthy households that to a large extent rely on off-farm income, over similarly wealthy farmers growing cash crops partly with the aid of employed labourers, over medium endowed but basically self-sufficient farmers and households that rely to some degree on off-farm or non-farm activities to poor households making a living through selling labour (e.g. to the wealthier farmers) (Fig. 1). The capacity and ability of farmers belonging to the different typologies to adopt new farm technologies can be expected to vary greatly.

Within the farm, field typologies can also be created based on soil sampling and analysis. Field typologies arise mainly due to previous preferential nutrient allocation and other management decisions during crop production (Tittonell et al., 2007b; Zingore et al., 2007a; Zingore et al., 2007b; Zingore et al., 2011). Field typologies have immediate practical implications to informing better targeting of nutrient resource allocation for farms with different background soil fertility, especially when there are large soil fertility gradients within farms. In this review we present the use of farm typologies in improving targeting of crop production intensification options, and the long-term impact and sustainability of these options are explored for low-input farming systems of Mozambique using three case study farms.

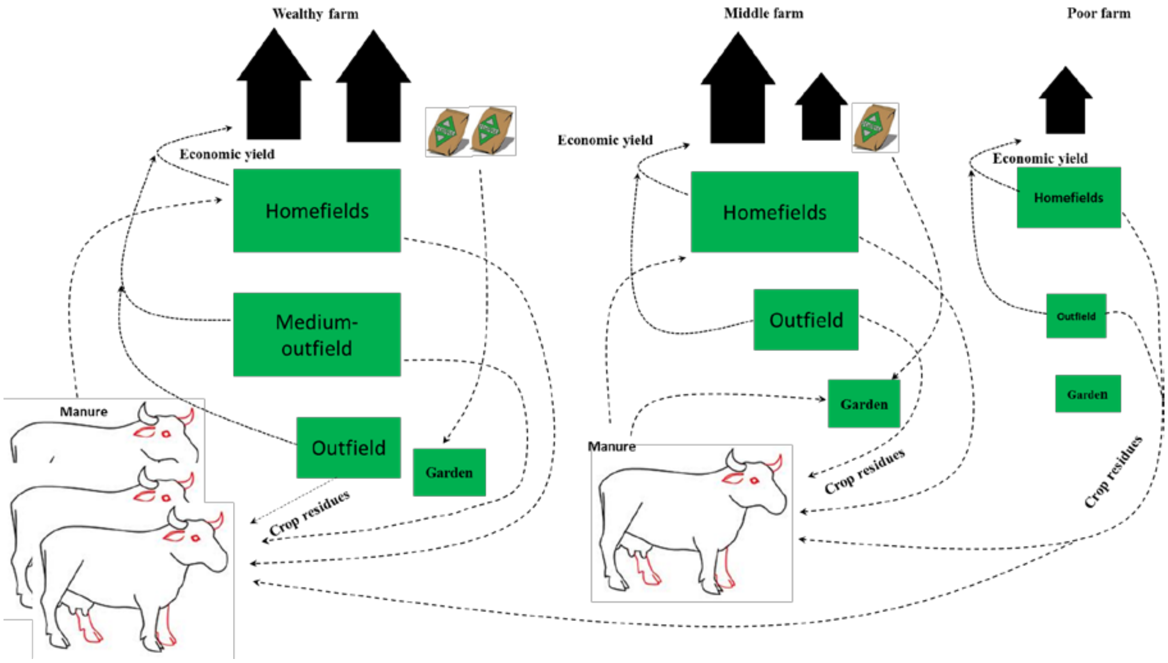

Figure 2. A schematic representation of a farm typology developed in Ruaca, central Mozambique. The intensification gradient shows clearly the differences exerted by differences in cattle ownership, field size, external input use and labour availability.

The often insufficient or even completely lacking nutrient replenishment from external sources has led to overall nutrient mining on arable land, but nutrient mining has not occurred homogeneously. Due to inadequate livestock manure or fertilisers, coupled with limited labour availability these nutrient sources are frequently applied only on limited portions of the farm each year (generally close to the farmstead) leading to heterogeneous soil fertility status across the farms (Mtambanengwe and Mapfumo, 2005; Rowe et al., 2006; Tittonell et al., 2007b). In some situations, the need to maximise outputs instead of soil fertility restoration lead to preferential allocation of limited nutrients to the same areas each year (Rusinamhodzi et al., 2013). This has led to development of fertile soils which do not respond greatly to fertiliser inputs (as the crops may be more limited by e.g. water than nutrient availability), to responsive more or less fertile soils where crop response to application of macronutrients can be large provided water availability suffice and weeding is carried out timely, and to non-responsive low-fertility soils where limiting Ca, Mg, S and/or micronutrient availability and poor physical properties preclude a positive crop response to macronutrient (N, P, K) application (Vanlauwe et al., 2006). This pattern of soil fertility gradients are most evident on average-endowed farms which have access to e.g. livestock manure but lack sufficient amounts and labour to apply to all fields, whereas highly endowed farms may have less gradients as resources may suffice for all fields and also poor farms have less gradients as there is little (if any) nutrient recycling to any of the fields.

Figure 3. Differences in soil fertility within farms may be large as a result of differing nutrient inputs. Eight-year old field a) at end furthest away from farmstead, and b) close to farmstead (photos: A.S. Dahlin).

3. Options for crop production intensification

Due to the large within-farm and between-farm variation in biophysical and socio-economic circumstances, interventions found to be successful on research stations or some farmers´ fields cannot be assumed to be appropriate to the majority of smallholder farmers (Mafongoya et al., 2006; Giller et al., 2009). Success of intensification techniques thus depends largely on recommendations taking into account local and farmer-specific constraints and opportunities (Cassman, 1999). Furthermore, it cannot be expected that a single solution will suffice to alleviate multiple limiting factors, but combinations of interventions and technologies are needed. For example, neither organic fertilisers or soil amendments nor inorganic fertilisers alone are good enough to improve crop productivity on many soils (Chivenge et al., 2009; Chivenge et al., 2011). Rather, intensification options include integration of crop and livestock production for enhanced nutrient use efficiency (nutrients used multiple times via recycling within the farming system), increased crop diversification, and agroforestry systems that promote nutrient and soil conservation (e.g. Cassman and Harwood, 1995; Mafongoya et al., 2006). Optimisation of planting dates, crop spacing, use of improved germplasm and increased weeding intensities can also be routes to increase crop productivity (Tittonell and Giller, 2012). In line with this, combinations of technologies for increased soil fertility and crop productivity are advocated in Integrated Soil Fertility Management (ISFM) and - in a somewhat more specific set - Conservation Agriculture (CA). ISFM is defined as a set of soil fertility management practices that should include the use of fertilizer, organic inputs and improved germplasm, adapted to local conditions of farmers to increase use efficiency of the applied nutrients and improving soil fertility and crop productivity (Vanlauwe et al., 2010).

Due to the low nutrient availability in most SSA arable soils, crop nutrient application is central to increasing productivity. Other factors such as plant available water, drainage and aeration, penetrability and rooting depth, weed seed banks, soil-borne pests and diseases and beneficial soil organisms are also important components of soil fertility and soil health. Soil organic matter (SOM) is of vital importance for all these characteristics; hence inputs and decomposition rates of organic carbon (C) and the resulting soil C concentrations are a centrepiece to soil fertility. Inputs can be achieved by additions of organic amendments, but also through (enhanced) crop production leaving roots, rhizodeposits and in some cases harvest residues to integrate with SOM during their turnover. Interventions and technologies which increase crop production thus increase SOM which in turn increases the soil's capacity to sustain crop production, creating a positive upward spiral. However, to harness soil fertility for increased crop production, good agronomic practices are also required. The response to individual management options depends to a great extent on the timeliness of farm management: ploughing and planting, weeding, harvesting, as well as on how these are carried out. Limiting labour availability is a major constraint in this respect, and this is aggravated by ill-health in diseases such as malaria and HIV/aids (Barnett, Tumushabe et al., 1995; FAO/WFP, 2007) as well as by urbanisation and a younger generation turning away from farming.

Figure 4. Where land availability suffices, large areas may be cropped to e.g. maize, but with limited management leading to low areal yields (photo: A.S. Dahlin).

3.1 Nutrient inputs

3.1.1 Mineral/manufactured fertilisers

The most significant environmental concern connected with smallholder farming systems in SSA is the progressive nutrient depletion and degradation of soils (Bationo et al., 2012). Ironically, single-nutrient fertilisation or fertilisation with just a few nutrients may increase the rate of mining of the remaining nutrients through an increase in nutrient uptake and export via increased crop production, which calls for balanced nutrient application to enhance or at least retain the current level of fertility. Mineral fertilisers have the potential to increase crop yields instantly (during the first growing season of application). They may also indirectly increase yields by increasing the amount of roots, rhizodeposits and harvest residues that may be retained as mulch, incorporated into the soil or contribute to livestock manure production if used as fodder. In this way the added nutrients contribute to increased SOM concentrations and soil fertility and may – given that good agronomic practices are applied - be cycled through crops and livestock multiple times before being exported with sold produce, lost from the system or fixed in inaccessible forms.

Fertiliser recommendations in most countries were developed based on practical considerations for extension to communicate similar messages rather than on the need to supply locally adapted, adequate nutrients for crop growth. Recommendations often ignored soil and climatic variation in the smallholder farming areas, were incompatible with smallholders' resources, or were simply inefficient (Kumwenda et al., 1996). To be efficient, mineral fertiliser applications should target the nutrients limiting crop productivity. This varies depending on soil type and nutrient supplying capacity, crop needs, and the availability of organic or inorganic soil amendments. Nitrogen and P are the two nutrients most commonly limiting crop production, but with this limitation addressed through N and P fertiliser application, also K, Ca and Mg may increasingly become limiting (Nyamangara et al., 2000). Furthermore, deficiency of micronutrients such as boron (B), copper (Cu) and zinc (Zn) may preclude a response to NP (and K) fertilisation (Wendt and Rijpma, 1997; Mugwira and Nyamangara, 1998; Kwari et al., 2009). To accommodate this, single and compound fertilisers are produced and nutrients are also added via lime and gypsum. However, the types of fertilizers and soil amendments available on the local market in most situations are not suited to address the locally existing nutrient deficiencies, thus calling for enhanced diversity of marketed fertilisers. Another obstacle is that the fertiliser products accessible on the market frequently come in large packages, unaffordable to many farmers. Smaller-size retail packages are therefore one way of increasing accessibility of fertilisers to smallholder farmers. In addition, household and farm characteristics, social and human capital, and farmer perceived effects of fertilisers on soil fertility are locally important determinants of fertiliser use (Mapila et al., 2012).The risk of crop failure resulting from low rainfall is a strong disincentive to the purchase and use of fertilizers on the subsistence crops (Probert et al., 1995).

Depending on fertiliser availability and mobility in the soil, application may be preferred as a single dose or as split application. Nitrogen fertilisers have high plant-availability but are highly mobile and reactive, and thus may be lost through leaching, volatilisation or denitrification. To achieve high N use efficiencies, split applications are thus recommended. Soluble P fertilisers, on the other hand, are fully soluble at the time of application but are less mobile in the soil and can be fixed to the soil matrix more or less rapidly; such fixation is particularly significant in soils high in sesquioxides, and in soils of high and low pH.

Phosphate rocks can vary greatly in P concentration and availability but must in all cases be ground finely to reach significant plant availability (Vanlauwe et al., 2000). The resultant rock dust is difficult to handle and a health hazard if inhaled and thus should be pelleted. Phosphate rocks are also mainly suitable on low pH soils (pH<5.5) where acidity contributes to rapid weathering of the added rock. Phosphate rocks therefore are mostly a means to replenish degraded soils or as a slow-release source for e.g. trees, and less suitable as fertilisers to annual crops (Bationo et al., 2012). Potassium fertilisers are used less in SSA than N and P (FAOSTAT, 2014), and often only on high-value crops such as tomatoes on smaller pieces of land. However, after decennia of often sole N and P fertiliser use there is now increasing evidence of K deficiency (e.g. Gikonyo and Smithson, 2004).

As many SSA soils are highly weathered and leached, base saturation levels are often low, affecting soil chemical and physical properties. Gypsum may be used to increase Ca saturation of the soils´ exchange complex and increase soil structure stability on non-acid soils. It simultaneously improves crop Ca supply and is sometimes used as a Ca fertiliser when liming is not needed or when sodium concentrations are excessive. Magnesium may be added via Mg fertilisers but also via liming with dolomite limestone instead of calcitic limestone. Sulphur is added with N in ammonium sulphate, with Ca in gypsum and K in potassium sulphate and may also be added into some NPK fertilisers. Compound fertilisers, such as mavuno fertiliser in Kenya, are produced by inclusion of Ca, Mg, S and a range of micronutrients along with N, P and K. However, often only a selection of micronutrients is added into NPK fertilisers along with S.

Figure 5. a) Placing of fertiliser can greatly increase use efficiency (photo: L. Rusinamhodzi). b) Nutrient deficiencies must be overcome by adequate inputs (here K deficiency in maize and common bean (*Phaseolus vulgaris* L.)) (photo: A.S. Dahlin).

Whereas over-use of mineral fertilisers and accompanying negative environmental effects is a major concern in many developed countries, this is rarely the case in SSA (Bationo et al., 2012). Instances where excessive nutrient discharge to water-bodies causes eutrophication are, on the other hand, normally connected with effluents from farming operations on the outskirts of cities (Mensah et al., 2001) or with sewage spillage from urban centres (Ong´ang´a and Righa, 2009; Nyenje et al., 2010). Other examples are eutrophication due to increased erosion and decreased trapping of nutrient loads connected with changes in riparian vegetation in the wake of increased human activity such as water withdrawal and tilling, and by increased trampling and grazing by livestock and game (e.g. Lake Naivasha; Harper and Mavuti, 2004).

Although significant negative environmental effects of nutrient loss from smallholder farming are not expected in the foreseeable future, nutrient use efficiency should be optimised to maximise economic return. To achieve this, the right fertiliser product (regarding nutrient composition) and application rate should be chosen to match crop needs as determined by plant species, expected or targeted yield, supply from soil pools, manure and crop residues, and the relative price of fertiliser and harvested products. The fertiliser further must be applied at a time synchronised with crop demand; this applies in particular to the mobile nutrients (N, K, Mg, S) for which also split application may be needed to decrease losses through leaching, volatilisation and denitrification to acceptable levels. Finally, the placing of the fertiliser within planting rows or pits and at certain depth may improve nutrient use efficiency considerably, both in rain-fed and irrigated systems. In extension materials this is referred to as the 4Rs, i.e. the right fertiliser product, right fertiliser rate, right time for fertiliser application, and right fertiliser placement (Bationo et al., 2012; IPNI, 2012). A fifth R may further be added, namely targeting the use of fertilisers (and other nutrient sources) to the most remunerative options, i.e. where they are likely to produce high economic return (Bationo et al., 2012). Their use should thus be targeted optimally in the crop rotation and – if there is a fertility gradient within the farm – to responsive fields.

3.1.2 Locally available resources

Locally available sources of nutrients and organic matter can be important components in building soil fertility and enhancing crop productivity. The major emphasis of ecological intensification is the use of locally available and adapted resources (Cassman, 1999). Although the content of N, P and K of these local resources may not suffice for crop production except on smaller areas such as vegetable gardens they also supply other macro- and micronutrients, thus complementing mineral inputs of N, P and K. Any addition of organic matter also contributes directly to SOM, thus improving soil physical properties such as water holding capacity, water infiltration and root resistance, soil biology and a mix of nutrients that are released over time. However, labour demands are high for managing, transporting and spreading organic amendments, which limits farmer interest and contribute to heterogeneous application across farms and the development of fertility gradients.

Livestock manure can be important in farming systems characterised by a high degree of integration between livestock and crop production. The quantity and nutrient content of manure produced are the most critical factors that determine its effectiveness as a nutrient source (Powell and Mohamed-Saleem, 1987; Snapp et al., 1998). Manure applications of about 17 t ha^{-1} in the short term have been found to be effective in improving soil organic carbon, phosphorus, pH, base saturation and restoration of crop productivity of a degraded sandy soil (Zingore et al., 2008). Nyamangara et al. (2001) demonstrated that manure application of 12.5 t ha^{-1} per year or 37.5 t ha^{-1} once in three years significantly improved the structural stability and water retention capacity of soils with low organic matter content. However such application rates are only feasible for smaller fields or for farmers who own much livestock suggesting a constraint on applicability of these results. The manure fertiliser value is also frequently low due to poor handling; e.g. cattle are often penned in unroofed kraals with soil floors at night, and trampling by cattle mixes manure with soil thus diluting its nutrient content (Rufino et al., 2007). The manure is often left in the cattle enclosure for months or even up to a year while further trampled by the animals and subjected to rain and winds. Under these conditions a major part of the original nutrient content may be lost through leaching, volatilisation and denitrification (e.g. Nzuma and Murwira 2000; Dahlin et al., 2005). Based on this, Rufino et al. (2006) estimated that up to 90 % of excreta N may be lost before collection and use. The resultant manure is a mineral-rich and thus heavy and bulky mass of low fertiliser value. The manure may be dug out of the kraal and heaped in the open before transportation to the fields where it is spread on the surface and ploughed under before planting. As a result N content of manure generally ranges between 0.25 and 1.4% N dry matter, with majority of them being below 1%, but with an ash content of 27-94% (Mugwira and Mukurumbira, 1986; Lekasi et al., 2003). Nitrogen mineralisation and contribution to plant nutrition from this poor quality manure is small; only about 3-6% N is mineralised in the first season (Murwira and Kirchmann, 1993). One further drawback is the high occurrence of weed seeds that can serve as weed source for cropped fields (Pleasant and Schlather, 1994) and decreases the attractiveness of the manure to some farmers. However, this can be decreased by e.g. pit composting that increases temperatures to levels that kill seeds while the protection against trampling, wind and rain increases its nutrient concentrations. A temperature of 55˚C is often suggested to suffice, although Larney and Blackshaw (2003) showed that some species remained viable up to >60˚C. Nevertheless, many seeds lose viability at a lower temperature and despite the labour demand, pit-composted manure is a viable option to increase manure nutrient content and nutrient release in a reasonably short time for crop uptake. Cut and carry system for livestock production offers better possibilities for production of large quantities of high-quality livestock manure than free-roaming production systems. A further factor is that high-quality feed given in these more intensive production systems also produce higher-quality fresh manure (Lekasi et al., 2003; Rufino et al., 2007). If feed is purchased this also implies import of plant nutrients which can benefit soil fertility and crop yields on the manured fields.

Figure 6. a) Nutrient losses may be large from livestock manure ‘stored’ in cattle enclosures (photo: A.S. Dahlin), b) crop residues contain nutrients that are returned to soil if retained in the field (photo L. Rusinamhodzi).

Crop harvest residues contain substantial amounts of nutrients and, if retained in the field, return nutrients and add organic matter, thus contributing to improved soil fertility (Mapfumo et al., 2007; Chivenge et al., 2009; Chivenge et al., 2011). When retained as mulch on the soil surface, crop residues increase water infiltration, reduces runoff and soil erosion and decreases evaporation (Vogel, 1993; Thierfelder and Wall, 2009; Rusinamhodzi et al., 2011). However, crop residues are often scarce and smallholder farmers in SSA have multiple alternative uses for them, e.g. as livestock feed during the dry season, as fuel, building material or for sale (Rufino et al., 2011; Valbuena et al., 2012). In areas where livestock roam freely after harvest of the main crops, farmers who aim to retain crop residues as mulch need to fence off their fields or protect somehow their crop residues. This affects livestock feed availability at the village level, i.e. reduces the quantities available for the neighbouring farmers and affects animal productivity (Rufino et al., 2011; Rusinamhodzi, 2013). On the other hand, when livestock access and graze on residues and weeds in the fields, part of the nutrients retained in these are transferred from the fields to the livestock enclosures and the fields of livestock owners (Rufino et al., 2011). For poor households lacking own livestock, this implies a transfer of nutrients to more endowed households that have livestock.

Other sources of nutrients may be available and although none of them will go a long way, they may contribute crop nutrient supply on part of the cultivated area. *Woodland litter*, where available, may be transferred to farm fields to increase C inputs albeit at increased labour costs. As with most crop residues, though, woodland litter generally has a high C/N ratio and thus do not contribute to short-term N supply (Bationo et al., 2012). Labour cost may also be high or labour unavailable, limiting its use especially at larger distances between woodland and field. Landscape degradation which is prevalent is most smallholder systems also mean that significant quantities of woodland litter cannot be collected for adequate C input (Nyathi and Campbell, 1993). *Compost* may be a way to recycle household and farmyard wastes. Often produced from a combination of organic wastes and household ash the compost has potential to contribute nutrients on a small area and has been advocated for use in the vegetable garden or applied in planting pits etc.

Wood ash is locally available at most households and is applied irregularly every year on fields close to the homestead or benefitted from in outfields during the initial years of converting virgin land to crop land through slash and burn. Wood ash is an alkaline material with a pH that ranges from 8 to 13 and contains macro- and micronutrients extracted from the soil during tree growth (Huang et al., 1992). Wood ash is regarded as an N-free fertiliser which is particularly suited for nutrient deficient acid soils found in the tropics because it is a direct source of other major elements, notably P, Ca, Mg and especially K while exerting a liming effect (Etiégni and Campbell, 1991). According to Etiégni and Campbell (1991), Ulery and Graham (1993) and Someshwar (1996) the properties of wood ash depend on various factors such as type of plant, part of plant combusted (bark, wood, leaves), soil type, climate, and conditions of combustion, collection and storage. As a consequence available data on the properties of wood ash are variable and generalizations are therefore difficult to make (Stromgaard, 1984; Shea et al., 1996). Kanmegne et al. (2007) showed that under the rainforest conditions of Cameroon an average of 205 kg of wood ash was produced per household annually, corresponding to a small but significant nutrient input to the arable fields. Wood consumption in Zimbabwe was estimated at 7 t per household annually (Grundy et al., 1993), suggesting an ash production of similar magnitude. Other studies from Kenya (Barnes et al.,

1984) and South Africa (Shackleton, 1993) report weekly per capita wood consumption figures of 6.8 kg and 13.2 kg, respectively. Experiments have shown that application of wood ash at rates relevant to crop needs can increase crop growth, particularly for legumes on less-fertile soils (Ferreiro et al., 2011; Dahlin et al., submitted). Field observations in most smallholder farms further suggest that household ash in combination with other homestead waste randomly spread in fields close to the house improves crop productivity. Wood ash applied at higher rates have also shown to improve soil properties such as pH, ECEC, aggregate stability and plant-available P on acid soils (Mbah et al., 2010).

Another nutrient source available at each household is excreta from household members. This constitutes a significant source of plant nutrients although its use in agriculture is frequently limited by cultural traditions and taboos (reviewed by Duncker et al., 1995). The nutrient content of human excreta in SSA was estimated to approximately equal that of the N and P fertiliser used across the continent (Rockström et al., 2005). For instance, Kanmenge et al. (2006) found that household excreta (5-7 persons) on average corresponded to 4 kg N, 0.64 kg P and 4.8 kg K ha^{-1} at a farm size of 6 ha agricultural land. In addition to these, it also contains other nutrients originating in the foods consumed and which may be poorly available on the local fertiliser market or simply too costly. Whereas the nutrients were formally recycled on a local scale through the use of 'bush latrines' their withdrawal from plant reach through introduction of deep pit latrines or flush toilets serve to further aggravate plant nutrient deficiencies in low-input small-holder agriculture and also do not efficiently sanitise the excreta but relocate them downstream. For increased human health and safe nutrient recycling of nutrients contained in human excreta, efficient and sustainable sanitisation is vital (Winblad and Simpson-Hébert, 2004). This can be achieved by ecological sanitation (Rockström et al., 2005) also by rural households, e.g. through ecological sanitation using urine diversion and composting of faeces in shallow pits. Use of diverted urine seems more widely acceptable and easily applicable than that of sanitised faeces (Duncker et al., 1997). However, due to its content of chloride (Cl) it should be targeted to Cl-tolerant crops (Mnkeni et al., 2008) and avoided on acid soils rich in cadmium (Cd) (Bingham et al., 1984; McLaughlin et al., 1995). Also, due to it increasing the soil electrical conductivity it may – if applied in large amounts – increase the effect of dry spells and may therefore be most efficient in areas of reliable rainfall. Use of sanitised human excreta in farm production thus requires education of users of the latrines as well as the sanitised products to gain wider and successful adoption, including avoidance of disease-transmittance.

Other locally available nutrient sources may be by-products from e.g. small and larger-scale industry found within the neighbourhood. It is vital that these – and mineral fertilisers – contain low concentrations of potentially harmful elements and substances in relation to their nutrient content to limit contamination of soils. Quality of fertilisers and amendments is thus a matter of high concentrations of plant-available nutrients and low concentrations of potentially toxic elements and substances. For example, while phosphate rock from the Minjingu deposit, Tanzania, holds an average P concentration of 28.6 % and a cadmium (Cd) concentration of 1 ppm, the Taiba deposit, Senegal, holds 35.9% P and 87 ppm Cd (van Kauwenbergh, 2002), giving very different contamination per unit added P. With the currently low application rates of fertilizers on most small-holder farms in SSA there has been little need to take such environmental considerations into account. However, unless some degree of quality control is exercised this may become an issue as inputs increase, as was the case in Europe during the first part of the 20th century, e.g. leading to an increase in soil Cd concentrations (Andersson, 1992).

3.1.3 Biological Nitrogen Fixation

Biological N_2 fixation (BNF) by legumes (and members of other plant families) can potentially contribute large amounts of N to the legume crop (Giller, 2001; Santi et al., 2013). The N can also benefit subsequent rotational crops through residual N effect (Rusinamhodzi et al., 2006; Ncube et al., 2009) but to some extent also intercropped crops grown during the same season. Reliance on BNF can ensure high productivity together with ecological sustainability given the right environmental conditions (Crews and Peoples 2004; Rusinamhodzi et al., 2012), but N losses via leaching and nitrous oxide emissions may also increase (Chikowo et al., 2004; Millar and Baggs, 2004; Chikowo et al., 2006; Dick et al., 2006). According to Giller (2001), three principal factors determine the amounts of N_2 fixed in the cropping systems: land size under legumes, ability of N_2 fixing plants to establish their symbioses which is often controlled by environmental conditions, and lastly the ability of the established symbioses to fix N_2. While amounts of fixed N have sometimes been estimated at hundreds of kg ha^{-1} (Haque and Jutzi, 1984; Giller, 2001), not all legumes fix N_2 or fix only small amounts even under optimum growing conditions (e.g. non-nodulating soybean (*Glycine max* (L.) Merr.) and *Cassia siamea* (Lam.)). Furthermore, also species and varieties that can potentially fix large amounts of N frequently only fix small amounts due to environmental limitations. The first and foremost determinant of N fixation rates/amounts is the biomass production providing a sink for the fixed N (Schubert, 1995). Hence, if e.g. nutrient deficiencies or drought are limiting growth, N_2 fixation will subsequently be low. In the field, deficiencies of P, K, S, and micronutrients such as Zn, molybdenum (Mo) and B are known to limit legume growth and N_2 fixation (O'Hara et al., 1988), with P availability often regarded as the most limiting factor (Giller and Cadisch, 1995). Availability of compatible and effective rhizobia is another important prerequisite and some species and varieties benefit from inoculation with appropriate strains, e.g. chickpea and non-promiscuous soybean (Giller, Sudarshana et al. 1988, Giller 2001) as well as the tree legumes *Calliandra calothyrsus, Gliricidia sepium, Leucaena leucocephala* and *Sesbania sesban* (Bala and Giller, 2006).

Most smallholder farmers prefer grain legumes due to their dual roles of food and soil fertility benefits, but the input of fixed N from grain legumes may only be significant in sustaining productivity of other crops if substantial and sufficient amounts of harvest residues are retained in situ (Giller 2001, Sanginga 2003; Rusinamhodzi et al., 2012). The extent to which the fixed N is exported from the field via harvested produce or retained in harvest residues and roots is determined by the harvest index. This differs widely between species and between varieties within species and lead to greatly differing residual N effect. For example pigeonpea (*Cajanus cajan* (L.) Millsp.) can add up to 60 kg of N ha^{-1} to the soil and accumulate up to 6 kg of P ha^{-1} and only 25% of this N and P is exported with the grain (Myaka et al., 2006). On the other hand, N harvest indexes of 65-70% have been reported for soybean varieties, whereas in the same experiments N harvest index varied between 2 and 44% in cowpea (*Vigna unguiculata* (L.) Walp.) (Muhammad et al., 2010).

Through the variability within the legume family, N fixing species can be found that produce grain, vegetable leaves and forage, green manure cover crops and trees for fuel-wood and construction timber. These can be fitted into production systems as rotation crops, intercrops, and relay crops, or grown outside the main fields and used for biomass transfer. However, irrespective of the cropping system legumes cannot be solely N providers, unless the residual N effect is very high (i.e. more than doubles the following harvest). Farmers need immediate economic return, thus legume species that have multiple functions are needed, and should produce food and fodder that are locally preferred and have a market. So far the potential for cropping systems based on legumes for their N supply have not been realised, due to lack and/or cost of appropriate germplasm, poor market infrastructure for legume grain and lack of information (Graham and Vance, 2003) which calls for targeted interventions by extension services and market actors. Such interventions should be designed to promote simultaneous development of the legume cropping in combination with sustainable market linkages that persists in the future (Rusinamhodzi et al., 2012). However, there are cases where legume technologies have spread spontaneously within the smallholder farming community. One such example is where green manures have given overall labour savings through suppression of weeds (Udensi et al., 1999; Versteeg et al. 1998). Other situations with high potential for uptake is where the capacity of some legumes (e.g. desmodium legumes (*Desmodium* spp.), soybean and cowpea) to trigger suicidal germination of *Striga* seeds (Khan et al., 2002; Singh, 2002; Carsky et al., 2000), is used to decrease the *Striga* seed bank (Ellis-Jones et al., 2004).

Many species of trees and bushes used in agroforestry systems are active N_2 fixers, but trees and bushes (whether N_2 fixers or not) may also improve the availability of other nutrients via nutrient pumping from deeper soil layers (Aweto and Iyanda, 2003; Gindaba et al., 2005). The access of nutrients and water from different soil layers has also an added advantage of reducing competition in the mixtures, and thus potentially higher total crop productivity (Sekiya and Yano, 2004). They further affect the farm environment regarding insolation, wind speed and air and soil humidity, may compete with the (annual) crops depending on planting pattern and management, and affect pest and diseases by acting as refuges that carry the pests and diseases across seasons but also their natural enemies (Myaka and Kabissa, 1996; Kuyah et al.). As with herbaceous legumes, trees and bushes need to fill multiple purposes to be attractive to farmers, e.g. for forage, green manure, firewood, construction timber, and for general fertility.

3.2 Liming

Most crop species require a soil pH above 5.5 below which aluminium (Al) and manganese (Mn) toxicity (frequently accompanying low pH) may cause root damage, although a number of crops (e.g. cassava (*Manihot esculenta* Crantz), coffee (*Coffea* spp.) and tea (*Camellia sinensis* (L.) Kuntze)) common in SSA have the capacity to withstand low pH and high levels of soluble Al. Liming is undertaken to increase pH and plant-available Ca (and Mg) and simultaneously decrease soluble concentrations of Al and Mn. Increasing pH of acid soils also enhances biological activity in the soil which together with the increased Ca concentration may improve soil physical properties, adding to the improved root environment for plants. The choice of liming material affects whether mainly Ca or also other nutrients are added to the soil; whereas calcitic limestone offers primarily Ca, dolomitic limestone also contains Mg and e.g. wood ash a range of nutrients.

3.3 Erosion control

Soil erosion is a major challenge in large tracts of SSA and contributes to the loss of nutrients. Studies indicate that annual erosion losses in low-input production systems in SSA are often about 10 kg N ha^{-1}, 2 kg P ha^{-1}, and 6 kg K ha^{-1} (Bationo et al., 2012; Stoorvogel and Smaling, 1990) although variation is high and estimated losses of 60 kg N ha^{-1}, 10 kg P ha^{-1}, and 40 kg K ha^{-1} are not unusual, especially in Eastern

Africa (Stoorvogel and Smaling, 1990). Water erosion can be especially serious on steep slopes and where precipitation intensities are high while wind erosion is generally most serious on coarser soils. In addition to loss of nutrients and organic matter, erosion leads to loss of anchorage and to abrasion damage (wind erosion), thus decreasing crop productivity. Control measures include surface mulch to reduce water and wind speed, avoid crust formation and improve infiltration rates, soil porosity and aggregate stability, while terraces, pitting and grass strips reduce water flow rates and increase water infiltration and sedimentation of carried soil particles and often serve to simultaneously improve rainwater management (see below). Farmers´ abilities to implement these measures in the field are, however, limited by the need to use plant residues as animal fodder and by labour shortage, especially the time-consuming task of building terraces. Farmers may also be unaware of the economic viability of control measures, or the viability may be uncertain due to e.g. high inflation (Barungi et al., 2013). Farmers may further hesitate to invest in erosion control measures under insecure land tenure (Mugagga and Buyinza, 2013). Subsequently, although many farmers in hilly landscapes apply at least one erosion control method, adoption intensities are often not sufficiently high to control erosion (Barungi et al., 2012).

Figure 7. Cropping on sloping land requires that erosion is counteracted by e.g. terracing and stabilising with trees, bushes and grasses along contours lines (photo: A.S. Dahlin).

3.4 Land preparation

Recent developments that include the integration of conservation agriculture in smallholder farming systems suggest that soil inversion is not necessary to ensure good crop establishment and the concomitant increase in crop productivity (Marongwe et al., 2011; Kassam and Brammer, 2012). However, new challenges have also arisen as a result of absence of tillage, especially severe weed infestation in the absence of herbicides (Muoni et al., 2013) or inadequate manual weeding. Other challenges are potential increases in disease pressure as crop residues retained on the soil surface may act as refuge for these organisms between growing seasons, although some studies also report disease suppression in no-tillage systems (Page et al., 2013).

Land preparation is traditionally carried out to give the soil a fine tilth in order to enhance seed germination and root development while also combating weeds and incorporating crop residues. However, it also increases the rate of SOM turnover and incorporation of plant residues may lead to increased soil erosion as they no longer provide surface mulch needed for erosion control. Land preparation in SSA is to a large extent carried out with hand tools (Mrabet, 2002). Animal traction (mainly by oxen) offer increased performance wherever available and afforded, although in areas of poor feed availability during the non-growing season oxen may be too weak to carry out the work at the on-set of the growing season (Mabuza et al., 2013). While animal traction can greatly increase the efficiency of land preparation, access differs between endowment groups and may also differ between male and female farmers as a consequence of cultural barriers, the suitability of equipment (e.g. its size and weight) and access to and ownership of animals and technology (Lubwama, 2000; Bwalya and Akombelwa, 1999). Land preparation is directly related to time of planting, and early planting is often associated with large yields although recent changes in climate or increased variability has shown that this is not always the case (Rurinda et al., 2013; Traore et al., 2013).

3.5 Rainwater harvesting and management

Approximately 95% of SSA agriculture is rainfed (Peacock et al., 2008) and especially in the drier areas subjected to variations in the amount and pattern of precipitation. Climate variability, especially of rainfall patterns, is the most limiting biophysical factor beside low soil fertility (Phillips et al., 1998; Challinor et al., 2007). The climatic variability affects farm productivity both directly through decreased yields under water limitation and decreased use efficiency of inputs such as fertiliser, improved germplasm and labour, but also indirectly through farmers´ precautionary strategies which limit crop production during favourable growing seasons and through coping responses in the face of climate shocks (Brown and Hansen, 2008).

Small-scale rainwater harvesting and management strategies in SSA include (i) collection of surface runoff from macro-catchment systems with water storage in e.g. ponds for supplementary irrigation (ii) collection of surface runoff from micro-catchment systems with water storage in the soil, and (iii) techniques for maximising infiltration, reducing surface runoff and soil evaporation and improving soil water availability (Biazin et al., 2012).

Small-scale water management systems may improve crop productivity especially when rainfall is near-normal or only moderately below normal conditions (Brown & Hansen, 2008). For example, rainwater harvesting techniques have high potential to supply water to overcome dry spells during the growing season in large parts of SSA (Brown and Hansen, 2008), thus enhancing input use efficiency and improving crop yields. Even limited irrigation to overcome drought during critical development stages of rain-fed crops has been shown to significantly increase yields (Raja et al., 2012). Small-scale water management systems may also extend the growing season and even add an extra growing season between rain-fed ones for small acreages. Water harvesting systems for supplemental irrigation have been shown to be labour intensive but risk-reducing investments that are economically viable only when combined with improved soil fertility management (Fox et al., 2005). On the other hand they may often be a prerequisite for a long-term positive return on fertiliser investment. Even so, seepage and evaporation losses can lead to large losses from the storage ponds (Ngigi et al., 2005) and should be minimised to increase the viability of water harvesting and the potential for uptake by farmers.

Figure 8. a) Farm-scale dam for storage of harvested rain water used for supplementary irrigation (photo: A.S. Dahlin), and b) planting pits with organic material (photo L. Rusinamhodzi).

Enhanced crop water supply may also be achieved by rainwater harvesting in the micro-scale and directing the water to infiltration areas where plants are grown (reviewed by Biazin et al., 2012). Increased infiltration may be achieved by e.g. terracing, micro-basins and pits, and by vegetation strips and trash or stone lines along contour lines, sometimes combined with application of organic material to the infiltration area. Such practices are frequently labour-intense which decreases farmer uptake. However, where benefits are rapid and labour is available, uptake can be considerable. For example, *zaï* pits are frequently dug and supportive stone structures built by young day labourers in Burkina Faso (Pretty et al., 2011). The increase in productivity generated on these fields has encouraged farmers to purchase cheap, degraded agricultural land, thus rehabilitating large areas (more than 3 million ha in 2011). These may produce yields of 0.4 Mg ha^{-1} in low-rainfall years, and up to 1.5 Mg ha^{-1} in years of good rainfall, whereas before restoration they did not support crop production (Kaboré and Reij, 2004).

Techniques for maximising infiltration *in situ*, reducing surface runoff and soil evaporation aim to turn blue water into green water, i.e. decrease the proportion evaporated directly from the soil while increasing the proportion of precipitated water that is transpired by plants thus increasing water productivity (i.e. biomass production per unit water) (Falkenmark and Rockström, 2004). Increased water infiltration and decreased evaporation may be achieved with different types of ridging, furrowing and hoeing, conservation tillage and by surface mulching with materials such as crop residues or stones (Biazin et al., 2012). The increased soil water availability in tied-ridge systems in the West African Savannah have been shown to benefit especially more drought-sensitive cereal crops (maize, pearl millet (*Pennisetum glaucum* (L.) R.Br) and sorghum (*Sorghum bicolor* (L.) Moench)), with response in cowpea only in dry years (reviewed by Hulugalle, 1990). For species sensitive to water-logging, yield even decreased during wet years in the same location. Gebrekidan (2003) similarly found that yield response to rainwater harvest and management was highest in seasons with low or poorly distributed precipitation. The response was also highest on shallow and coarse textured soils and higher under fertilized than under unfertilized conditions.

Consistent positive responses to tied-ridging can therefore be expected mainly in areas where long- and short-term droughts are frequent and water-infiltration rate and water-retention are low.

Mulching serves to increase water productivity by increasing both water retention and infiltration as water flow slows down and infiltration rates may increase in response to enhanced SOC concentrations and decreased soil bulk densities (Adekalu et al., 2007). It also decreases evaporative losses by lowering wind speed at the soil surface and enhances plant root functioning by preventing excessively high soil temperatures (Agbede et al., 2013; Lal, 1974), allowing higher rainfall productivity. As organic mulches also release or bind plant nutrients, the overall effect on crop growth and yield is dependent on mulch physical and chemical composition (Tian et al., 1993; Agbede et al., 2013).

3.6 Weed, disease and animal pest control

Control of weeds, animal pests and diseases is needed to enable crops to capitalise on enhanced production conditions and inputs, and ascertain product quality. Their control is often interdependent as weeds can act as pest hosts and bridge gaps between crops in space and time (Chikoye et al., 2000). Pesticides applied judiciously at specific growth stages, including the use of treated seed has the potential to combat weeds, insect pests and diseases and increase yields and profit. Chikoye et al. (2007) for example reported that herbicide control of weeds decreased costs by up to 50% compared with manual weeding in cassava, yam (*Dioscorea* spp.) and soybean. However, smallholder farmers in SSA often lack access to herbicides of the proper formula or funds to purchase them and where they are used may be done so in ways which are hazardous to farmers, consumers of agricultural products and the environment (Melinfonwu 1994; van Huis and Meerman, 1997; Williamson et al., 2008). The use of pesticides also has drawbacks such as development of pesticide resistance, secondary pest outbreaks and pest resurgence and may be furthermore be uneconomical. Integrated approaches are thus needed which introduce additional system components which may provide pest suppression and which limit the use of pesticides.

Weeds are major crop pests in SSA and reduce crop yield by competition, allelopathy and parasitism, causing yield losses ranging from 25% to total crop failure (Van Rijn, 2000). Competition between the crop and weeds for the growth-limiting resources such as light, water and nutrients is generally the major cause of yield reduction by weeds (Kropff, 1988). Indirectly, weeds also hamper harvesting because they infest, for example, wheat with their seed and they may also harbour insects, fungi and viruses which may adversely affect the quality of the crop (Nieto et al., 1968). Although the full magnitude of weed infestation is often not appreciated by farmers (Melifonwu, 1994), weeding may be the farm activity consuming most farm resources (incl. labour) (Vissoh et al., 2004). The significance of competition differs over time and development stage of the crop, why the timing of weed control must be adjusted to the critical period for weed control for the respective crop. This period determines when weeding must begin and how long the crop should be kept weed-free to avoid yield losses (Hall et al., 1992). The end of the period coincides with the time when the crop has developed a closed canopy (Zimdahl, 1999). In Nigeria this was shown to be approximately 12 weeks for monocropped cassava but approximately 8 weeks in mixed cassava-maize stands (Melifonwu, 1994), thus supporting the suggestion of relatively higher weed-suppression in intercropped than in mono-cropped fields as a consequence of increased shading (Benvenuti et al., 1994). The competitiveness of the crop species and the weeds is also likely to differ under different temperature, moisture and nutrient availability (Zimdahl, 2004). Timely weed control is important in particular in relation to potential top-dressing with nutrients as these are otherwise partly used by weeds at the expense of the crop. If labour suffices, top-dressing may be applied first and incorporated simultaneously with weeding, but if limiting labour would result in a time lapse between fertiliser application and weeding, weeding should therefore be carried out first.

Figure 9. Timeliness of weeding is crucial for crop development. This whole field had the same pre-history and received the same amount of manure and fertilizer. The part to the right of the picture was weeded according to plan, whereas the part to the left was not weeded at the right time (photo: A.S. Dahlin).

Due to the high labour requirement for weeding, strategies must be sought to reduce the critical period of weeding and reduce the required frequency of weeding in a season. Optimisation of planting densities and arrangement may suppress weeds and reduce the critical period of weed control and the weeding requirements to attain maximum yield (Mashingaidze et al., 2009). Udensi and Chikoye (2013) thus found that maize planting densities of 50-80 plants ha^{-1} enhanced weed suppression compared with lower planting densities, while avoiding yield decline due to intraspecific competition. Crops can be favoured in competition against weeds by use of equidistant planting which reduces self-shading of the crop and time to reach a closed canopy, increases light interception (Weiner et al., 2001; Andrade et al., 2002; Olsen and Weiner, 2007), and suppresses weeds (Begna et al., 2001a; Weiner et al., 2001) which ultimately increases crop yield (Murphy et al., 1996; Barbieri et al., 2000; Weiner et al., 2001; Andrade et al., 2002). Mashingaidze et al. (2009) thus found that the weed-free period required to reach maximum maize grain yield under sub-humid and semi-arid conditions in Zimbabwe was 3 weeks shorter (*ca*. 6 instead of *ca*. 9 weeks) with 60-cm row spacing than with 75- and 90-cm spacing, given the same total plant density. Furthermore, the weed-suppressive effect is likely to benefit also the next crop as the weeding carried out is likely to have reduced weed seed production significantly in the narrow spacing compared with the wide spacings.

Herbaceous cover crops may be used to suppress weeds during and after the growing season, thus reducing the requirement for weeding and increasing crop yield (Vesteeg et al., 1998, Udensi et al., 1999). However, increases in crop yield are not always achieved as interactions may also be negative if the cover crop competes successfully with the main crop (Chikoye et al., 2002; Olorunmaie 2010). For example Chikoye et al. (2002) found that *Mucuna cochinchinensis* and *Pueraria phaseoloides* competed strongly with maize leading to decreased yields, whereas cassava yields were not significantly affected at one location and increased in another.

Legumes also offer possibilities to counteract weeds through chemical interaction, thus decreasing the seed bank in the soil. A specific and highly important example of the latter is the suicidal germination of *Striga* spp. triggered by allelophatic compounds released by some legumes (e.g. varieties of desmodium (Khan et al., 2002; Vanlauwe et al., 2008), cowpea (Singh, 2002), and soybean (Carsky et al., 2000). *Striga* spp are parasitic weeds that constitute a severe constraint to cereal production in SSA, probably the most serious of biological constraints to food production (Ejeta and Butler 1993). They infect major SSA crops such as maize, sorghum, millet species, rice (*Oryza sativa* L.) and sugar cane (*Saccharum* spp.) but also fodder grasses (Ellis-Jones et al., 2004) and frequently cause harvest losses of more than 50%, and thus strongly contribute to the decreasing areal yields of Sub-Saharan Africa (Kanampiu et al., 2002). However, farm management can counteract the weed relatively successfully. In addition to crop rotations and intercropping (see below) with suitable legumes, removal of the sprouting plant and measures to decrease the spread of weed seeds via farm tools, crop seeds and crop residues are important (Ejeta, 2007). Improved soil fertility and plant nutrient availability also enhance the plants´ resilience to attack (Ransom, 2000; Jamil et al., 2012; Joel et al., 2007).

Selection and planting of locally adapted crops of a suitable growth habit may also be used to suppress weeds. Cropping of vigorous, early-growing and branching cassava varieties has for example been found to improve crop competitiveness in non-weeded stands: root yield losses due to weed infestation decreased from 68% in up-right non-branching types to 40% in branching types (Akobundu 1980). Also early-developing, leafy, reduced-stature maize has been found to compete more successfully with weeds than late-maturing, big-leaved maize (Begna et al., 2001b).

Insect pests and diseases Approaches to decrease insect pests and diseases may include crop rotations to break temporal host continuity and intercropping to break spatial host continuity, although the effectiveness depends on the broadness of the host plant range, potential existence of structures for long-term survival in the absence of a host and dispersion ability (as reviewed by Ratnadass et al., 2012). For example, disease reduction using rotation with non-hosts is thus generally more effective for soil or residue-borne pathogens with low mobility, slow dispersal and which furthermore lack long-term survival structures, and decrease in herbivore crop damage by intercropping is usually more pronounced for herbivores that have limited ability for directed flight (e.g. cabbage aphids) than for competent flyers with a good sense of smell (e.g. cabbage butterflies). As a majority of plant viruses are transmitted by insects (Brunt et al. 1996), intercropping also has the potential to affect viral infections. Intercropping of cowpea with maize thus led to decreased viral infection and more than doubled cowpea pod weight per plant compared with monocropped cowpea (Aliyu and Balogun, 2012). To achieve suppressiveness of crop rotations or intercropping, proper combinations of crops must be implemented so that inadvertent hosts are not introduced. For example, *Mucuna pruriens* (which may be used to counteract *Striga*) has been found to host the ear borer (Sétamou et al., 2000), a pest of maize and cacao, decreasing it´s value as an intercrop or break crop in areas of ear borer occurrence and highlighting the need to adjust control measures to local conditions.

Push-pull systems are designed by at least two plant species in addition to the main crop, one with the capacity to actively repel an insect pest by its content of semiochemicals and one with the capacity to attract it, thus diverting the pest from the main crop. If the attractive crop is not fit as a host for full progeny development, or if it prevents its migration it serves as a trap crop (Khan et al., 2011), thus decreasing the onward population size of the pest. A decrease in pest numbers may also be achieved by increased predation induced by the trap (or otherwise attractive) plant in response to pest attack (Ratnadass et al., 2012). Such push-pulls systems may possibly in the longer-term lead to selection of pests populations that avoid the trap crop (Thompson and Pellmyr, 1991). Nevertheless, push-pull systems have been introduced which have had a major impact on crop productivity; e.g. a system for the management of maize stem borer which has been widely adopted by farmers in East Africa. It is based on intercropping of maize with repellent crops such as silverleaf desmodium (*Desmodium uncinatum*) and trap crops such as Napier grass (*Pennisetum purpureum*). The adoption success of the system can be sought in the simultaneous suppression of *Striga* while the push and pull crops may be used as green manure and fodder (Khan et al., 2011) and thus contribute to the favourable economic outcome of the system (de Groote et al., 2010).

Figure 10. a) Intercropping of maize with legumes may not only add N to the system but also supresses Striga and may repel maize stem borer (photo: L. Rusinamhodzi), and b) silverleaf desmodium (*Desmodium uncinatum* (Jacq .))(photo: A.S. Dahlin).

While the push-pull systems often rely on above-ground dispersal and effects of semiochemicals, release of allelopathic substances below ground may affect organisms that are less migratory. Apart from suppression of *Striga* (see above), this has been put to use in systems with trap crops. For example *Solanum sisymbriifolium* stimulates hatching of potato cyst nematodes but the life cycle of the nematode is disrupted (Ratnadass et al., 2012), although *S. sisymbriifolium* can be quite invasive in its own right and its introduction into a new area should be thoroughly deliberated beforehand (ISSG, 2014). Other allelophatic substances derived from live plants (e.g. the legumes *Crotalaria juncea*, *Cassia spectabilis* and *Mucuna deeringiana*) or released during plant decomposition (e.g. of brassicas or alliums) may be directly toxic to nematodes, fungi, or bacteria. The effect in a particular case depends on species combinations and also other potential effects of allelophatic crops. Bado et al. (2011) thus found that peanut intercropping in sorghum decreased nematode numbers and infection of the sorghum, whereas cowpea intercropping increased them. However, the positive N effect of cowpea overrode the effect of increased nematode numbers and improved sorghum yields.

The crop species included in rotations and mixed stands also have more indirect effects on soil health and fertility and on the promotion or suppression of transmittors and natural enemies of pests. Although indirect, this effect may be larger and longer-lasting than e.g. inoculating with known pest antagonists or beneficial soil organisms (Ratnadass et al., 2012). Higher plant species diversity has been suggested to increase below-ground biodiversity by providing more ecological niches, and that this may lead to a higher degree of suppression of plant pathogens (Ratnadass et al., 2012). Increased numbers of plant pest predators have also been reported, although the pest suppressiveness of a soil is multi-facetted and effects of crop diversity may vary over time. One reason for this may be interactions between soil organism populations and soil fertility as expressed in nutrient supplying capacity and physical conditions for crop roots. For instance, as crop nutrition improves through inclusion of N_2 fixing legumes in the cropping system, the plant´s ability to overcome infection may increase and yields may improve in spite of pest infection (Bado et al., 2011).

Although introduction of exotic pest enemies into the soil often does not result in long-term suppression of pests, introduction of natural enemies for the control of insect and mite pests above ground has been more successful, especially so when the pest organism also has been (accidentally) introduced (Belotti et al., 2012). Introduction of *Anagyrus lopezi*, a parasitoid of cassava mealybug (*Phenacoccus manihoti*) has decreased yield losses due to the mealybug across Africa, giving benefit-cost ratios for the control of 200 to 740 (Zeddies et al., 2001). The use of bio-pesticides, i.e. micro-organism based products and biochemicals may not yet have a wide market in SSA, but producers of high-value vegetables and flowers for the export market may pave the way, e.g. in Kenya where also small-scale out-growers are adopting integrated pest management (Grzywacz et al., 2009).

Pest resistant and weed competitive crop varieties are another important component of integrated pest management. For instance, cassava cultivation in Uganda, under pressure from spreading cassava mosaic virus and brown streak virus, was revived through introduction of disease-resistant varieties, which contributed to improved economical margins and transformed the intervention area from being food deficient to being a net exporter of foods (Roothaert and Magado, 2011). To take full advantage of the improved varieties, other agronomic measures for the prevention of pests must also be observed, such as eradication of infected plants and using clean propagation material and farm tools, and these may in cases be the only measures available for control of diseases (e.g. for *Xanthomonas* wilt in banana and plantain (*Musa* spp.); Blomme et al., 2005; Ocimati et al., 2013). Such disease management may need to be carried out in a concerted manner on a larger scale to limit (re)infection of newly planted fields from neighbouring farms (Sivirihauma et al., 2013). Also biological pest control may require action on a larger scale, including monitoring and prediction to target the right organisms at the right time.

3.7 Improved crop varieties

New crop varieties showing high yield potential paired with being adapted to the respective production niches (e.g. specialty varieties with high protein or vitamin A concentrations) and biophysical conditions (tolerant to environmental stresses such as pests, and low water and nutrient availability) have been found to increase crop productivity and yields in farmers´ fields. Ugandan sweet potato yields for instance increased from 4.4 to 10 ton ha^{-1} in response to improved varieties and cassava yields increased five-fold after the release of new varieties resistant to cassava mosaic virus and brown streak virus (Pretty, 2011). Although harvest index has generally increased as breeding has progressed (Hay, 1995), this is less evident in pulses as other characteristics have been prioritised in the breeding. For instance, a somewhat lower harvest index has been considered good, e.g. for dual-purpose grain legumes where larger amounts of harvest residues will contribute more to soil C and residual N to be used by following crops (see above).

3.8 Mycorrhiza management

Arbuscular mycorrhizal fungi (AMF) potentially contribute to plants and crop productivity via enhanced uptake of mineral nutrients, improved soil structure and suppression of soil-borne diseases. The abundance and significance of AMF is most prominent on low-fertility soils (Smith and Read, 2008) and hence potentially may be very important in SSA agriculture. It may also be particularly important for crops with poorly developed root system (such as tuber crops), crops propagated in nurseries and crops with high P demand (such as legumes) (Hayman, 1986), again stressing their potential importance in SSA cropping systems. However, AMF communities are strongly affected by land management. Application of organic soil amendments and cropping of host crops enhances AMF abundance, whereas tilling, frequent fallowing and cropping of non-host crops, and high soil nutrient concentrations of especially P tend to decrease AMF numbers and diversity (Smith and Read, 2008; Karasawa and Takebe, 2011). Furthermore, less viable propagules and colonisation were found after wildfire (Vilariño and Arines, 1991; Pattinson et al., 1999) suggesting that the common practice of burning fields to decrease pest infestation also decreases AMF abundance.

Where AMF numbers or diversity are low, inoculation may enhance root colonisation and crop growth (Lekberg and Koide, 2005). However, many factors affect the success rate of AMF inoculation (see review by Verbruggen et al., 2013). Sites where AMF numbers and diversity are low due to former land management are possibly the most likely to respond positively to inoculation. The species of fungi, application modes and prior soil management are also likely to affect the competitiveness of the introduced fungi in relation to the native ones. One potentially successful approach may be to add functional types of AMF that are missing (e.g. that are compatible with a particular crop) at the respective site, and decrease the numbers of native AMF by intense tilling operations prior to patchy application of the inoculum (Verbruggen et al., 2013). Inoculation of plantlets in the nursery has also been tried and has been found to suppress nematode infection in banana and plantain, although evaluation of the longer-term effect in the field remains (Jefwa et al., 2010).

3.9. Cereal-legume intercropping

Intercropping is the systematic growing of two or more crops in proximity to promote interactions between them. Intercropping is more practiced in resource-poor communities where it diversifies and stabilizes crop production and economic returns, distributes farm labour more uniformly and often gives better control of weeds than sole cropping (Midmore, 1993). Intercropping requires rearrangement of planting patterns through substitutive or additive designs to maintain the productivity of the main crop (Liebman and Dyck, 1993; Giller, 2001). Competition can also be reduced by staggering the planting dates of the companion crops in the intercropped system (Francis et al., 1982). Staggered planting is also used as a risk reduction strategy to avoid total crop failure when expected rainfall is uncertain and within-season fluctuations are common (Cooper et al., 2008). Midmore (1993) suggested that to ensure high yield, the main crop should be planted first while choosing a plant population density and row orientation that allow sharing of resources and manipulation of competitiveness to suit desired and targeted yields. Competition can furthermore be reduced by manipulating planting densities in intercropping for different environments and these are often reduced when rainfall and soil fertility conditions are sub-optimal.

Figure 11. a) Staggered intercropping of maize with pigeonpea giving a semi-permanent crop cover, and b) monocropped maize with long periods without crop cover. The fields had the same pre-history but after three years the intercropped field has considerably less weeds (photos A.S. Dahlin).

Intercropping maize and (grain) legumes is a way to achieve both food security and cash income for smallholder farmers (Shumba et al., 1990; Sakala, 1994; Myaka and Kabissa, 1996; Rusinamhodzi et al., 2006; Waddington et al., 2007; Kimaro et al., 2009; Mucheru-Muna et al., 2009; Rusinamhodzi et al., 2012). The inclusion of legumes in the cereal-based cropping systems has many added advantages such as soil fertility replenishment and control against pests and diseases (cf. Rusinamhodzi et al., 2012; Thierfelder et al., 2012). Intercropping maize and pigeonpea for example has been shown to be highly profitable in Africa (Sakala, 1994; Chianu et al., 2010; Ngwira et al., 2012, Rusinamhodzi et al., 2012), although it can potentially increase the labour input especially for weeding due to impeded manoeuvre between the rows (Mucheru-Muna et al., 2009; Rusinamhodzi et al., 2012). Ngwira et al. (2012) also reported higher rates of return in a maize-pigeonpea intercropping system compared to maize cropping alone, although maize yields were lower in this study due to drought stress. The authors concluded that intercropping maize and pigeonpea under no-till was an attractive option due to associated maize yield improvement and attractive economic returns when the prices of maize and pigeonpea grains are favourable.

Opposite results were, however, reported by Waddington et al. (2007) who showed that intercropping may be an unattractive option compared to growing sole maize due to the small yield benefits compared to the relatively high investment costs for legume intercropping. Under similar conditions, Shumba et al. (1990) showed that intercropping maize and cowpea can reduce maize yields by up to 70%. These studies have shown that intercropping cannot be considered beneficial in every situation but effects vary across locations, seasons and crops used for intercropping.

3.10. Conservation agriculture

Conservation Agriculture (CA) is a cropping system originally developed in the Americas and Australia that combines three key principles: (i) minimum soil disturbance, i.e. no soil inversion by the hoe or mouldboard plough, (ii) in situ crop residue retention of available plant material (living or dead) on the soil surface, and (iii) crop rotations and associations to reduce and overcome pest and disease problems in the system (FAO 2002; Kassam et al., 2009). It is a complex but fairly flexible agricultural system that can be widely adapted to local site conditions (Wall, 2007). Development and research agents have, however, been promoting CA as a fixed recipe or blanket recommendation and there is need to take into account farmers' conditions and socio-economic constraints for improved impact. Potential benefits of CA have been widely summarized in recent reviews (Hobbs, 2007; Wall, 2007; Kassam et al., 2009); these include increased rainfall infiltration, reduced evaporative losses, increased SOC, and early planting which often lead to high yield, but it's feasibility and applicability in certain environments and under specific farmers circumstance of southern Africa have also been questioned by Giller et al. (2009) and Baudron et al. (2011). The increases in SOC due to CA are also a subject of a bigger debate with many authors reporting inconclusive evidence (e.g. Govaerts et al., 2009).

Positive impacts of CA on crop yield through moisture conservation are often observed in low rainfall environments (Rusinamhodzi et al., 2011); it thus follows that in high rainfall areas, waterlogging problems may arise. It is also apparent in several studies that improving maize yields under CA depends on the duration and promotion of good agronomic practices such as targeted fertiliser application, timely weeding and crop rotations. Legume production as currently practised on smallholder farms does not cover more than 10% of cultivated area (e.g. Mapfumo and Giller, 2001) meaning that only 10% of the cultivated area may be rotated with legumes per year. For many years, most farmers in Africa have not been able to achieve sufficient fertilisation and crop rotations and it is unlikely that they will do so simply because CA has been introduced. It is also likely that farmers who can achieve the crop management required already have relatively high crop productivity and may not see major benefits of shifting from current practices. Conservation agriculture requires more N fertiliser inputs especially in the short-term together with a complete change of how crop and animal production components are integrated at the farm level. As a result, the minimum requirements for successful CA in much of Africa do not exist, and the technology may need to be tailored to specific circumstances for improved impact.

4. Targeting intensification options to farm types

The short-term needs of farmers to provide for their families must be met in combination with long-term sustainability of agricultural production systems. There is scope for using strategies that can ensure better interventions targeting the various farm typologies. To sustainably intensify crop production, both fertilizer use and nutrient use efficiencies have to substantially increase for all farm typologies. The Abuja Declaration on Fertilizer for an African Green Revolution (2006) committed to increase fertilizer use in Africa to 50 kg nutrients ha^{-1} by 2015, in order to improve agricultural productivity and thus food security (IFDC, 2007). Progress to achieve this target has been variable across countries. However, these initiatives need supporting management at the farmer level to have meaningful impact. The real opportunity for farmers to increase productivity in the short-term is through efficient targeting of the limited nutrient resources they are currently accessing. While there has indeed been much work on approaches to improve nutrient use efficiencies, the results have largely remained unused, as they failed to address the heterogeneous biophysical and socio-economic conditions on the ground.

Abundant literature suggests that farmers are often doing the best they can with available resources, and within the confines of their current knowledge. However, most farmers often lack a good understanding of how best to manage resources when they become available. For example, poor efficiency of fertilizer despite its use can be largely due to problems in timely delivery of the inputs, inappropriate fertilizer types and poor targeting of fertilizers to fields with different soil fertility constraints. Many farmers cannot use the fertilizer recommendations generated by national extension agents, as they are often beyond their economic means or are rarely updated to factor in changing trends. Similarly, intensification options have not been developed to address specific constraints faced by farmers. There is therefore an opportunity to work towards a better adapted pathway of diagnosis and recommendation of options that address the variable soil fertility conditions, farmers' capacity to invest in the suggested options as well as to address the vagaries associated with droughts.

The process to develop site-specific crop production intensification options considers complex factors that include edaphic, climatic as well as socio-economic factors. Most farmers' fields are in the following 4 categories: (i) low-responsive fertile soils where nutrient availability is not limiting production; (ii) high-responsive fertile soils; (iii) high-responsive infertile soils; and (iv) low-responsive degraded infertile soils. The NUANCES framework provides a good starting point in this process although the ultimate farmers' decision is underpinned by the resources at their disposal and market opportunities for their produce. For instance, cases of crop productivity being improved due to cereal-legume intercropping are abundant in the literature. However, the marketing conditions for legumes remain fragmented in much of Africa and pose a serious threat to continued integration of legumes into the farming systems. Chemical fertilisers alone often do not increase crop yields especially in soils with depleted organic matter, but on the other hand application of cattle manure alone does not meet the nutrient requirements of crops (Rusinamhodzi et al., 2013). Thus, a combination of organic and chemical fertiliser is required to achieve high yields (Chivenge et al., 2009; Chivenge et al. 2011). Hence, farmers who own cattle and can achieve significant amounts of manure still need to purchase mineral fertiliser. On the other hand, farmers who do not own cattle but are able to purchase fertilisers may have to identify alternative C input with crop residue retention among the most promising. However, current biomass productivity is often still low and does not allow the in-situ retention of crop residues in the field to provide soil cover in mixed crop-livestock systems.

Retention of crop residues will lead to depressed yields in the short term due to immobilisation of N and increases the need for fertiliser investment. This contrasts sharply with farmers' needs and makes CA unattractive for most farmers; the main objectives of farmers are to achieve food security and cash income. Therefore the short term needs of farmers maybe a threat to the uptake of CA. There is need to target technologies to the needs of farmers by recognising the spatial and temporal variability due to differences in biophysical and socio-economic conditions i.e. creating so-called 'recommendation domains'. Farmer participation in setting the research agenda in agricultural research and development is important as it allows exploration of options that are appropriate under their conditions (Johnson, Lilja et al. 2003, Rusinamhodzi and Delve 2011). The approach is necessary to reveal intrinsic farmer preferences for new technologies against established technologies, and opportunities as well as constraints for their widespread use (Chianu, Vanlauwe et al. 2006). For example, farmers in Mozambique strongly believed that fertilizers kill the soil yet they also recognised that soils have lost fertility. They strongly rely on local methods to rebuild soil fertility and integration with legumes seems the most promising entry point. Efforts to improve fertiliser use may need to overcome this initial resistance.

5. Long term effects of selected interventions – A modelling case study from central Mozambique

The possible impact of selected crop intensification options discussed in the preceding sections were analysed for three case study farms that differed in resource endowment in central Mozambique. Several scenarios were created using the biophysical as well as the socio-economic status of the case study farms, and their long-term effect analysed with the aid of modelling tools. The farming systems of central Mozambique are dominated by extensive production systems in which slash and burn, and fallowed fields are common. Traditional food crops such as maize, sorghum (*Sorghum bicolor* (L.) Moench) and pearl millet are dominant (Rohrbach and Kiala, 2007). Fewer farmers grow groundnuts (*Arachis hypogaea* L.), cowpea and local varieties of pigeonpea on small pieces of land. Cultivation on mountain slopes is common. In central Mozambique, labour shortages have significant impact on weeding activities as planting is often staggered as a strategy to deal with climatic uncertainties. The labour shortages often lead to severe weed pressure which is only controlled by burning the entire field before seeding of the next crop. Cattle are important livestock in the farming systems although very few farmers own them in significant numbers. Manure is reserved for the vegetable gardens were large application rates can be achieved due to the small areas cropped to vegetables; vegetable gardens provide important cash needs for most families especially in the dry season when water is limiting but sufficient for irrigation of vegetable gardens, which are often of small sizes (ca. 0.1-0.5 ha).

Figure 12. a) Slashed and burnt area (photo: A.S. Dahlin), and b) cropped slope in central Mozambique (photo: L. Rusinamhodzi).

Figure 13. a) Weed-infested fields and b) cattle grazing in maize field after harvest (photos: L. Rusinamhodzi).

The cropping systems in much of central Mozambique can be regarded as *‘plant and hope systems’* in which nutrient inputs are almost non-existent, rainfall is erratic, and labour availability insufficient for the large tracts of land that are cultivated. This extensification system is used as a risk reduction strategy in response to the declining crop yields of particularly maize. In these systems, choice of planting time probably has the largest effect on crop productivity as it is critical to avoid the devastating effects of long dry spells. However, due to dysfunctional weather prediction systems, offsetting the devastating effects of dry spells is rather a case of serendipity than a result of systematic management decisions. The extension support is almost non-existent especially at the local level, resulting is limited external ideas to stimulate innovation and raise the perennially small yields.

5.1 Farm typologies in central Mozambique: an example from Ruaca community

A categorization of farmers into wealth or resource groups (RG) was done based on a total of 52 farmers selected randomly in Ruaca, central Mozambique (Rusinamhodzi et al., 2012). Four resource groups were identified using the size of cropped land, the number of cattle owned, the farmers’ production orientation and the characteristics of the main house (Table 1). The high-resourced farmers in category RG1 depended on off-farm activities for most their livelihoods, provided an important link with traders and employed labourers. Farmers in category RG4 were under-resourced and frequently worked as casual labourers for wealthier farmers in the village. The middle resourced farmers (RG2 and RG3) constituted a larger proportion of farmers and derived most of their livelihood from farming activities; they often intensified vegetable production in the dry season when field activities had subsided. During the dry season, these farmers drew water from small rivers flowing from the mountains using a low-cost furrow irrigation system. The extreme resource groups (RG1 and RG4) cannot be regarded as deriving their livelihoods from farming activities, and the incentive to intensify their cropping systems to increase own production less important; targeting crop intensification options to these is thus futile. Principal components analysis showed that more than 97% of the variability in resource ownership was explained by the first three principal components, PC1 (89%), PC2 (6.7%) and PC3 (1.9%). PC1 was strongly related to livestock ownership and PC2 was related to land size owned and area of land cropped.

Table 1. Perception of wealth and the resource groups identified by farmers in Ruaca, central Mozambique. Numbers in parenthesis are the number of farmers in that particular resource group (adapted from Rusinamhodzi, Corbeels et al. (2012)).

RG1 (6)	RG2 (13)	RG3 (19)	RG4 (14)
Land size ≥ 10 ha, >10 cattle, > 10 goats, permanent house, farm workers, transport: car, bicycle, ox-cart. Have jobs in the city. Main house has bricks walls and iron sheets. Access to clean water and good sanitation. Children go to school. Access to credit and loans.	Land size ≥ 10 ha, 5-10 cattle, > 10 goats, permanent house, farm workers, transport: ox-cart and bicycle. Consistently food secure, more off-farm activities and income. Access to clean water and good sanitation. Children go to school.	Land size 2-5 ha, < 5 cattle owned, < 3 goats, medium farm compound, occasionally sell labour, production is just enough to feed the family.	Land size 0.5-1 ha, small farm compound, sells labour, and consistently food insecure. They are often heavy drinkers and children often do not go to school. Lack of blankets, utensils and clothes.

5.2 Criteria for selecting case study farms

The farm typology provided a starting point in identifying an intensification gradient which was important in selecting case study farms. It was important that selected farms derived most of their livelihood from farming (i.e. belonging to RG2 and RG3) while being good representatives of farmers in the study site. Three farmers (Topu, Meki and Madalena) were selected for the scenario analysis (Table 2, Fig. 2). A striking characteristic of the study farms as well as the majority of farmers in Ruaca is that a greater proportion of their fields do not receive nutrient inputs. Only fields that are close to the home receive manure and the vegetable gardens receive both manure and mineral fertiliser (NH_4NO_3 and NPK) in a somewhat irregular pattern across seasons. Ash from the household cooking fire is also applied irregularly on portions of the fields close to the homestead.

Farmer Topu has the largest and highest-resourced farm, often hires in labourers to work on the outfield (i.e. field far from homestead) during weeding times and pays through some of the maize produce. He owns more cattle than the other case study farmers, and uses these for tillage and transportation of produce. The farm is self-sufficient, and food often lasts until the next harvest, with significant sales in between. Farmer Meki is a middle-resourced farmer who sells labour to others, especially ploughing for a fee. The family is usually self-sufficient for 9 months but suffers food deficit for about 3 months of the year, although some good years they can sustain themselves with their own food production for the full year. They only cultivate fields close to the house. Farmer Madalena is the least resourced of the farmers selected. She sometimes hires labour (paid immediately in kind) as she has very small labour available within the household. Her food production often feeds the family for 4 months only and she has to buy for 8 months; in a good year she manages to sell some produce, though.

Figure 14. a) Sample buildings on high-resourced, b) middle-resourced and c) poor farm (photos: L. Rusinamhodzi).

Farmer Madalena only uses a little goat manure on the vegetable garden during the dry season, due to the small number of animals she owns. Her fields are, however, grazed by other farmers´ livestock after harvest; thus there is a very weak integration between main crop and livestock production (Fig. 15). Farmers Meki and Topu use similar inputs although Farmer Topu has a larger farm, uses more manure and fertiliser, has larger land utilization and crop-livestock integration than Farmer Meki. It is clear that in some instances variability is larger within than across farms as shown by the characteristics of Farmer Meki and Farmer Topu. The fields close to the house receive large inputs through manure, household ash and management for Farmer Topu, but the outfields are less managed, thus creating a wide variability within the farm (Fig. 15).

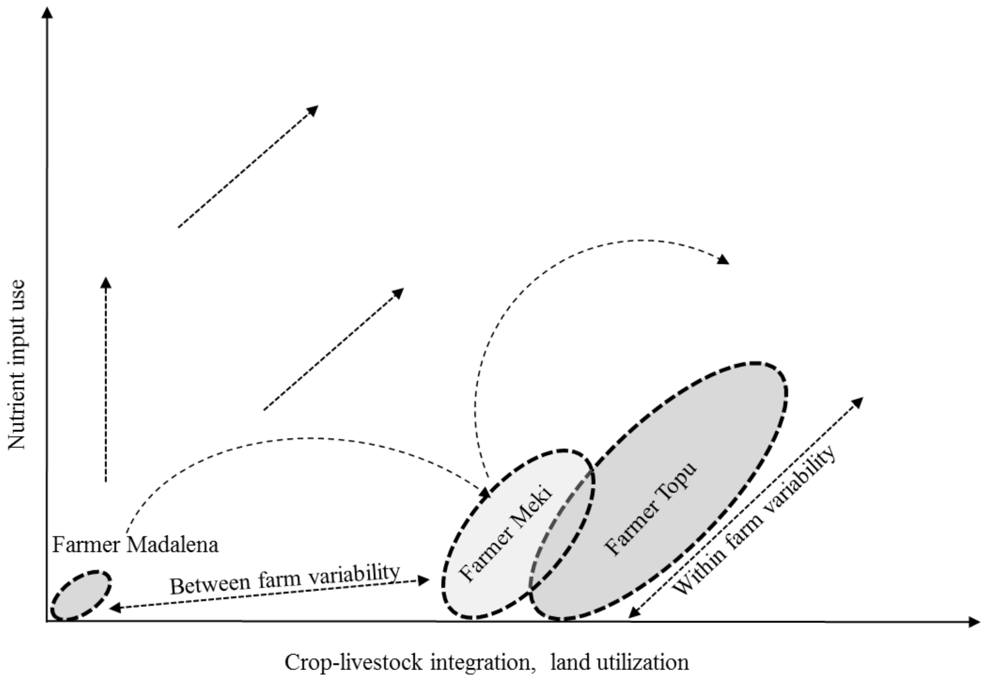

Figure 15. Relative differences in characteristics of the case study farms where land utilization is the ratio of total land under crops to total land owned. Arrows show possible development pathways, i.e. whether farmers will increase nutrient use and manage a purely crop-based system or increase the integration of crop and livestock thereby using manure for crop production and crop residues for livestock feed.

Table 2. A brief comparison of the case study farms selected for the scenario analysis.

Factor	Farmer		
	Topu	Meki	Madalena
Farmers' age	55	74	64
Land size (ha)	18 (3)*	4 (4)	6 (2)
Labour availability (productive persons)	3	4	1
Number of cattle	9	4	0
Number of goats	10	4	4
Manure used (carts farm^{-1} yr^{-1})	12	5	0
Fertiliser used (kg farm^{-1} yr^{-1})	150	100	0
Farm yield (maize) (kg farm^{-1} yr^{-1})	8000	2500	2500
Annual income from own production (MT)	18200	3750	6250
Annual income from own production (US$)	607	125	208

*Numbers in parenthesis indicate the size of the homefields; Meki did not have an outfield.

5.3 Modelling framework

Although the major focus of farmers is most likely to increase crop productivity in the short term, sustainability is also important for the future development of smallholder agriculture. Research had demonstrated the linkage between soil quality, crop yield, and agricultural sustainability (Karlen, et al., 2001). In the modelling analysis, soil organic carbon was used as a measure of the sustainability of the options considered for intensification of crop production. The FIELD sub-model of the NUANCES-FARMSIM model (van Wijk et al., 2009) was used to simulate crop production and the dynamics of C and nutrients in the soils. In the model, crop production is calculated as the product of resource availabilities and efficiencies (Tittonell et al., 2010b). FIELD calculates yields on a seasonal basis using resource interactions to predict light-determined, water- and nutrient-limited crop yields (N, P and K). Seasonal availability of soil nutrients is calculated following the QUEFTS approach (Smaling and Janssen, 1993) and soil organic matter dynamics calculated with a 4-pool soil C model following first-order kinetics. Detailed explanations of the model structure were provided by Tittonell et al. (2008, 2010b). The cropping system considered in the simulation scenarios was continuous maize production in line with current farmers' practice using a 10 year rainfall dataset for the site derived from a weather station at Sussundenga Research Station (ca. 40 km from the case study farms).

5.3.1 Modelling the effects of weeds on crop productivity

Availability of labour for sufficient weed control is critical in low-input systems to ensure as large crop productivity as possible (van Wijk et al., 2009; Harris and Orr, 2013). Several farm activities take place at certain moments in the crop production cycle; this leads to a temporal variability in the demand for labour needed to perform activities such as weeding to prevent loss of productivity. In the modelling approach, the demand for labour for an activity was compared with values of labour availability at the farm level; if in a season labour availability was larger or equal to labour demand, no reduction was made to the biophysically-determined crop production values. When labour was not sufficient, the biophysically determined levels of production were reduced by multiplying them by a 'labour reduction factor'. The reduction factor was developed as a function of the amount of labour required for an activity and the corresponding labour available to the farmer on a seasonal basis.

5.3.2 Modelling the effects of maize-legume intercropping and CA

Cereal-legume intercropping is one of the ways to improve food security and soil fertility whilst generating cash income of the rural poor (Rusinamhodzi et al., 2006). With the same inputs, the intercrop strategy allows the manipulation of various arrangements or planting dates of the same or different crops to achieve the desired objectives of food security and cash income. Recently, maize-legume intercropping combined with practices such as mulch retention has been shown potential to alleviate the food and cash constraints of smallholder farmers (Mucheru-Muna et al., 2009; Rusinamhodzi et al., 2012). However, it has also been revealed that this intercropping system mainly is successful in certain seasons for certain farmers under certain market conditions (Rusinamhodzi et al., 2012). In this study we employ a simple semi-empirical radiation-based model approach to explore the potential of crop production intensification using maize-legume intercropping. The modelling approach has been developed and adapted to the semi-arid conditions of southern Africa (Tsubo et al., 2005a; Tsubo et al., 2005b). The intercropping system involves both mulch retention of the main crop maize and inclusion of a legume crop. Mulch improves water use efficiency (WUE) by improving available moisture in drier periods through increased infiltration and reduced soil evaporation. The water capture efficiency in the model was thus allowed to increase by 10% (Wang et al., 2011) during the drier years when rainfall was below the long-term average of 750 mm per season. The major assumption was that the impact of mulch is relevant to the water capture efficiency and not the water conversion efficiency. To simulate the effect of CA on crop yields, FIELD was parameterized against long-term maize yield data from a tillage and residue management experiment on a sandy soil from Domboshawa, Zimbabwe (Vogel, 1993; Nehanda, 2000).

5.4 Crop management scenarios

The model scenarios were developed based on the conditions prevailing in Ruaca, central Mozambique, with a focus on nutrient inputs and weed management. The general field and crop management, incl. nutrient input data and weed management, for the baseline scenario were derived from the resource flow mapping of each of the three case study farms. Moreover, field measurements of current crop productivity were made on selected farmers' fields to corroborate farmers´ information. Weed biomass was also estimated at maize harvest time to understand the contribution of weeds to C input in cases where fire is not used for land clearance. Other management variables, such as time of ploughing, were deemed relatively less important in these systems and thus not varied in the scenarios.

Scenario 1 Baseline scenario- no systematic nutrient inputs, labour constraints
Farmers do not use mineral fertiliser or livestock manure for main crop production, and crop residues are consumed by animals. Weeding is only done once per season, labour is the major input and thus major constraint to farm food self-sufficiency. Outfields benefit from long-term fallowing, followed by slash and burn (relevant in the initial years after field opening).

Scenario 2. No nutrient inputs, no labour constraints
The assumption here is that the farmer uses additional resources to hire labour and achieve optimum weeding in the homefields. This was done to find out the contribution of outfields to total farm yield if the farmers could have access to additional labour only. This is necessary to assess contribution of outfields to farm productivity when farmers can afford optimum weeding in the whole farm.

Scenario 3 Fertiliser available, labour constraints
The farmer has access to mineral fertiliser, and applies 30 kg N, 20 kg of P and 20 kg K ha^{-1} per season to homefields, and therefore nutrients are less limiting to crop productivity on homefields. The outfields receive no nutrient inputs and labour still constrains the productivity of the farm.

Scenario 4 Fertiliser available, no labour constraints, decreased area
Farmers have access to mineral fertiliser, and apply 30 kg N, 20 kg of P and 20 kg K ha^{-1} per season to homefields only. Labour is not limiting as farmers abandon the outfields and concentrate management efforts on the homefields and thus can achieve optimal weed control.

Scenario 5 Crop residue retention + fertiliser, labour constraints
Farmers have access to mineral fertiliser, and applies 30 kg N, 20 kg of P and 20 kg K ha^{-1} per season in the homefields where crop residues from the previous season are also retained. This scenario is realistic due to the small livestock densities observed, although crop residues need to be protected in the dry season. However labour for efficient weeding is scarce, thus crop productivity is limited by labour availability.

Scenario 6 Crop residue retention + fertiliser, no labour constraints, decreased area
This scenario is similar to scenario 5.4.5, labour is not limiting as farmers abandon the outfields and concentrate management efforts on the homefields.

Scenario 7 Manure used, labour constraints
Farmers have access to manure depending on their own number of cattle and apply this in the homefields. The outfields receive no nutrient inputs and labour still constrains the productivity of the farm. This scenario is not applied to farmer Madalena who does not own cattle.

Scenario 8. Manure used, no labour constraints, decreased area
This scenario is similar to scenario 5.4.6, labour is not limiting as farmers abandon the outfields and concentrate management efforts on the homefields.

Scenario 9. Manure and fertiliser used, labour constraints
Farmers have access to manure depending on their own number of cattle and apply this in the homefields combined with mineral fertiliser at 30 kg N, 20 kg of P and 20 kg K ha^{-1} per season. The outfields receive no nutrient inputs and labour still constrains the productivity of the farm. This scenario is not applied to farmer Madalena who does not own cattle.

Scenario 10. Manure and fertiliser used, no labour constraints, decreased area
This scenario is similar to scenario 5.4.9, labour is not limiting as farmers abandon the outfields and concentrate management efforts on the homefields.

Scenario 11 Maize-legume intercropping, residue retention + fertiliser, decreased area
In this scenario, we assume that farmers can intercrop maize and pigeonpea in the homefields to address the N limitations. Deficiencies of P and K in legumes will be addressed through the application of fertiliser, and manure (if available on farm) is used for the maize component. The outfields are abandoned thus liberating sufficient labour to achieve optimum weed control.

5.5 Field scenarios

The field characteristics used in the simulations are shown in Table 3. Generally, the homefields contained less SOC and N compared to the outfields mainly due to longer periods of continuous maize cropping in combination with crop residue burning. However, the homefields generally contained more P, possibly due to the irregular but recurrent application of household ash. There was no relationship between farm type (resource endowment) and soil fertility, probably due to almost similar management intensities across farms and differing soil types. The higher soil organic C and total N concentrations in Farmer Meki´s homefields were probably linked to the higher clay content of these fields as well as a shorter total period of cropping. More marked soil fertility differences in this particular site are expected in the vegetable gardens where preferential application of manure and fertiliser take place. However, vegetable gardens are excluded from the modelling analysis as they occupy very small areas in comparison to the farm sizes and they contribute little to main food production.

Table 3. Selected soil characteristics of the fields belonging to the case study farms used in the in the simulations.

Farmer (resource level)	Field type	Area (ha)	Age (yr[b])	SOC (%)	P (mg kg^{-1})	pH	Clay (%)	Silt (%)	N (%)	Bulk density (kg m^{-3})
Topu	Home	3	20	0.4	35	6.2	10	2	0.03	1420
(high)	Out	15	8	0.6	36	6.2	8	2	0.04	1400
Meki	Home	4	15	0.8	11	5.7	18	5	0.06	1500
(middle)	Out[a]	-		-	-	-	-	-	-	-
Madalena	Home	2	36	0.4	22	5.2	12	2	0.03	1422
(low)	Out	4	6	1.1	15	6.2	12	2	0.07	1370

[a] This farm only has homefields.

[b] Weighted average for whole area.

5.6 Model outputs

A graphical analysis of the model outputs vs observed yields showing the spread of data around the 1:1 line suggested that the FIELD model was sufficiently robust to model the different options for crop production intensification (Fig. 16). The main deviation was that there was a general overestimation of crop yield in the fertiliser as well as the combined manure + fertiliser treatment treatments.

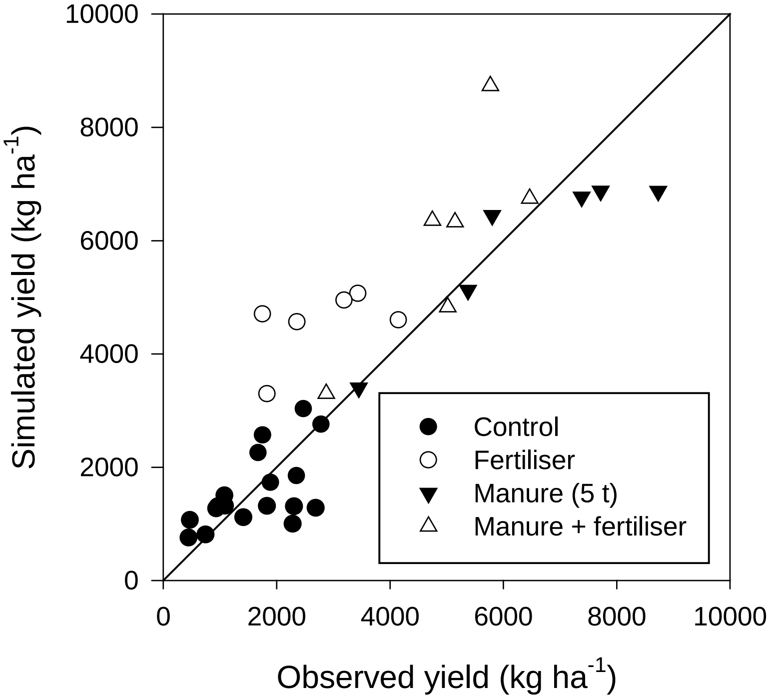

Figure 16. The ability of FIELD –QUEFTS to simulate the maize productivity under different management scenarios. Results showed that the model simulated reasonably well.

5.6.1 Effects of fertiliser application and weeding on crop productivity in continuous monocropped maize systems

The modelling output showed that there is little scope for all farm types to improve crop productivity at current weed management (Fig. 17-19). For example, applying fertiliser (30 kg N, 20 kg P and 10 kg K ha^{-1}) alone or in combination with crop residue retention only approximately doubled maize productivity from an average of 0.2 t ha^{-1} to ca. 0.380 t ha^{-1} on the poorest farm, and the yields showed a declining trend over the simulation period. Under current weed management, there was also no clear difference in productivity whether farmers applied fertiliser alone or in combination with crop residue retention.

Poorly resourced farm. The modelling results suggested that the poorest farmer could raise her productivity from 0.2 t ha^{-1} to ca 0.7 t ha^{-1} on homefields when adequate weed control was achieved (Fig. 17). The application of fertiliser alone or in combination with crop residue retention could further raise the productivity to an average of 1.1 and 1.2 t ha^{-1}, respectively. In both situations, the yields showed a declining trend over the simulation period.

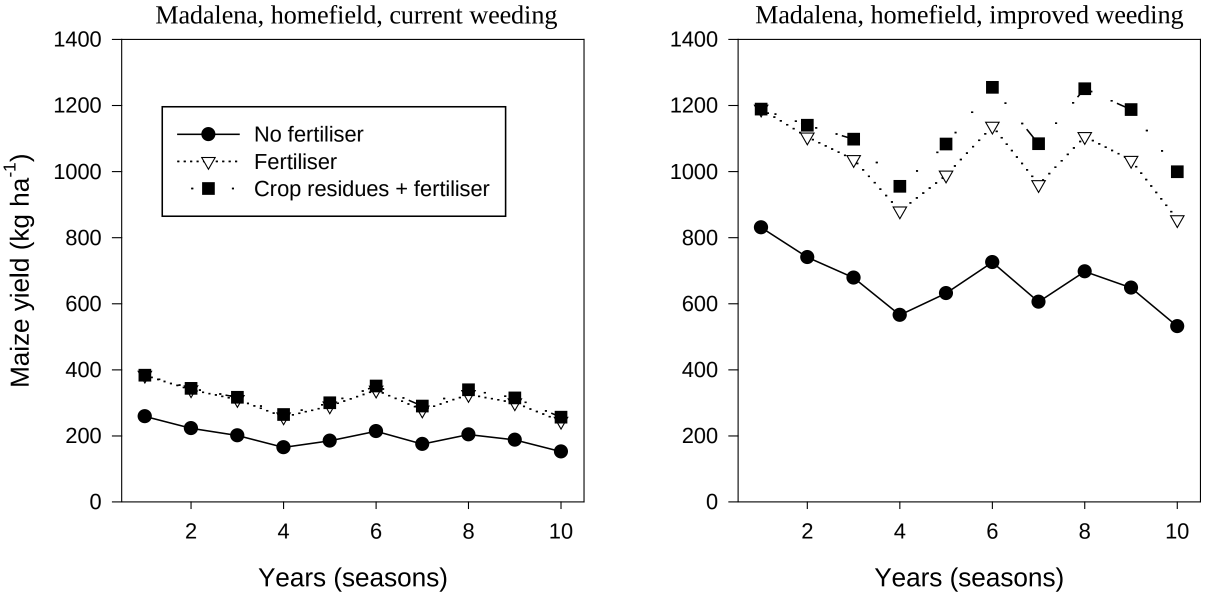

Figure 17. Simulation of maize productivity in homefields under inadequate and optimum weed control for the poorest (Madalena) case study farm.

Middle resourced farm: The middle resourced farm had relatively more fertile fields than the poorest farm and thus its current productivity was larger than the poorer farm at the same weed management regimes. They also owned cattle which meant that they had an extra option for soil nutrient replenishment. The model simulations suggested that adequate weeding alone raised initial productivity from an average 0.5 t ha^{-1} to about 1.2 t ha^{-1} (Fig. 18). They also showed farmers could increase their productivity to about 0.9 t ha^{-1} if they applied manure in combination with fertiliser even without adequate weed control. However, when optimum weeding was achieved, the application of manure (3 t ha^{-1}) and fertiliser achieved a yield of 2.2 t ha^{-1} which showed an increasing trend from the base year. Although the retention of previous crop residues and fertiliser increased yield to about 2.0 t ha^{-1}, it was still smaller than the combination of manure and fertiliser and equally affected by seasonal fluctuation of rainfall.

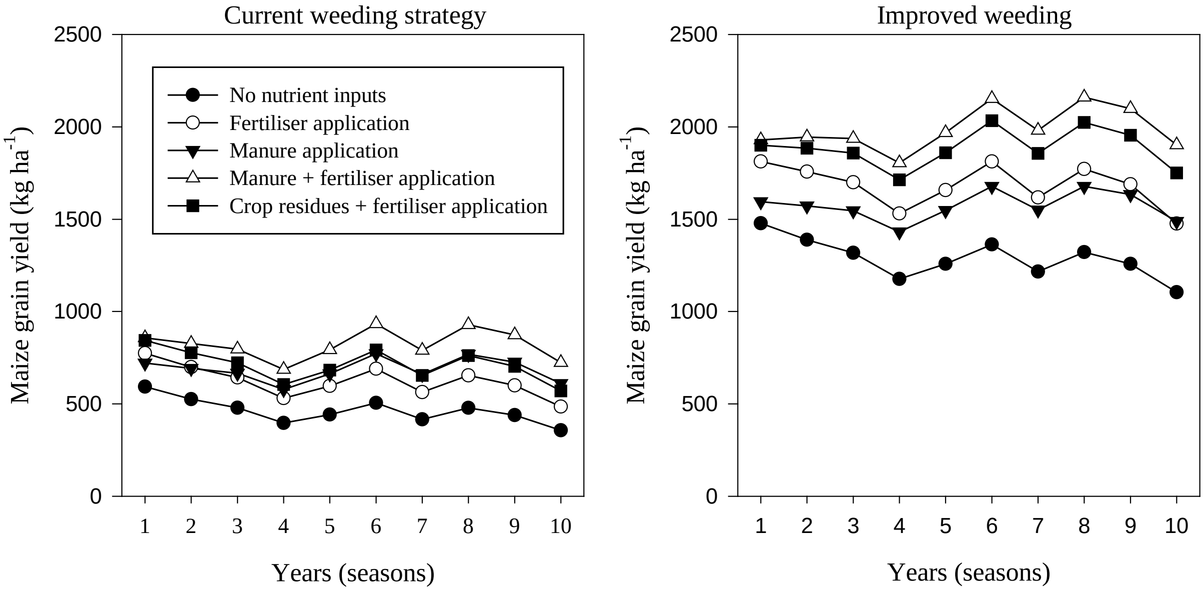

Figure 18. Simulation of maize productivity in homefields under inadequate and optimum weed control for the middle-rich (Meki) case study farm.

High resourced farm. The high resource farm had similar options of rebuilding soil fertility as the middle resource farm although they had larger potential quantities of manure. They could thus achieve about 5 t of manure per hectare of homefield compared to 3 t ha^{-1} for the middle resourced farms. The soil fertility status of the homefields of the richer farm was, however, poor and similar to the poorest farm. As a result the model output showed that the baseline productivity with inadequate weed control was similar to the poorest farm at 0.2 t ha^{-1} but could be raised to 1.0 t ha^{-1} with the application of manure in combination with fertiliser (Fig. 19). The other options such as application of manure only, fertiliser only and fertiliser in combination with crop residues retention fell in between. With adequate weed management, the farmer could achieve a yield of around 1.0 t ha^{-1} without nutrient inputs, although it declined with continuous maize cultivation. The combination of manure and fertiliser with improved weeding had potential to achieve up to 2.5 t ha^{-1} in the long-term. The richer farm could achieve a higher yield of around 2.0 t ha^{-1} with the application of manure only which was larger than a combination of fertiliser and crop residue retention.

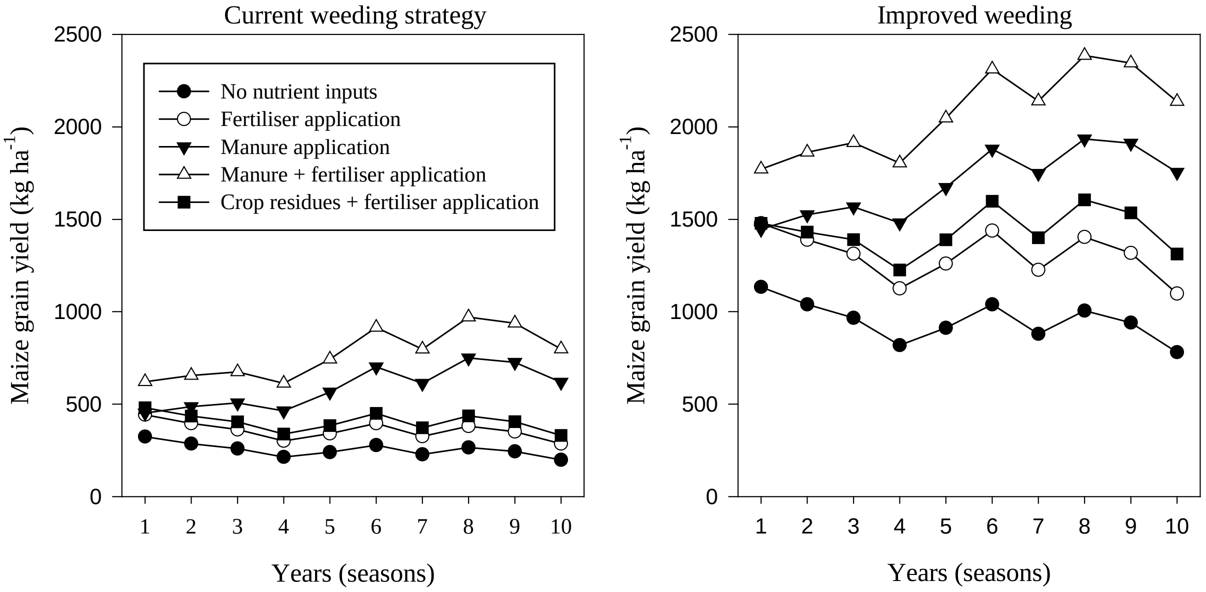

Figure 19. Simulation of maize productivity in homefields under inadequate and optimum weed control for the richest (Topu) case study farm.

5.6.2 Contribution of outfields under current and improved weed management regimes

The total farm yield of maize grain in the baseline scenario of the poorly-resourced farmer was about 3.5 t grain over the 6 ha of land, and decreased to about 2.5 t over the ten year period (Fig. 20a). Abandoning all outfields to achieve optimum weeding with fertiliser application to the homefields initially yielded a total farm production of 2.4 t grain, but decreased over the 10 year period. The outfields thus contributed strongly to total farm production and improved management of the homefields could not fully compensate for the abandonment of the outfields of this farm. The total farm yield of maize grain in the baseline scenario of the high-resourced farmer was about 6 t grain over the 18 ha of land, and decreased to about 5 t over the ten year period. Abandoning the outfields to achieve optimum weeding with fertiliser application to the homefields yielded 4.5 t. Optimum weeding of homefields combined with fertiliser and manure application produced yields of just over 5 t (i.e. similar to the present total farm production), and this tended to increase over time to on average close to 7 t at the end of the 10 year period (Fig. 19a), suggesting that with improved management the homefields could fully replace the abandoned outfields in time, even if not immediately. The middle-resourced farmer had no outfields and intensification of resources to a smaller land area thus would require that some of the homefields be abandoned. Assuming that only one third of the field area was retained, productivity more than tripled under improved weed management combined with manure application or fertiliser application with residue retention. This gave a farm production that was similar to that of the low-input, poorly weeded management but which increased over time whereas the low-input management lead to decreasing farm production over time.

The focus of the modelling study was to explore options for intensification through abandoning the outfields and concentrating limited resources such as nutrients and labour to the homefields. However, the productivity of outfields under assumed improved weeding was also explored. The outfields of the case study farm of the richer farm type was situated on very sandy soil of poor fertility whereas the outfield of the poorest farm was on relatively fertile soil. Although the richer farm's fields were of poor fertility and poor productivity (0.3 t ha^{-1}), the farmer achieved significant yields by cultivating a large area such that at current weed management, about 6 t of maize grain was achieved for the farm (Fig. 20a). The poor farm obtained about half that amount. Assuming that the farmers would use more of their produce to hire additional labour and achieve optimum weed control in the outfield, productivity of the rich farm´s outfield increased to about 1.3 t ha^{-1} and total yield for the farm to about 20 t. The poor farm could achieve productivity of 1.6 t ha^{-1} at optimum weed control in the outfield, the smaller land area meant that the total yield was only increased to 6 t. The productivity of maize in the outfields in both cases decreased over the simulation period (Fig. 20b), though; hence total farm production decreased. While this suggests farmers may increase their production through improved weeding, hiring labour comes at a price and may only be economically viable and sustainable if plant nutrients are also applied and soil fertility is maintained or improved.

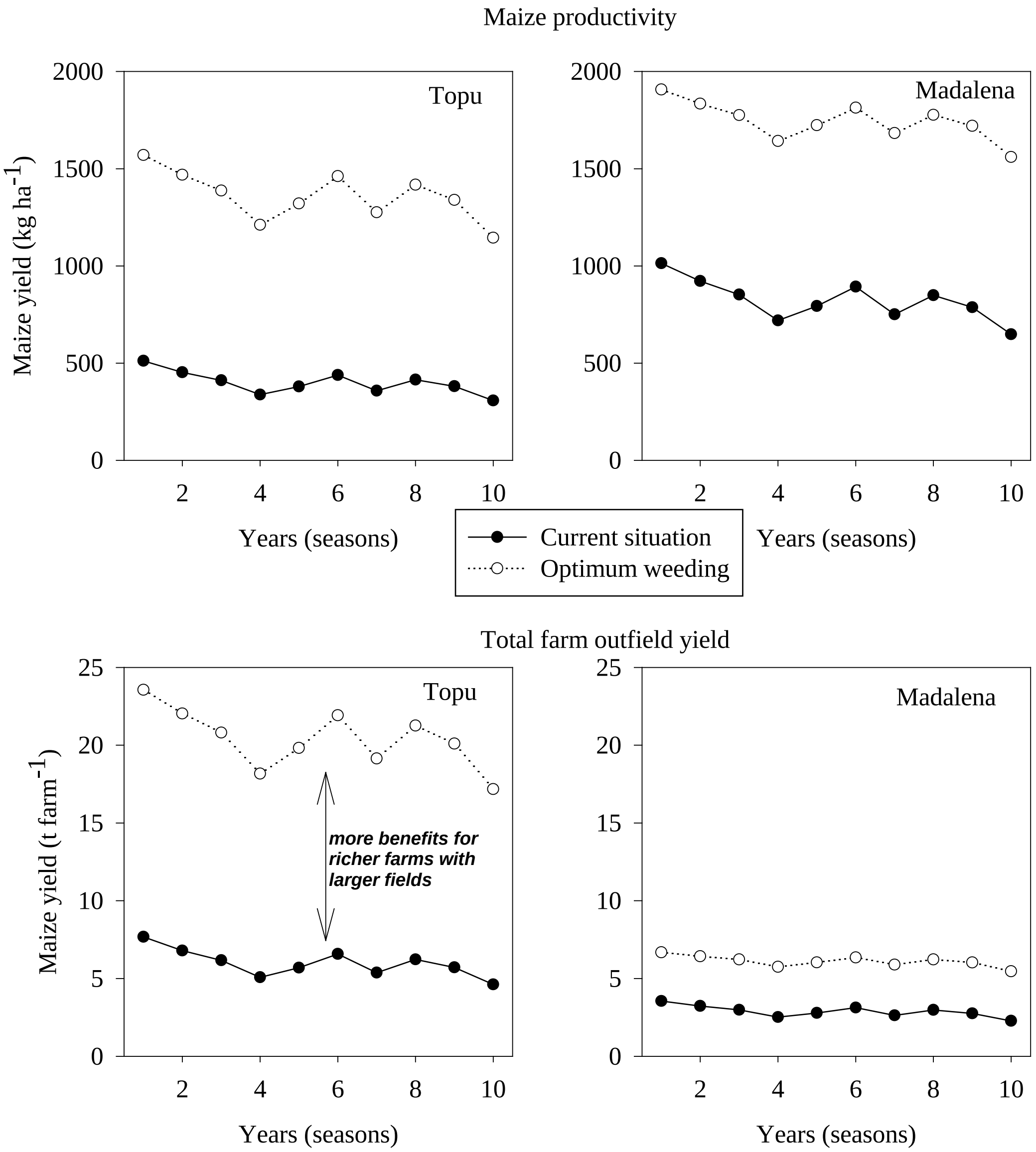

Figure 20a. Maize productivity (top) and total farm yield from the outfields under current and improved weeding; larger yields are possible for farms with large outfields.

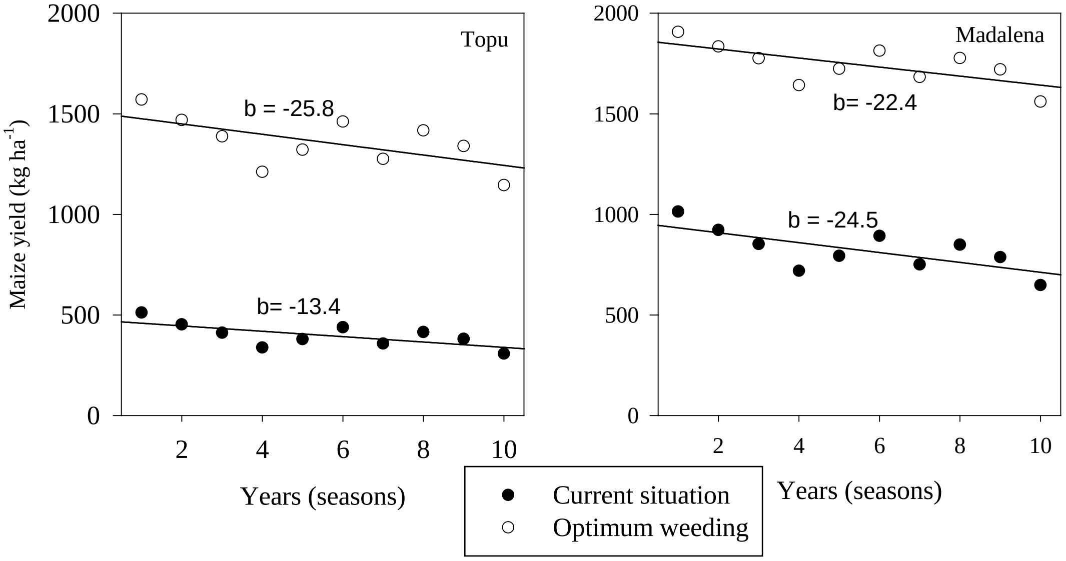

Figure 20b. Maize yield decline in outfields of farmers Topu and Madalena without nutrient inputs at current and optimum weeding.

5.6.3 Soil organic carbon dynamics in homefields under continuous maize monocropping

Soil organic carbon increase is underpinned by C inputs into the soil in amounts that exceed those dissipated by the oxidation process. Hence options that include crop residue retention and manure application have a greater opportunity to significantly increase SOC. Results across farms suggested the increases in SOC were indeed directly related to the C input into the soil as well as to the initial SOC.

Poorly resourced farm. The model suggested that application of fertiliser with removal of above-ground biomass at the poorly resourced farm did not sustain SOC under either weeding regime. Instead it led to a steady decline of the same order of magnitude as that in the unfertilised scenario, i.e. from about 11 t ha^{-1} to 10 t ha^{-1} over the 10 year period (Fig. 21). Simulations suggested the farmer´s most feasible option to improve C input into the soil was through crop residue retention (because she did not own any cattle). Crop residue retention combined with fertiliser application increased SOC under both weeding regimes, although the increase was higher for the current weeding regime (to about 13 t ha^{-1}) than for the improved weeding (to about 12 t ha^{-1}). On the other hand, when crop residues were removed from the field there was little difference between the weeding regimes.

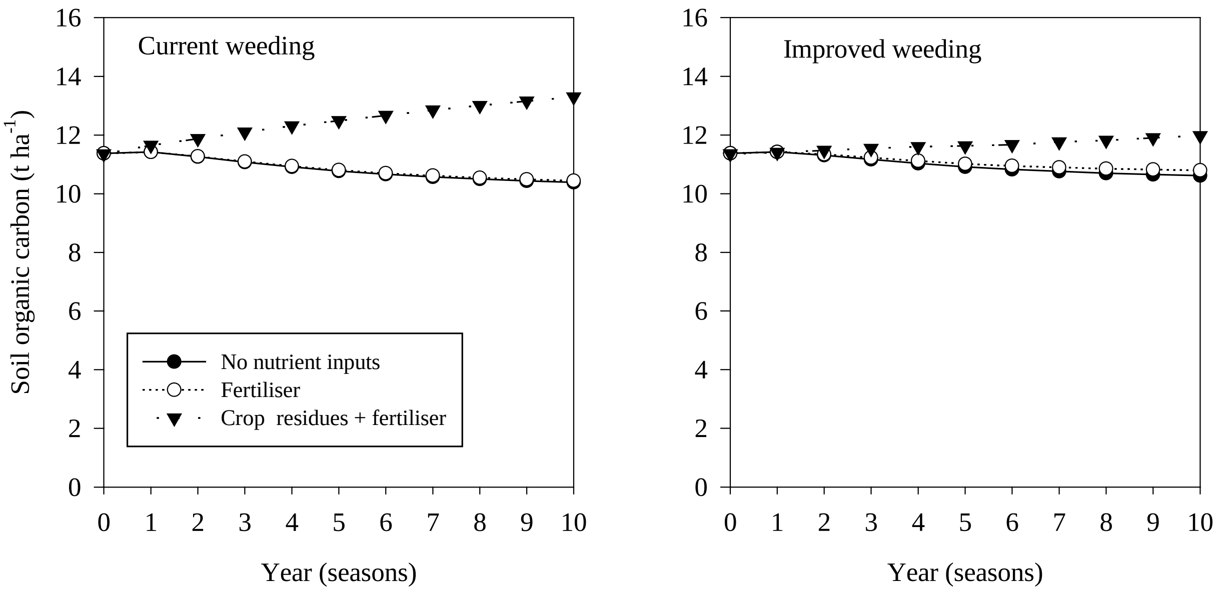

Figure 21. Simulation of soil organic carbon content at current production as well as under different options of intensification with and without optimum weed control for the poorest case study farm in Ruaca, central Mozambique. The “no nutrient input’ scenario follow the same curve as the ‘fertiliser’ for the current weeding regime.

Middle resourced farm. For the middle-resourced farmer, fertiliser application without adequate weeding slightly improved SOC stocks compared to the unfertilised scenario, but the total SOC concentrations nevertheless decreased over time (Fig. 22). Crop residue retention combined with fertiliser application with or without adequate weeding just about maintained the SOC at 24 t ha^{-1}. The manure treatments in combination with fertiliser application increased SOC at both weeding regimes to about 26 t ha^{-1}. The general effect of weeding regime on SOC concentrations was small just like on the poorly-resourced farm. A difference between the farms, though, was that crop residue retention combined with fertiliser application just sufficed to maintain the SOC content on this farm but increased SOC content on the poorly-resourced one, reflecting the higher original SOC content of the middle-resourced one.

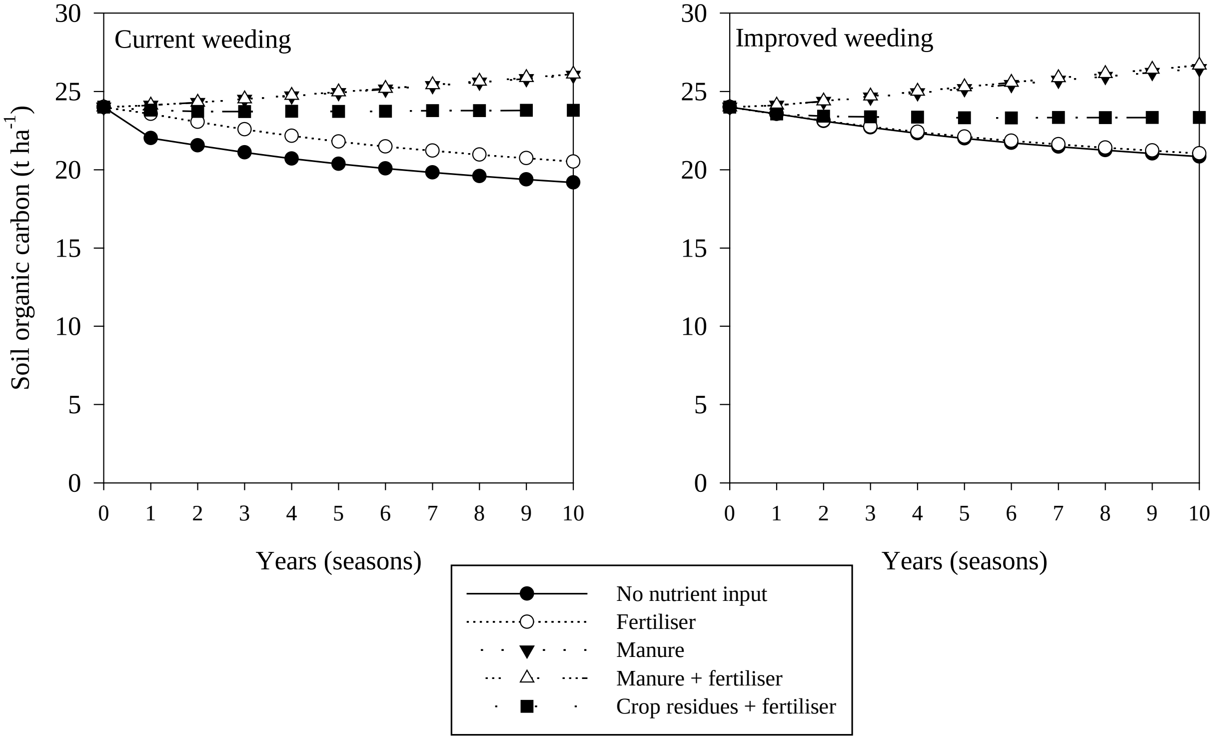

Figure 22. Simulation of soil organic carbon content at current production as well as under different options of intensification with and without optimum weed control for the middle-resourced case study farm (Meki) in Ruaca, central Mozambique.

High-resourced farm. The simulations indicated that the richest farmer almost maintained the SOC content at current management, although with a slight, but steady decline (Fig. 23). Equally to the poorly-resourced farm established on similar soil type and with similar original SOC levels, crop residue retention combined with fertiliser application increased SOC levels, slightly more under the current weeding regime than under improved weeding. The farmer could achieve a manure application rate of 5 t ha^{-1} every year which ensured large crop productivity and in turn large C input to the homefields. As a result the model simulated an increase in SOC from about 11 t ha^{-1} to about 21 t ha^{-1} at both current and improved weeding scenarios.

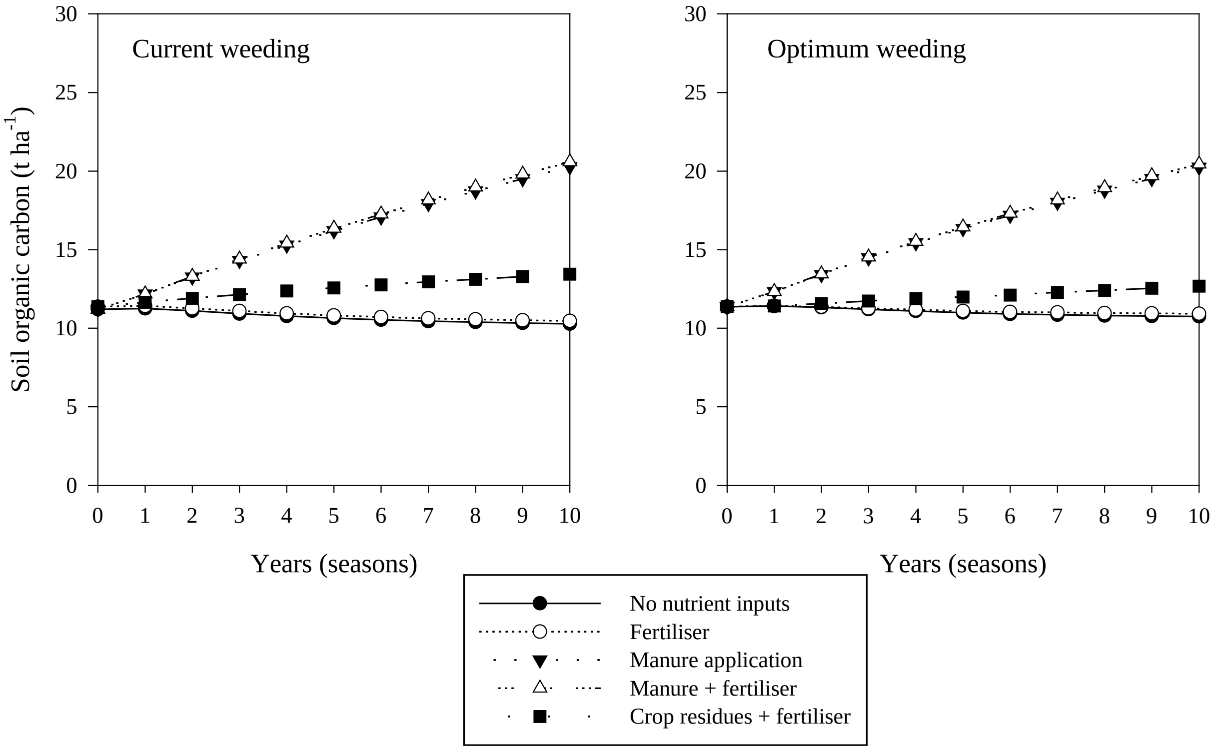

Figure 23. Simulation of soil organic carbon content at current production as well as under different options of intensification with and without optimum weed control for the richest case (Topu) study farm in Ruaca, central Mozambique.

5.6.4 Maize productivity under intercropping

The modelling output showed that intensifying maize production through maize-legume intercropping can raise maize productivity in the long-term. Maize productivity increased from about 2 t ha^{-1} to about 2.7 t ha^{-1} over a 10-year period for the highest-resourced farmer and to about 2.3 t ha^{-1} for the middle-resourced farmer (Fig. 24). The poorly-resourced farmer could potentially increase her yield from about 1.5 t ha^{-1} to 1.8 t ha^{-1} over a 10 year period with intercropping. The yield showed an increasing trend from the base year despite variability in rainfall. Farmer Topu could achieve a total maize grain yield output of about 7.8 t from the homefields, farmer Meki about 9 t and farmer Madalena about 3.8 t with intercropping combined with fertiliser and (for farmers Topu and Meki) manure application.

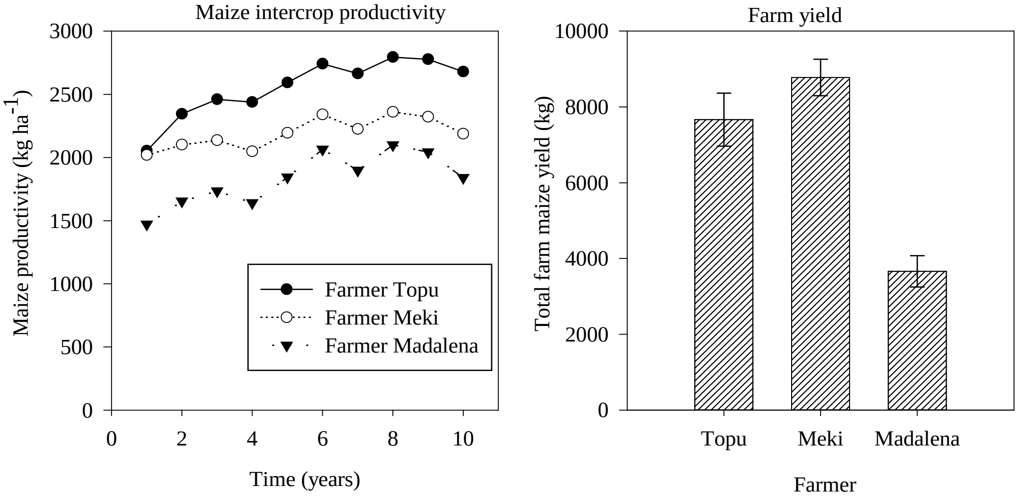

Figure 24. Simulation of maize yield in homefields under maize-legume intercropping for the three case study farms in Ruaca, central Mozambique; a) areal productivity per year, and b) average yearly farm production over the 10 year period.

5.6.5 Pigeonpea productivity under intercropping

The modelling output showed that farmers Topu and Meki have an opportunity to produce an average of 250 kg of pigeonpea per hectare using the intercrop systems, whereas farmer Madalena can achieve about half that amount at 120 kg ha^{-1}. The farm benefit for farmer Topu is about 0.8 t per year, Meki at about 1 t and Madalena at 0.2 t per year (Fig. 25). The larger farm yield for farmer Meki is mainly due to a better initial soil fertility status and a larger cultivated homefield of 4 ha compared to 3 and 2 ha for Topu and Madalena respectively. The simulations also showed that despite the year to year variability in climatic variables (especially seasonal rainfall), the legume yields were relatively stable with no significant differences between the initial and final years.

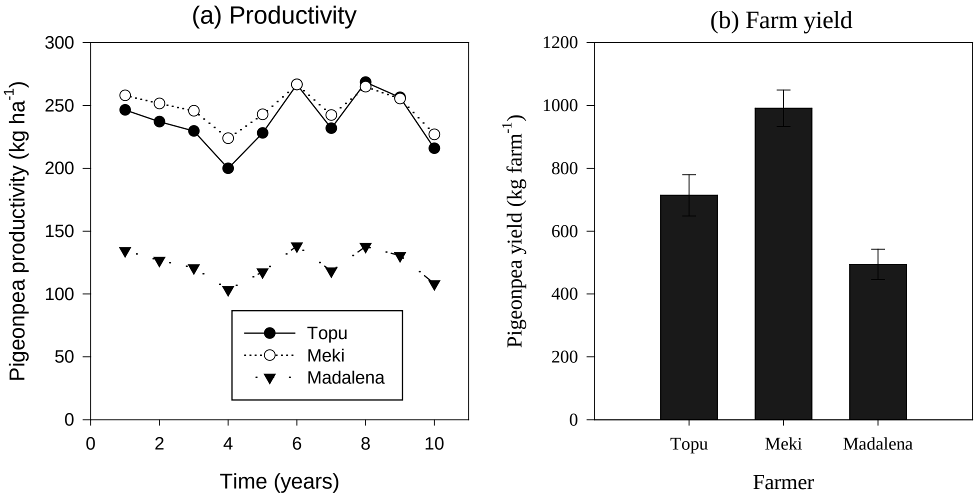

Figure 25. Simulation of pigeonpea yield in homefields under maize-legume intercropping for the three case study farms in Ruaca, central Mozambique; a) areal productivity per year, and b) average yearly farm production over the 10 year period.

5.6.6 Soil organic carbon in intercropping

Farmer Meki's field had a relatively large initial fertility as indicated by 0.8% SOC which was double the amount of SOC in farmers Topu and Madalena's fields. At the end of a 10-year simulation, the SOC content in farmer Topu's field had increased substantially and was very close to the amount in farmer Meki's field. SOC more than doubled from 11 t ha^{-1} to about 26 t ha^{-1} in farmer Topu's field, increased from 22 to 28 t ha^{-1} for farmer Meki and from 11 to 15 t ha^{-1} for farmer Madalena (Fig. 26). The large increase in SOC in farmer Topu's field was due to a larger C input into the soil as farmer Topu could achieve a manure rate of 5 t ha^{-1} and a biomass production of 4.8 t ha^{-1} whereas farmer Meki could apply about 3 t ha^{-1} manure and had a modelled biomass production of 4.3 t ha^{-1}. Farmer Madalena did not have additional C input beyond *in situ* crop residue retention which only amounted to 3.2 t ha^{-1}.

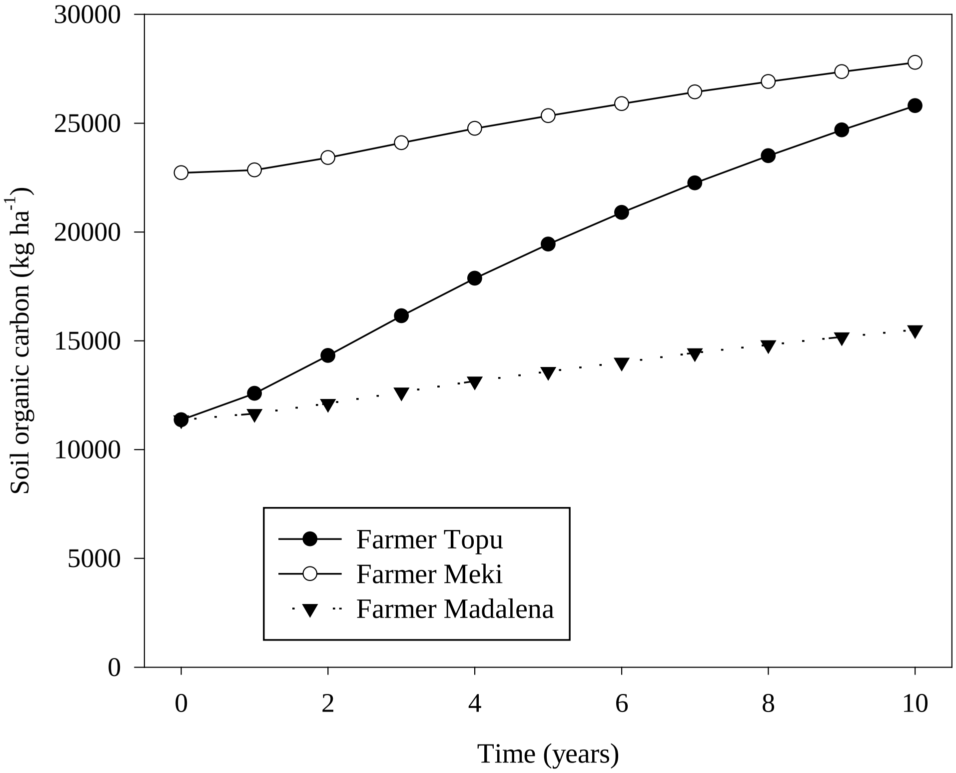

Figure 26. Simulation of soil organic carbon content in homefields under maize-legume intercropping for the three case study farms in Ruaca, central Mozambique.

5.7 Discussion of case study outcomes

The FIELD model proved to be sufficiently robust in predicting the effects of the tested crop production intensification options, although the yield increase via fertiliser use was exaggerated. The results nevertheless provide some key lessons and insights where reliable conclusions about opportunities for crop production intensification can be made. This pertains in particular to the effect of weed management. Further parameterisation and testing within the modelling framework is important to verify the outcomes of this study.

The objective of the modelling study was to understand the long-term impact of selected crop production intensification options on three case study farms differing in resource endowment. The case study farms were carefully selected to reveal local differences of farm development pathways in the modelling exercises. It was observed that different farms in the same locality have different opportunities for intensification of crop production. The site chosen in central Mozambique is characterised by extensification strategies in which farmers manage crop production is expansive outfields that can be more than 5 km away from the house. Such systems are constrained primarily by labour availability at the farm level; thus the ability of farmers to invest in extra external labour largely determines their food security status. Differences among the three selected farms showed that options for crop production intensification needed to be tailored to the farmer's circumstances. For example, farmers who owned cattle (RG2 and RG3) had more options for C input through manure besides crop residues. On the other hand, the cattle owners also require the crop residues for feed and to improve manure quality; thus it is difficult to have both resources at the same time unless sufficient grazing lands are available for use in the dry season. Therefore, the scenario with both crop residues and manure assumes that the communal pastures provide sufficient feed during the dry season. Success of the options thus depends on how limited resources, especially labour, is allocated across the farm (van Wijk et al., 2009).

These model outcomes suggest that the choices farmers make to increase productivity by expanding the land in the absence of nutrient application may be the most rewarding in the short term given that labour suffices for efficient weeding (and other farm operations such as land preparation and seeding). However, the decreasing yields over time indicated by the simulations in the unfertilised scenarios suggest that increased yields by area expansion are unsustainable, and that this is possibly aggravated by improved weeding (cf. Topu's field) and the resulting higher yield exports. Hence, the contribution of the outfields to overall farm production cannot be expected to be sustained over time, necessitating exploitation of new land areas if such are available. Furthermore, as the availability of labour during peak times is limited within the local community the practical feasibility and economic benefit of optimum weeding over large tracts of land may be limited unless new technologies are introduced.

On the other hand, results indicated that intensification of crop production on smaller land areas close to the homestead may produce similar quantities of produce as the current extensive production system, and with increasing productivity over time. There were, however, differences between the case study farms depending on their assets in the form of current soil fertility, number of cattle, labour availability within the household and potential to pay for hired labour. Nevertheless, considering that cropping of large tracts of land does not only require much labour for weeding but also for land preparation and seeding and that the outfields are frequently situated at great distance from the homestead, intensified and more strongly integrated production of crops and livestock promises to enhance livelihoods also in areas where land availability is not critical today.

The combined practice of residue retention and fertiliser application increased SOC for both farms on sandy soils, and in both cases the model suggested that the increase was larger under the current than under improved weed management. Such a difference was not visible when fertiliser was applied but crop residues and weeds were removed. This suggests a significant contribution of weeds to SOC when fire is not used for land clearance. Consequently, effective weeding may lead to less SOC accumulation as crop biomass was exported and crop residues produced were not enough to fully replace the contribution of weeds to C input and physical disturbance also favoured turnover of SOC. Such an effect was also suggested by Araujo-Junior et al. (2013). However, as crop production is the primary goal of farmers a slower increase in SOC must be regarded as a small penalty for increased yields.

The model outputs showed that manure and crop residue retention has great potential to increase yields and SOC for the richest and middle resourced farms. The effects of manure on crop yields and soil quality has been demonstrated previously (Nyamangara et al., 2005; Zengeni et al., 2006; Rufino et al., 2007; Zingore et al., 2008; Rusinamhodzi et al., 2013), however such positive results depend on how much and what quality of manure can be obtained at the farm level (Nzuma and Murwira, 2000; Lekasi et al., 2003; Materechera, 2010). In systems where animal and crop production are integrated, crop residues are hardly available to be applied back into the field because they are required to provide animal feed, and refusals are used to improve manure quality. Thus the benefits of crop residues and manure application are constrained by the level of crop and livestock integration (Rusinamhodzi, 2013). In much of central Mozambique, livestock densities are small which may allow farmers without livestock to retain crop residues for soil fertility replenishment in their homefields.

The model outputs showed that fertiliser application alone did not significantly increase crop productivity but only when used in combination with manure or crop residues retention, and optimum weed control. These results supports the need for integrated soil fertility management (ISFM) demonstrated by previous studies that have shown that not a single source of nutrients is sufficient to increase productivity in most smallholder farmers' soils (Chivenge et al., 2009; Vanlauwe et al., 2010; Rusinamhodzi et al., 2013). Accessibility to fertiliser is limited as markets remain fragmented in central Mozambique and elsewhere in southern Africa. Even where fertiliser is available, the quantities farmers can afford in some instances are much less than the optimum application rates. However, the use of high rates of fertiliser in small vegetable gardens and in tobacco fields suggests that farmers are willing to invest in fertiliser if they see the immediate benefits of doing so. For efficient fertiliser use extension including suitable fertiliser rates, application technologies and times are also needed, though, as current use suggests that the nutrient use efficiency may be low.

The simulations showed that intercropping has potential to increase the productivity of the maize crop while providing an additional yield of the associated legume crop even in the less fertile fields. The productivity and advantages of intercropping have long been demonstrated (Trenbath, 1976, 1986, 1993; Myaka and Kabissa, 1996; Myaka et al., 2006; Rusinamhodzi et al., 2006; Kimaro et al., 2009; Mucheru-Muna et al., 2009; Ngwira et al., 2012; Rusinamhodzi et al., 2012), and are suitable for the low input systems in much of Africa due to their small initial input requirements. The simulation outputs further suggests that SOC concentrations under intercropping may be slightly higher than under monocropped maize. However, it appears that the presence or absence of a pigeonpea market and cattle are either drivers or barriers to successful maize-pigeonpea intercropping (Rusinamhodzi et al., 2012). Delayed maturity in pigeonpea will lead to yield loss as it increases the likelihood of destruction by cattle in the dry season, whereas an unfavourable market will discourage farmers from producing the legume.

6. Conclusion and vision

Options formulated to address poor crop productivity on smallholder farms in Africa are abundant but those relevant to address farmers' needs are few. Differences in resource ownership and bio-physical circumstances lead to different opportunities for farmers in the same locality. On the other hand interventions to address poor crop productivity perform differently in both time and space. While targeted interventions for individual farmers might not be feasible, efforts to tailor interventions to defined targeted farmers should be pursued where possible. This emphasises the need for efficient two-way communication as development workers and researchers normally know more about the technologies and their effects but have scant knowledge of the intended users and the circumstances in which they operate their opportunities as well as the constraints they face.

Farm sizes continue to dwindle in many parts of SSA, and intensification of crop production is needed to address the persistent food shortages. This report has revealed the occurrence of local opportunities to increase current crop productivity which in some cases do not need substantial capital inputs by the farmers, but more efficient use and targeting. The study has also revealed that despite the large technical efficiency, some production options such as CA might not fit within the broader farming system as well as within the farmers' production orientation and resource capacities. Thus "silver bullets" to address farmers constraints do not exist.

Acknowledgements

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References

Agbede TM, Adekiya AO and Ogeh JS. 2013. Effects of Chromolaena and Tithonia mulches on soil properties, leaf nutrient composition, growth and yam yield. *West African Journal of Applied Ecology* 21: 15-29.

Akobundu IO. 1980. Weed Control in Cassava Cultivation in the Subhumid Tropics. *Tropical Pest Management* 26: 420-426.

Aliyu TH and Balogun OS. 2012. Effect of spatial arrangement on the incidence of virus diseases associated with cowpea intercropped with maize. *International Journal of Virology* 8: 299-306.

Andersson A. 1992. *Trace elements in agricultural soils—fluxes, balances and background values.* Swedish Environmental Protection Agency, Report 4077. pp 1–40

Andrade FH, Calviño P, Cirilo A and Barbieri P. 2002. Yield responses to narrow rows depend on increased radiation interception. *Agronomy Journal* 94: 975–980.

Araujo-Junior CF, Rodrigues BN, Chaves JCD and Junior GMY. 2013. Soil Physical Quality and Carbon Stocks Related to Weed Control and Cover Crops in a Brazilian Oxisol. In: Soloneski S and Larramendy M (eds). *Weed and Pest Control - Conventional and New Challenges*: pp 181-205. ISBN 978-953-151-0984-0986. InTech. http://dx.doi.org/0910.5772/54363

Aweto AO and Iyanda AO. 2003. Effects of Newbouldia laevis on soil subjected to shifting cultivation in the Ibadan area, south western Nigeria. *Land degradation and development* 14: 51-56.

Bado V, Sawadogo A, Thio B, Bationo A, Traoré K and Cescas M. 2011. Nematode infestation and N-effect of legumes on soil and crop yields in legume-sorghum rotations. Agricultural Sciences 2: 49-55.

Bala A and Giller KE. 2006. Relationships between rhizobial diversity and host legume nodulation and nitrogen fixation in tropical ecosystems. *Nutrient Cycling in Agroecosystems* 76: 319–330.

Barbieri PA, Sainz Rozas HR, Andrade FH and Echeverria HE. 2000. Row spacing effects at different levels of nitrogen availability in maize. *Agronomy Journal* 92: 283–288.

Barnes C, Ensminger J and O'Keefe P. 1984. *Wood Energy and Households: Perspectives on Rural Kenya*. Uppsala, Sweden, Beijer Institute and Scandinavian Institute of African Studies.

Barnett T, Tumushabe J, Bantebya G, Ssebuliba R, Ngasongwa J, Kapinga D, Ndelike M, Drinkwater M, Mitti G and Haslwimmer M. 1995. The social and economic impact of HIV/AIDS on farming systems and livelihoods in rural Africa: Some experience and lessons from Uganda, Tanzania and Zambia. *Journal of International Development* 7: 163-176.

Barungi A, Ngo´ngo´la DH, Edriss A, Mugisha J. 2013. Profitability of soil erosion control technologies in Eastern Uganda highlands. *African Crop Science Journal* 21, suppl. 3: 637 – 645.

Barungi M, Ng'ong'ola DH, Edriss A, Mugisha J, Waithaka M and Tukahirwa J. 2012. Factors influencing the adoption of soil erosion control technologies by farmers along the slopes of Mt. Elgon in eastern Uganda. *Journal of Sustainable Development* 6: 9 - 25.

Bationo A, Fairhurst T, Giller KE, Kelly V, Lunduka R, Mando A, Mapfumo P, Oduor G, Romney D, Vanlauwe B, Wairegi L and Zingore S. 2012. *Africa Soil Health Consortium: Handbook for Integrated Soil Fertility Management*. CAB International. ISBN (e-book): 978 1 78064 285 7; ISBN (paperback): 978 1 78064 291 8. Available at http://www.cabi.org/ashc/uploads/file/ASHC/ASHC_Handbook_Table_of_contents.pdf (downloaded 2014.01.20)

Begna SH, Hamilton RI, Dywer LM, Stewart DW, Cloutier D, Assemat L, Foroutan-Pour K and Smith DL. 2001a. Weed biomass production response to plant spacing and corn (*Zea mays*) hybrids differing in canopy architecture. *Weed Technology* 15: 647–653.

Begna SH, Hamilton RI, Dywer LM, Stewart DW, Cloutier D, Assemat L, Foroutan-Pour K and Smith DL. 2001b. Morphology and yield response to weed pressure by corn hybrids differing in canopy architecture. *European Journal of Agronomy* 14: 293–302.

Bellotti A, Herrera Campo BV and Hyman G. 2012. Cassava Production and Pest Management: Present and Potential Threats in a Changing Environment. *Tropical Plant Biology* 5:39–72.

Benvenuti S, Macchia M and Stefani A. 1994. Effects of shade on reproduction and some morphological characteristics of Abutilon theophrasti Medicos, Datura stramonium L. and Sorghum halepense L. Pers. *Weed Research* 34: 283-288.

Bingham FT, Sposito G and Strong JE. 1984. The effect of chloride on the availability of cadmium. *Journal of Environmental Quality* 13: 71-74.

Blomme G, Mukasa H, Ssekiwoko F and Eden-Green S. 2005. On-farm assessment of banana bacterial wilt control options. In: Tenywa JS, Adipala E, Nampala P, Tusime G, Okeri R and Kyanuhangire W (eds). *African Crop Science Conference Proceedings*, Volume 7, Part 1, Kampala, Uganda, 5–9 December 2005. African Crop Science Society, pp. 317–320. Available at: http://www.acss.ws/?t=a_conf&s=4 (accessed 24 April 2013).

Brunt AA, Crabtree K, Dallwitz MJ, Gibbs AJ and Watson L. 1996. *Viruses of plants*. CAB International, Wallingford. ISBN-13: 978-0851987941. 1488 p.

Bwalya GM and Akombelwa M. 1999. Animal traction development and gender: experiences from Western Province, Zambia. In: Starkey P and Kaumbutho P (eds). *Meeting the challenges of animal traction*. A resource book of the Animal Traction Network for Eastern and Southern Africa (ATNESA), Harare, Zimbabwe. Intermediate Technology Publications, London. 326 p.

Carsky RJ, Berner DK, Oyewole BD, Dashiell K and Schulz S. 2000. Reduction of Striga hermonthica parasitism on maize using soybean rotation. *International Journal of Pest Management* 46: 115-120.

Cassman KG. 1999. Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. *Proceedings of the National Academy of Sciences of the United States of America* 96: 5952-5959.

Chianu J, Vanlauwe B, Mukalama J, Adesina A and Sanginga N. 2006. Farmer evaluation of improved soybean varieties being screened in five locations in Kenya: implications for research and development. *African Journal of Agricultural Research* 1: 143-150.

Chianu J., Nkonya EM, Mairura FS, Chianu JN and Akinnifesi FK. 2010. Biological nitrogen fixation and socioeconomic factors for legume production in sub-Saharan Africa: a review. *Agronomy of Sustainable Development* 31: 139-154

Chikowo R, Mapfumo P, Leffelaar PA and Giller KE. 2006. Integrating legumes to improve N cycling on smallholder farms in sub-humid Zimbabwe: resource quality, biophysical and environmental limitations. *Nutrient Cycling in Agroecosystems* 76: 219-231.

Chikowo R, Mapfumo P, Nyamugafata P and Giller KE. 2004. Mineral N dynamics, leaching and nitrous oxide losses under maize following two-year improved fallows on a sandy loam soil in Zimbabwe. *Plant and Soil* 259: 315-330.

Chikoye D, Ellis-Jones J, Avav TR, Kormawa PM, Udensi UE, Tarawali G and Nielsen OK. 2007. Promoting integrated management practices for speargrass (Imperata cylindrica (L.) Raeusch.) in soybean, cassava and yam in Nigeria. *Journal of Food, Agriculture & Environment* 5: 202-21.

Chikoye D, Manyong VM, Carsky RJ, Ekeleme F, Gbehounou G and Ahanchede A. 2002. Response of speargrass (Imperata cylondrica) to cover crops integrated with hand weeding and chemical control in maize and cassava. *Crop Protection* 21: 145 – 156.

Chikoye D, Manyong VM and Ekeleme F. 2000. Characteristics of speargrass (Imperata cylindrica) dominated fields in West Africa: crops, soil properties, farmer perceptions and management strategies. *Crop Protection* 19: 481-487.

Chivenge P, Vanlauwe B, Gentile R, Wangechi H, Mugendi D, van Kessel C and Six J. 2009. Organic and Mineral Input Management to Enhance Crop Productivity in Central Kenya. *Agronomy Journal* 101: 1266-1275.

Chivenge P, Vanlauwe B and Six J. 2011. Does the combined application of organic and mineral nutrient sources influence maize productivity? A meta-analysis. *Plant and Soil* 342: 1-30.

Cooper PJM, Dimes J, Rao KPC, Shapiro B, Shiferaw B and Twomlow. S 2008. Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change? *Agriculture, Ecosystems & Environment* 126: 24-35.

Crews TE and Peoples MB. 2004. Legume versus fertilizer sources of nitrogen: ecological tradeoffs and human needs. *Agriculture, Ecosystems & Environment* 102: 279-297.

De Groote H, Vanlauwe B, Rutto E, Odhiambo GD, Kanampiu F and Khan ZR. 2010. Economic analysis of different options in integrated pest and soil fertility management in maize systems of Western Kenya. *Agricultural Economics* 41: 471-482.

Dick J, Skiba U, Munro R and Deans D. 2006. Effect of N-fixing and non N-fixing trees and crops on NO and N2O emissions from Senegalese soils. *Journal of Biogeography* 33: 416-423.

Dixon JA, Gibbon DP and Gulliver A. 2001. *Farming systems and poverty improving farmers' livelihoods in a changing world*. Rome; Washington D.C., FAO. 41 p.

Duncker LC, Matsebe GN and Moilwa N. 2007. *The Social/Cultural Acceptability of Using Human Excreta (Faeces and Urine) for Food Production in Rural Settlements in South Africa*. Water Research Commission Report No TT 310/07. ISBN 978-1-77005-592-6. Available at http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.131.665&rep=rep1&type=pdf (accessed 2014.02.14).

Ejeta G. 2007. The Striga scourge in Africa: a growing pandemic. In: Ejeta G and Gressel J (eds). *Integrating New Technologies for Striga Control: Towards ending the witch-hunt*. World Scientific Publishing Co. Pte Ltd, 5 Tol Tuck Link, Singapore. pp 3-16.

Ejeta G and Butler LG. 1993. Host-parasite interactions throughout the Striga life cycle, and their contributions to Striga resistance. *African Crop Science Journal* 1: 75-80.

Ellis-Jones J, Schulz S, Douthwaite B, Hussaini MA, Oyewole BD, Olanrewaju AS and White R. 2004. An assessment of integrated Striga hermonthica control and early adoption by farmers in northern Nigeria. *Experimental Agriculture* 40: 353–368.

Etiégni L and Campbell AG. 1991. Physical and chemical characteristics of wood ash. *Bioresource Technology* 37: 173-178.

Falkenmark M and Rockström J. 2004. Balancing Water for Humans and Nature: The New Approach in Ecohydrology. Earthscan, UK.

FAO. 2002. *Conseration agriculture: Case studies in Latin America and Africa*. FAO Soils Bulletin. Rome, FAO. 78.

FAO/WFP. 2007. *Food Supply Assessment Mission to Swaziland*. Food and Agriculture Organization/World Food Programme, Rome.

FAOSTAT. 2014. http://faostat3.fao.org/faostat-gateway/go/to/download/E/EF/E

Fox P, Rockström J and Barron J. 2005. Risk analysis and economic viability of water harvesting for supplemental irrigation in semi-arid Burkina Faso and Kenya. *Agricultural Systems* 83: 231-250.

Francis CA, Prager M and Tejada G. 1982. Effects of relative planting dates in bean (Phaseolus vulgaris L.) and maize (*Zea mays* L.) intercropping patterns. *Field Crops Research* 5: 45-54.

Gikonyo EW and Smithson PC. 2004. Effects of farm-yard manure, potassium and their combinations on maize yields in the high and medium rainfall areas of Kenya. In: Bationo A (ed). *Managing nutrient cycles to sustain soil fertility in Sub-Saharan Africa*. pp 137-149. Academy Science Publishers, Nairobi. ISBN 9966-24-075-6

Giller KE. 2001. Nitrogen Fixation In Tropical Cropping Systems. Wallingford, UK, CABI Publishing.

Giller KE and Cadisch G. 1995. Future benefits from biological nitrogen fixation: An ecological approach to agriculture. *Plant and Soil* 174: 255-277.

Giller KE, Rowe EC, de Ridder N and van Keulen H. 2006. Resource use dynamics and interactions in the tropics: Scaling up in space and time. *Agricultural Systems* 88: 8-27.

Giller KE, Sudarshana MR, Thompson JA and Rupela OP. 1988. Evaluation of 15N-isotope dilution for measurement of nitrogen fixation in chickpea (Cicer arietinum L.). *Biology and Fertility of Soils* 6: 347-351.

Giller KE, Witter E, Corbeels M and Tittonell P. 2009. Conservation agriculture and smallholder farming in Africa: The heretics' view. *Field Crops Research* 114: 23-34.

Gindaba J, Rozanov A, Negash L. 2005. Trees on farms and their contribution to soil fertility parameters in Badessa, eastern Ethiopia. *Biology and Fertility of Soils* 42: 66-71.

Govaerts B, Verhulst N, Castellanos-Navarrete A, Sayre KD, Dixon J and Dendooven L. 2009. Conservation agriculture and soil carbon sequestration: Between myth and farmer reality. *Critical Reviews in Plant Sciences* 28: 97-122.

Graham PH and Vance CP. 2003. Legumes: importance and constraints to greater use. *Plant Physiology* 131: 872-877.

Grundy IM, Campbell BM, Balebereho S, Cunliffe R, Tafangenyasha C, Fergusson R and Parry D. 1993. Availability and use of trees in Mutanda Resettlement Area, Zimbabwe. *Forest Ecology and Management* 56: 243-266.

Grzywacz D, Cherry A and Gwynn R. 2009. Biological pesticides for Africa: Why has so little of the research undertaken to date resulted in new products to help Africa´s poor? *Outlook on Pest Management* 20: 77-81

Harper D and Mavuti K. 2004. Lake Naivasha, Kenya: Ecohydrology to guide the management of a tropical protected area. *Ecohydrology and Hydrobiology* 4: 287-305.

Harris D and Orr A. 2014. Is rainfed agriculture really a pathway from poverty? *Agricultural Systems* 123: 84-96.

Hay RKM. 1995. Harvest index: a review of its use in plant breeding and crop physiology. *Annals of Applied Biology*, 126: 197–216.

Hayman DS. 1986. Mycorrhizae of nitrogen-fixing legumes. MIRCEN Journal 2: 121-145.

Hobbs PR. 2007. Conservation agriculture: what is it and why is it important for future sustainable food production? *Journal of agricultural Science* 145: 127-137.

Huang H, Campbell AG, Folk R and Mahler RL. 1992. Wood ash as a soil additive and liming agent forwheat: Field studies. *Communications in Soil Science and Plant Analysis* 23: 25-33.

IPNI (International Plant Nutrition Institute). 2012. *4R Plant Nutrition: A Manual for Improving the Management of Plant Nutrition*. (order at: http://www.ipni.net/ipniweb/portal.nsf/0/231EA9CAE05F5D24852579B200725EA2)

ISSG, Invasive Species Specialist Group. 2014. http://www.issg.org (accessed 2014.01.14)

Jefwa J, Vanlauwe B, Coyne D, van Asten P, Gaidashova S, Rurangwa E, Mwashasha M and Elsen A. 2010. Benefits and potential use of arbuscular mycorrhizal fungi (AMF) in banana and plantain (Musa spp.) systems in Africa. *Acta Horticulturae* 879: 479-486.

Joel DM, Hershenhorn J, Eizenberg H, Aly R, Ejeta G, Rich PJ, Ransom JK, Sauerborn J and Rubiales D. 2007. Biology and Management of Weedy Root Parasites. *Horticultural Reviews* 33: 267-328.

Johnson N L, Lilja N and Ashby JA. 2003. Measuring the impact of user participation in agricultural and natural resource management research. *Agricultural Systems* 78: 287-306.

Jones A, Breuning-Madsen H, Brossard M, Dampha A, Deckers J, Dewitte O, Gallali T, Hallett S, Jones R, Kilasara M, Le Roux P, Micheli E, Montanarella L, Spaargaren O, Thiombiano L, Van Ranst E, Yemefack M and Zougmoré R (eds). 2013. *Soil Atlas of Africa*. European Commission, Publications Office of the European Union, Luxembourg. 176 pp.

Kaboré PD and Reij C. 2004. The emergence and spreading of an improved traditional soil and water conservation practice in Burkina Faso. *Environment and Production Technology Division Discussion Paper 114*. Washington, DC, IFPRI, pp. 1–28.

Kanampiu F, Ransom J, Gressel J, Jewell D, Friesen D, Grimanelli D and Hoisington D. 2002. Appropriateness of biotechnology to African agriculture: Striga and maize as paradigms. *Plant Cell, Tissue and Organ Culture* 69: 105–110.

Kanmegne J, Smaling EMA, Brussaard L, Gansop-Kouomegne A and Boukong A. 2007. Nutrient flows in smallholder production systems in the humid forest zone of southern Cameroon. In: Bationo A, Waswa B, Kihara J and Kimetu J (eds). *Advances in Integrated Soil Fertility Management in sub-Saharan Africa: Challenges and Opportunities*. Springer Netherlands. pp 261-276.

Karlen DL, Andrews SS and Doran JW. 2001. Soil quality: Current concepts and applications. *Advances in Agronomy*, Academic Press. Volume 74: 1-40.

Kassam A and Brammer H. 2013. Combining sustainable agricultural production with economic and environmental benefits. *The Geographical Journal* 179: 11-18.

Kassam A, Friedrich T, Shaxson F and Pretty J. 2009. The spread of conservation agriculture: justification, sustainability and uptake. *International Journal of Agricultural Sustainability* 7: 292-320.

Kimaro AA, Timmer VR, Chamshama SAO, Ngaga YN and Kimaro DA. 2009. Competition between maize and pigeonpea in semi-arid Tanzania: Effect on yields and nutrition of crops. *Agriculture, Ecosystems & Environment* 134: 115-125.

Koning N and van Ittersum MK. 2009. Will the world have enough to eat? *Current Opinion in Environmental Sustainability* 1: 77-82.

Kropff MJ. 1988. Modelling the effects of weeds on crop production. *Weed Research* 28: 465-471.

Kumwenda JDT, Waddington SR, Snapp SS, Jones RB and Blackie MJ. 1996. *Soil Fertility Management Research for the Maize Cropping Systems of Smallholders in Southern Africa: A Review*. NRG Paper 96-02. Mexico, D.F, CIMMYT.

Kumwenda JDT, Waddington SR, Snapp SS, Jones RB and Blackie MJ. 1997. Soil fertility management in the smallholder maize-based cropping systems of Africa. In: *The Emerging Maize Revolution in Africa: The Role of Technology, Institution and Policy,* Michigan State University, USA, 9-12 July, 1995.

Kuyah S, Öborn I, Malmer A, Jonsson M, Dahlin AS, Nyaga J, Magaju C, Barrios E, Namirember S, Muthuri C, Nyberg Y. Synergies and trade-offs amongst ecosystem services provided by trees in agricultural landscapes of Sub-Saharan Africa. (Under review Agriculture, Ecosystems and Environment).

Kwari JD, Kamara AY, Ekeleme F and Omoigui LO. 2009. Relation of yields of soybean and maize to sulphur, zinc and copper status of soils under intensifying cropping systems in the tropical savannas of north-east Nigeria. *Journal of Food, Agriculture & Environment* 7: 129-133.

Lal R. 1974. Soil temperature, soil moisture and maize yield from mulched and unmulched tropical soils. *Plant and Soil* 40: 129-143.

Lekasi JK, Tanner JC, Kimani SK and Harris PJC. 2003. Cattle manure quality in Maragua District, Central Kenya: effect of management practices and development of simple methods of assessment. *Agriculture, Ecosystems & Environment* 94: 289-298.

Lekberg Y and Koide RT. 2005. Is plant performance limited by abundance of arbuscular mycorrhizal fungi? A meta-analysis of studies published between 1988 and 2003. *New Phytologist* 168: 189–204.

Liebman M and Dyck E. 1993. Crop rotation and intercropping strategies for weed management. *Ecological Applications* 3: 92-122.

Lubwama FB. 2000. Gender issues in animal traction and rural transport in Uganda. In: Kaumbutho P G, Pearson RA and Simalenga TE (eds), 2000. *Empowering Farmers with Animal Traction. Proceedings of the workshop of the Animal Traction Network for Eastern and Southern Africa (ATNESA)* 20-24 September 1999, Mpumalanga, South Africa. p. 344. ISBN 0-907146-10-4.

Mabuza ML, Sithole MM, Wale E, Ortmann GF and Darroch MAG. 2013. Factors influencing the use of alternative land cultivation technologies in Swaziland: Implications for smallholder farming on customary Swazi Nation Land. *Land Use Policy* 33: 71– 80.

Mafongoya PL, Bationo A, Kihara J and Waswa S. 2006. Appropriate technologies to replenish soil fertility in southern Africa. Nutrient Cycling in Agroecosystems 76: 137-171.

Mango NAR. 1999. Integrated soil fertility management in Siaya district, Kenya. *Managing Africa's Soils No. 7*. NUTNET. 28 pp.

Mapfumo P and Giller KE. 2001. *Soil fertility management strategies and practices by smallholder farmers in semi-arid areas of Zimbabwe*, Patancheru, AP, India: ICRISAT/FAO, 2001: 53.

Mapfumo P, Mtambanengwe F. and Vanlauwe B. 2007. Organic matter quality and management effects on enrichment of soil organic matter fractions in contrasting soils in Zimbabwe. *Plant and Soil* 296: 137-150.

Mapila MATJ, Njuki J, Delve RJ, Zingore S and Matibini J. 2012. Determinants of fertiliser use by smallholder maize farmers in the Chinyanja Triangle in Malawi, Mozambique and Zambia. *Agrekon* 51: 21-41.

Marongwe LS, Kwazira K, Jenrich M, Thierfelder C, Kassam A and Friedrich T. 2011. An African success: The case of conservation agriculture in Zimbabwe. *International Journal of Agricultural Sustainability* 9: 153-161.

Materechera SA. 2010. Utilization and management practices of animal manure for replenishing soil fertility among smallscale crop farmers in semi-arid farming districts of the North West Province, South Africa. *Nutrient Cycling in Agroecosystems* 87: 415-428.

Mbah CN, Nwite JN, Njoku C and Nweke IA. 2010. Response of maize (*Zea mays* L.) to different rates of wood-ash application in acid ultisol in Southeast Nigeria. *African Journal of Agricultural Research* 5: 580-583.

McLaughlin MJ, Maier NA, Freeman K, Tiller KG, Williams CMJ and Smart MK. 1995. Effect of potassic and phosphatic fertilizer type, fertilizer Cd concentration and zinc rate on cadmium uptake by potatoes. *Fertilizer Research* 40: 63-70.

Melifonwu AA. 1994. Weeds and their control in cassava. *African Crop Science Journal* 2: 519-530.

Mensah E, Amoah P, Drechsel P and Abaidoo RC. 2001 Environmental Concerns of Urban and Peri-urban Agriculture: Case Studies from Accra and Kumasi. In: Drechsel P and Kunze D (eds). *Waste Composting for Urban and Peri-urban Agriculture: Closing the Rural–Urban Nutrient Cycle in Sub-Saharan Africa*, pp 55-68. International Water Management Institute, Food and Agriculture Organization of the United Nations, CABI Publishing, Wallingford.

Midmore DJ. 1993. Agronomic modification of resource use and intercrop productivity. *Field Crops Research* 34: 357-380.

Millar N and Baggs EM. 2004. Chemical composition, or quality, of agroforestry residues influences N2O emissions after their addition to soil. *Soil Biology & Biochemistry* 36: 935-943.

Mnkeni PNS, Kutu FR, Muchaonyerwa P and Austin LM. 2008. Evaluation of human urine as a source of nutrients for selected vegetables and maize under tunnel house conditions in the Eastern Cape, South Africa. *Waste Management and Research* 26: 132-9.

Mtambanengwe F and Mapfumo P. 2005. Organic matter management as an underlying cause for foil fertility gradients on smallholder farms in Zimbabwe. *Nutrient Cycling in Agroecosystems* 73: 227-243.

Mucheru-Muna M, Pypers P, Mugendi D, Kung'u J, Mugwe J, Merckx R and Vanlauwe B. 2009. A staggered maize-legume intercrop arrangement robustly increases crop yields and economic returns in the highlands of Central Kenya. *Field Crops Research* 115: 132-139.

Mugagga F and Buyinza M. 2013. Land tenure and soil conservation practices on the slopes of Mt Elgon National Park, Eastern Uganda. *Journal of Geography and Regional Planning* 6: 255-262.

Mugwira LM and Mukurumbira LM. 1986. Nutrient supplying power of different groups of manure from communal areas and commercial feedlots. *Zimbabwe Agricultural Journal* 83: 25-29.

Mugwira LM and Nyamangara J. 1998. Organic carbon and plant nutrients in soils under maize in Chinamhora Commual Area, Zimbabwe. In: Bergström L and Kirchmann H (eds). *Carbon and nutrient dynamics in natural and agricultural tropical ecosystems*, CAB International, Wallingford, UK. pp 15-21.

Muhammad A, Dikko AU, Audu M and Singh A. 2010. Comparative Effects of Cowpea and Soybean Genotypes on N2 - Fixation and N-Balance in Sokoto Dry Sub-Humid Agro-Ecological Zone of Nigeria. *Nigerian Journal of Basic and Applied Science* 18: 297-303.

Muoni T, Rusinamhodzi L and Thierfelder C. 2013. Weed control in conservation agriculture systems of Zimbabwe: Identifying economical best strategies. *Crop Protection* 53: 23-28.

Murphy SD, Yakubu Y, Wiese SF and Swanton CJ. 1996. Effect of planting patterns and inter-row cultivation on competition between corn and late emerging weeds. *Weed Science* 44: 865–870.

Murwira HK and Kirchmann H. 1993. Carbon and nitrogen mineralisation of cattle manures subjected to different treatments in Zimbabwean and Swedish soils. In: K. Mulongoy and R. Merckx. *Soil Organic Matter Dynamics and Sustainability of Tropical Agriculture*. New York, John Wiley and Sons. pp 189-198.

Myaka FA and Kabissa JCB. 1996. Fitting Short Duration Cowpea into a Cotton-Based Cropping System in Tanzania: Effect of Planting Pattern, Time of Planting Cowpea, and Insecticide Application to the Cotton. *Experimental Agriculture* 32: 225-230.

Myaka FM, Sakala WD, Adu-Gyamfi JJ, Kamalongo D, Ngwira A, Odgaard R, Nielsen NE and Høgh-Jensen H. 2006. Yields and accumulations of N and P in farmer-managed intercrops of maize-pigeonpea in semi-arid Africa. *Plant and Soil* 285: 207-220.

Ncube B, Dimes JP, van Wijk MT, Twomlow SJ and Giller KE. 2009. Productivity and residual benefits of grain legumes to sorghum under semi-arid conditions in south-western Zimbabwe: Unravelling the effects of water and nitrogen using a simulation model. *Field Crops Research* 110: 173-184.

Nehanda G. 2000. *The effects of three animal-powered tillage systems on soil-plant-water relations and maize cropping in Zimbabwe*. PhD Thesis, Hardcover, University of Zimbabwe.

Ngwira AR, Aune JB and Mkwinda S. 2012. On-farm evaluation of yield and economic benefit of short term maize legume intercropping systems under conservation agriculture in Malawi. *Field Crops Research* 132: 149-157.

Nieto HJ, Brondo MA and Gonzalez JT. 1968. Critical Periods of the Crop Growth Cycle for Competition from Weeds. *Pest Articles & News Summaries*. Section C. Weed Control 14: 159-166.

Nyamangara J, Gotosa J and Mpofu SE. 2001. Cattle manure effects on structural stability and water retention capacity of a granitic sandy soil in Zimbabwe. *Soil and Tillage Research* 62: 157-162.

Nyamangara J, Mudhara M and Giller KE. 2005. Effectiveness of cattle manure and nitrogen fertilizer application on the agronomic and economic performance of maize. *South African Journal of Plant and Soil* 22: 59-63.

Nyamangara J, Mugwira LM and Mpofu SE. 2000. Soil fertility status in communal areas of Zimbabwe in relation to sustainable crop production. *Journal of Sustainable Agriculture* 16: 15-29.

Nyathi P and Campbell BM. 1993. The acquisition and use of miombo litter by small-scale farmers in Masvingo, Zimbabwe. *Agroforestry Systems* 22: 43-48.

Nyenje PM, Foppen JW, Uhlenbrook S, Kulabako R and Muwanga A. 2010. Eutrophication and nutrient release in urban areas of sub-Saharan Africa — A review. *Science of the Total Environment* 408: 447–455.

Nzuma JK and Murwira HK. 2000. Improving the Management of Manure in Zimbabwe. *Managing Africa's Soils Series 15* London, IIED-Drylands Programme. pp. 20.

Ocimati W, Karamura D, Rutikanga A, Sivirihauma C, Ndungo V, Ntamwira J, Kamira M, Kanyaruguru J-P and Blomme G. 2013. Agronomic practices for Musa across different agro-ecological zones in Burundi, Eastern Democratic Republic of Congo and Rwanda. In: Blommer G, van Asten P and Vanlauwe B (eds). *Banana systems in the humid highlands of Sub-Saharan Africa - Enhancing resilience and productivity*. CAB International 2013, Wallingford, UK. ISBN-13: 978 1 78064 231 4.

O'Hara G, Boonkerd N and Dilworth M. 1988. Mineral constraints to nitrogen fixation. *Plant and Soil* 108: 93-110.

Olsen J and Weiner J. 2007. The influence of Triticum aestivum density, sowing pattern and nitrogen fertilization on leaf area index and its spatial variation. *Basic and Applied Ecology* 8: 252–257.

Ong´ang´a O and Righa M. 2009. Dynamics of Sewage Spillage and Storm Water Pollution on Lake Victoria Basin-A Case Study of Kisumu Municipality. *World lake conference*, 13th Conference Wuhan 2009 Conference. http://wldb.ilec.or.jp/data/ilec/WLC13_Papers/S3/s3-3.pdf

Page K, Dang Y and Dalal R. 2013. Impacts of conservation tillage on soil quality, including soil-borne crop diseases, with a focus on semi-arid grain cropping systems. *Australasian Journal of Plant Pathology* 42: 363–377.

Pattinson GS. Hammill KA, Sutton BG and McGee PA. 1999. Simulated fire reduces the density of arbuscular mycorrhizal fungi at the soil surface. *Mycological Research* 103: 491-496

Peacock, T, Ward C and Gambarelli G. 2008. *Investment in Agricultural Water for Poverty Reduction and Economic Growth in Sub-Saharan Africa: Synthesis Report*. A Collaborative Program of AfDB, FAO, IFAD, IWMI, and the World Bank. Available at http://www.fanrpan.org/documents/d00508/Agric_water_investments_World_Bank.pdf

Pleasant JMt and Schlather KJ. 1994. Incidence of weed seed in cow (Boss p.) manure and its importance as a weed source on croplands. *Weed technology* 8: 304-310.

Powell JM and Mohamed-Saleem MA. 1987. Nitrogen and phosphorus transfers in a crop-livestock system in West Africa. *Agricultural Systems* 25: 261-277.

Pretty J, Toulmin C and Williams S. 2011. Sustainable intensification in African agriculture. *International Journal of Agricultural Sustainability* 9: 5-24.

Probert ME, Okalebo JR and Jones RK 1995. The use of manure on smallholders' farms in semi-arid eastern Kenya. *Experimental Agriculture* 31: 371-381.

Raintree JB and Warner K. 1986. Agroforestry pathways for the intensification of shifting cultivation. *Agroforestry Systems* 4: 39-54.

Ransom JK. 2000. Long term approaches for the control of Striga in cereals: field management. *Crop Protection* 19: 759–763.

Rockström J, Nilsson Axberg G, Falkenmark M, Lannerstad M, Rosemarin A, Caldwell I, Arvidson A and Nordström M. 2005. *Sustainable Pathways to Attain the Millennium Development Goals: Assessing the Key Role of Water, Energy and Sanitation*. Stockholm Environment Institute, Stockholm. ISBN 91 975238 4 4. Available at http://www.sei-international.org/mediamanager/documents/Publications/Water-sanitation/sustainable_pathways_mdg.pdf. (accessed 2014-02-14)

Rohrbach D and Kiala D. 2007. Development options for local seed systems in Mozambique. *Journal of SAT Agricultural Reasearch* 3: 1-28.

Roothaert RL and Magado R. 2011. Revival of cassava production in Nakasongola District, Uganda. *International Journal of Agricultural Sustainability* 9: 76-81.

Rowe EC, van Wijk MT, de Ridder N and Giller KE. 2006. Nutrient allocation strategies across a simplified heterogeneous African smallholder farm. *Agriculture, Ecosystems & Environment* 116: 60-71.

Rufino MC, Dury J, Tittonell P, van Wijk MT, Herrero M, Zingore S, Mapfumo P and Giller KE. 2011. Competing use of organic resources, village-level interactions between farm types and climate variability in a communal area of NE Zimbabwe. *Agricultural Systems* 104: 175-190.

Rufino MC, Rowe EC, Delve RJ and Giller KE. 2006. Nitrogen cycling efficiencies through resource-poor African crop–livestock systems. *Agriculture, Ecosystems & Environment* 112: 261–282.

Rufino MC, Tittonell P, van Wijk MT, Castellanos-Navarrete A, Delve RJ, de Ridder N and Giller KE 2007. Manure as a key resource within smallholder farming systems: Analysing farm-scale nutrient cycling efficiencies with the NUANCES framework. *Livestock Science* 112: 273-287.

Rurinda J, Mapfumo P, van Wijk MT, Mtambanengwe F, Rufino MC, Chikowo R and Giller KE. 2013. Managing soil fertility to adapt to rainfall variability in smallholder cropping systems in Zimbabwe. *Field Crops Research* 154: 211-225.

Rusinamhodzi L. 2013. *Nuances and nuisances: crop production intensification options for smallholder farming systems of southern Africa*. PhD Thesis. Plant Sciences. Wageningen University, Wageningen.

Rusinamhodzi L, Corbeels M, Nyamangara J and Giller KE. 2012. Maize-grain legume intercropping is an attractive option for ecological intensification that reduces climatic risk for smallholder farmers in central Mozambique. *Field Crops Research* 136: 12-22.

Rusinamhodzi L, Corbeels M, Van Wijk MT, Rufino MC, Nyamangara J and Giller KE. 2011. A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. *Agronomy for Sustainable Development* 31: 657-673.

Rusinamhodzi L, Corbeels M, Zingore S, Nyamangara J and Giller KE. 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* 147: 40-53.

Rusinamhodzi L and Delve RJ. 2011. Participatory variety selection of pulses under different soil and pest management practices in Kadoma District, Zimbabwe. In: Bationo A, Waswa B, Okeyo JM, Maina F and Kihara JM. *Innovations as Key to the Green Revolution in Africa*, Springer Netherlands: 1015-1022.

Rusinamhodzi L, Murwira HK and Nyamangara J. 2006. Cotton-cowpea intercropping and its N2 fixation capacity improves yield of a subsequent maize crop under Zimbabwean rain-fed conditions. Plant and Soil 287: 327-336.

Sakala WD. 1994. *Crop management interventions in traditional maize pigeonpea intercropping systems in Malawi*. M.Sc. Report, University of Malawi.

Sanginga N. 2003. Role of biological nitrogen fixation in legume based cropping systems; a case study of West Africa farming systems. *Plant and Soil* 252: 25-39.

Sanginga N and Woomer PL (eds). 2009. *Integrated soil fertility management in Africa: Principles, practices and developmental process*. Nairobi, Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture.

Santi C, Bogusz D and Franche C. 2013. Biological nitrogen fixation in non-legume plants. Annals of Botany: 1-25.

Schubert S. 1995. Nitrogen assimilation by legumes – processes and ecological limitations. *Fertilizer Research* 42: 99-107.

Sekiya N and Yano K. 2004. Do pigeon pea and sesbania supply groundwater to intercropped maize through hydraulic lift? - Hydrogen stable isotope investigation of xylem waters. *Field Crops Research* 86: 167-173.

Shackleton CM. 1993. Fuelwood harvesting and sustainable utilisation in a communal grazing land and protected area of the eastern Transvaal lowveld. *Biological Conservation* 63: 247-254.

Shea RW, Shea BW, Kauffman JB, Ward DE, Haskins CI and Scholes MC. 1996. Fuel biomass and combustion factors associated with fires in savanna ecosystems of South Africa and Zambia. *Journal of Geophysical Research: Atmospheres* 101(D19): 23551-23568.

Shumba E, Dhilwayo H and Mukoko O. 1990. The potential of maize-cowpea intercropping in low rainfall areas of Zimbabwe. *Zimbabwe Journal of Agricultural Research* 28: 33-38.

Singh BB. 2002. Breeding cowpea varieties for resistance to Striga gesnerioides and Alectra vogelii. In: Fatokun CA, Tarawali SA, Singh BB, Kormawa PM and Tamo M (eds). *Challenges and Opportunities for Enhancing*

Sustainable Cowpea Production. Proceedings from the World Cowpea Conference III held at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria, 4-8 September 2000. IITA, Ibadan, Nigeria.

Sivirihauma C, Rutikanga A, Murekezi C, Blomme G, Anuarite U, Ocimati W, Lepoint P and Ndungo V. 2013. Xanthomonas wilt incidence in banana plots planted with asymptomatic suckers from a diseased field compared with plots using suckers from a disease-free zone in North Kivu, Eastern Democratic Republic of Congo. In: Blommer G, van Asten P and Vanlauwe B (eds). *Banana systems in the humid highlands of Sub-Saharan Africa - Enhancing resilience and productivity*. CAB International 2013, Wallingford, UK. ISBN-13: 978 1 78064 231 4.

Smaling EMA and Janssen BH. 1993. Calibration of quefts, a model predicting nutrient uptake and yields from chemical soil fertility indices. *Geoderma* 59: 21-44.

Smith SE and Read DJ. 2008. *Mycorrhizal symbiosis*, 3rd edn. Cambridge, UK: Academic Press.

Snapp SS, Mafongoya PL and Waddington S. 1998. Organic matter technologies for integrated nutrient management in smallholder cropping systems of southern Africa. *Agriculture, Ecosystems & Environment* 71: 185-200.

Someshwar A. 1996. Wood and combination wood-fired boiler ash characterisation. *Journal of Environmental Quality* 25: 962-972.

Stoorvogel JJ and Smaling EMA. 1990. *Assessment of soil nutrient depletion in sub-saharan Africa: 1983-2000*. Report 28, Wageningen, Netherlands: Winand staring centre for integrated land, soil and water research.

Stromgaard P. 1984. The immediate effect of burning and ash-fertilization. *Plant and Soil* 80: 307-320.

Thierfelder C, Cheesman S and Rusinamhodzi L. 2012. Benefits and challenges of crop rotations in maize-based conservation agriculture (CA) cropping systems of southern Africa. *International Journal of Agricultural Sustainability* 11: 1-17.

Thierfelder C and Wall PC. 2009. Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. *Soil and Tillage Research* 105(2): 217-227.

Tittonell P, Corbeels M, van Wijk MT and Giller KE. 2010b. FIELD--A summary simulation model of the soil-crop system to analyse long-term resource interactions and use efficiencies at farm scale. *European Journal of Agronomy* 32: 10-21.

Tittonell P, Corbeels M, Van Wijk MT, Vanlauwe B and Giller KE. 2008. Combining organic and mineral fertilizers for integrated soil fertility management in smallholder farming systems of Kenya: Explorations using the crop-soil model FIELD. *Agronomy Journal* 100: 1511-1526.

Tittonell P, Muriuki A, Shepherd KD, Mugendi D, Kaizzi KC, Okeyo J, Verchot L, Coe R and Vanlauwe B. 2010a. The diversity of rural livelihoods and their influence on soil fertility in agricultural systems of East Africa - A typology of smallholder farms. *Agricultural Systems* 103: 83-97.

Tittonell P, Vanlauwe B, de Ridder N and Giller KE. 2007b. Heterogeneity of crop productivity and resource use efficiency within smallholder Kenyan farms: Soil fertility gradients or management intensity gradients? *Agricultural Systems* 94: 376-390.

Tittonell P, Vanlauwe B, Leffelaar PA, Rowe EC and Giller KE. 2005a. Exploring diversity in soil fertility management of smallholder farms in western Kenya - I. Heterogeneity at region and farm scale. *Agriculture Ecosystems & Environment* 110: 149-165.

Tittonell P, Vanlauwe B, Leffelaar PA, Shepherd KD and Giller KE. 2005b. Exploring diversity in soil fertility management of smallholder farms in western Kenya: II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. *Agriculture, Ecosystems & Environment* 110: 166-184.

Tittonell P, Zingore S, van Wijk MT, Corbeels M and Giller KE. 2007a. Nutrient use efficiencies and crop responses to N, P and manure applications in Zimbabwean soils: Exploring management strategies across soil fertility gradients. *Field Crops Research* 100: 348-368.

Traore B, Corbeels M, van Wijk MT, Rufino MC and Giller KE. 2013. Effects of climate variability and climate change on crop production in southern Mali. *European Journal of Agronomy* 49: 115-125.

Trenbath BR. 1976. Plant interactions in mixed crop communities. In: Papendick RI, Sanchez PA and Triplett GB (eds). *Multiple cropping*, Madison, Wis., ASSA, CSSA, and SSSA. pp 129-170.

Trenbath BR. 1986. Resource use by intercrops. In: Francis CA (ed). *Multiple Cropping Systems.* New York, Macmillan. pp 57-81.

Trenbath BR. 1993. Intercropping for the management of pests and diseases. *Field Crops Research* 34: 381-405.

Tsubo M, Walker S and Ogindo HO. 2005. A simulation model of cereal-legume intercropping systems for semi-arid regions: I. Model development. *Field Crops Research* 93: 10-22.

Tsubo M, Walker S and Ogindo HO. 2005. A simulation model of cereal-legume intercropping systems for semi-arid regions: II. Model application. *Field Crops Research* 93: 23-33.

Udensi EU, Akobundu IO, Ayeni AO and Chikoye D. 1999. Management of cogongrass (Imperata cylindrica) using velvet bean (Mucuna prunens var. utilis) and herbicides. *Weed Technology* 13: 201-208.

Udensi EU and Chikoye D. 2013. Effect of relative proportion and density on competition between Speargrass (Imperata cylindrica (L.) Raeuschel) and Maize (*Zea mays* L.) in a moist savannah of Southwestern Nigeria. *Journal of Animal & Plant Sciences* 18: 2761-2774.

Ulery AL and Graham RC. 1993. Forest fire effects on soil color and texture. *Soil Science Society of America Journal* 57: 135-140.

Waddington SR, Mekuria M, Siziba S and Karigwindi J. 2007. Long-term yield sustainability and financial returns from grain legume-maize intercrops on a sandy soil in subhumid north central Zimbabwe. *Experimental Agriculture* 43: 489-503.

Valbuena D, Erenstein O, Homann-Kee Tui S, Abdoulaye T, Claessens L, Duncan AJ, Gérard B, Rufino MC, Teufel N, van Rooyen A and van Wijk MT. 2012. Conservation Agriculture in mixed crop–livestock systems: Scoping crop residue trade-offs in Sub-Saharan Africa and South Asia. *Field Crops Research* 132: 175-184.

Wall PC. 2007. Tailoring conservation agriculture to the needs of small farmers in developing countries: An analysis of issues. *Journal of Crop Improvement* 19: 137-155.

Van Huis A and Meerman F. 1997. Can we make IPM work for resource-poor farmers in sub-Saharan Africa? *International Journal ofPest Management* 43: 313-320.

van Kauwenberg SJ. 2002. *Cadmium content of phosphate rocks and fertilizers.* IFA Technical Conference, Chennai, India 24-27 September 2002.

van Wijk MT, Tittonell P, Rufino MC, Herrero M, Pacini C, de Ridder N and Giller KE. 2009. Identifying key entry-points for strategic management of smallholder farming systems in sub-Saharan Africa using the *dynamic farm-scale simulation model NUANCES-FARMSIM. Agricultural Systems* 102: 89-101.

Wang X, Dai K, Zhang D, Zhang X, Wang Y, Zhao Q, Cai D, Hoogmoed WB and Oenema O. 2011. Dryland maize yields and water use efficiency in response to tillage/crop stubble and nutrient management practices in China. *Field Crops Research* 120: 47-57.

Vanlauwe B, Bationo A, Chianu J, Giller KE, Merckx R, Mokwunye U, Ohiokpehai O, Pypers P, Tabo R, Shepherd KD, Smaling EMA, Woomer PL and Sanginga N. 2010. Integrated soil fertility management: Operational definition and consequences for implementation and dissemination. *Outlook on Agriculture* 39: 17-24.

Vanlauwe B, Diels J, Sanginga N, Carsky RJ, Deckers J and Merckx R. 2000. Utilization of rock phosphate by crops on a representative toposequence in the Northern Guinea savanna zone of Nigeria: response by maize to previous herbaceous legume cropping and rock phosphate treatments. *Soil Biology & Biochemistry* 32: 2079-2090.

Vanlauwe B, Kanampiu F, Odhiambo GD, De Groote H, Wadhams LJ and Khan ZR. 2008. Integrated management of Striga hermonthica, stemborers, and declining soil fertility in western Kenya. *Field Crops Research* 107: 102–115.

Vanlauwe B, Tittonell P and Mukalama J. 2006. Within-farm soil fertility gradients affect response of maize to fertiliser application in western Kenya. *Nutrient Cycling in Agroecosystems* 76: 171-182.

Weiner J, Griepentrog H-W and Kristensen L. 2001. Suppression of weeds by spring wheat Triticum aestivum increases with crop density and spatial uniformity. *Journal of Applied Ecology* 38: 784–790.

Wendt JW and Rijpma J. 1997. Sulphur, zinc, and boron deficiencies in the Dedza Hills and Thiwi-Lifidzi regions of Malawi. *Tropical Agriculture* 74: 81-89.

Verbruggen E, van der Heijden MGA, Rillig MC and Kiers ET. 2013. Mycorrhizal fungal establishment in agricultural soils: factors determining inoculation success. *New Phytologist* 197: 1104–1109.

Versteeg MN, Amadji F, Eteka A, Gogan A and Koudokpon V. 1998. Farmers' adoptability of mucuna fallowing and agroforestry technologies in the coastal savanna of Benin. *Agroforestry Systems*. 56: 269 – 287.

Vilariño A and Arines J. 1991. Numbers and viability of vesicular-arbuscular fungal propagules in field soil samples after wildfire. *Soil Biology & Biochemistry* 23: 1083-1087.

Williamson S, Ball A and Pretty J. 2008. Trends in pesticide use and drivers for safer pest management in four African countries. *Crop Protection* 27: 1327– 1334.

Winblad U and Simpson-Hébert M (eds). 2004. *Ecological Sanitation – revised and enlarged edition*. Stockholm, Sweden: SEI.

Vissoh PV, Gbehounou G, Ahanchede A, Kuyper TW and Röling NG. 2004. Weeds as agricultural constraint to farmers in Benin: results of a diagnostic study. *NJAS - Wageningen Journal of Life Sciences* 52: 305-329.

Vogel H. 1993. Tillage effects on maize yields, rooting depth and soil water and water content on sandy soils in Zimbabwe. *Field Crops Research* 33: 367-384.

Zeddies J, Schaab RP, Neuenschwander P and Herren HR. 2001. Economics of biological control of cassava mealybug in Africa. *Agricultural Economics* 24: 209–219.

Zengeni R, Mpepereki S and Giller KE. 2006. Manure and soil properties affect survival and persistence of soyabean nodulating rhizobia in smallholder soils of Zimbabwe. *Applied Soil Ecology* 32: 232-242.

Zimdahl RL. 1999. *Fundamentals of Weed Science*. San Diego, CA, USA: Academic Press. 556 pp.

Zimdahl RL. 2004. *Weed-Crop Competition: A Review*. Blackwell Publishing, Oxford, UK, ISBN 0-8138-0279-2. 220 pp.

Zingore S, Delve RJ, Nyamangara J and Giller KE. 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* 80: 267-282.

Zingore S, Murwira HK, Delve RJ and Giller KE. 2007a. Soil type, management history and current resource allocation: Three dimensions regulating variability in crop productivity on African smallholder farms. *Field Crops Research* 101: 296-305.

Zingore S, Murwira HK, Delve RJ and Giller KE. 2007b. Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. *Agriculture, Ecosystems & Environment* 119: 112-126.

Zingore S, Tittonell P, Corbeels M, van Wijk M and Giller KE. 2011. Managing soil fertility diversity to enhance resource use efficiencies in smallholder farming systems: a case from Murewa District, Zimbabwe. *Nutrient Cycling in Agroecosystems* 90: 87-103.

Review of interventions and technologies for sustainable intensification of smallholder crop production in sub-humid sub-Saharan Africa

– with an assessment of effectiveness of selected options on differently endowed case study farms

In November 2011, the Swedish Ministry of Foreign Affairs allocated specific funding to the Swedish University of Agricultural Sciences (SLU) for work to support global food security. The allocation was made with the long-term aim to reduce hunger and malnutrition by supporting improvement of agricultural productivity. As part of this a review of the knowledge base was made in the field of sustainable intensification of crop production on smallholder farms, and reported in this working paper. The main focus is soil fertility and plant nutrition, as these are frequently highlighted as a major constraint to crop productivity in sub-Saharan Africa, but the paper also includes a range of agronomic interventions and technologies needed for crops to take advantage of increased nutrient supply. Finally, the paper also includes scenarios of increased production intensity and current practices in production systems of central Mozambique, and assesses their long-term effects on crop productivity and soil fertility.

The **Swedish Unversity of Agricultural Sciences (SLU)** has core competence within the agricultural sciences, including forestry and veterinary sciences. The areas of expertise cover urgent global issues such as food production, energy supply, climate change, biodiversity conservation and control of infectious diseases in animal and man.

To strengthen SLU's involvement in issues related to improving productivity in agriculture, food security and sustainable livelihood in low-income countries, the university has established the programme **Agricultural Sciences for Global Development, (SLU Global)**. The programme's mission is to coordinate and visualize SLU's competence in research, education and expert council within the frame of the Swedish Policy for Global Development.

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