3. Integrated Soil Fertility Management in Sub-Saharan Africa

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3.1 Introduction

Soil fertility decline on smallholder farms contributes to low per capita food production in sub-Saharan Africa (SSA). Nutrient depletion for agricultural land in 37 African countries was estimated to average 660, 75 and 450 kg/ha of N, P and K between the years 1960 and 2000 (Smaling et al., 1997). These figures represent the balance between nutrient inputs as fertilizer, manure, atmospheric deposition, biological N2 fixation (BNF) and sedimentation, and nutrient outputs as harvested products, crop residue removal, leaching, gaseous losses, surface runoff and erosion. The gap between actual and rainfed potential yield has been estimated to be more than 4 t/ha for cereals and 2 t/ha for pulse crops (Haggblade and Hazell 2010; Haggblade and Plerhoples 2010). Actual mean yield for rainfed maize and irrigated rice is 10 to 30% and 30 to 50%, depending on country, of estimated potential yield (Global Yield Gap Atlas 2016). The yield gaps are attributed to a range of biotic and abiotic constraints, poor agronomic practices and low use of agricultural inputs including fertilizer.

Improved soil fertility management is key to increased smallholder agricultural productivity where fertilizer application to cropland averages about 15 kg/ha/yr. Fertilizer use needs to be specific to crops and agro-ecological zones (AEZ) and with the application of the right nutrients at the right rates, times and placements (the 4Rs of nutrient stewardship) to ensure nutrient use efficiency, environmental sustainability and profitable yield increases.

Fertilizer use must be coupled with optimized use of organic resources for nutrient supply and maintenance or improvement of soil aggregation, soil microbial activity, soil water infiltration and retention, resistance to erosion and nutrient transformation. However, the availability of organic resources is not sufficient to meet the nutrient needs of substantially increased productivity. For example, a 5 t/ha maize grain harvest, depending on the harvest index, requires the uptake of approximately 100, 24, and 85 kg/ha of N, P, and K (Table 3.1).

3.2 Integrated Soil Fertility Management

Vanlauwe et al. (2010) defined Integrated Soil Fertility Management (ISFM) as a set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs and improved germplasm adapted to local conditions, aimed at high agronomic use efficiency of the applied nutrients and improving crop productivity. It implies efficient use of fertilizer and organic resources coupled with such good agronomic practices as planting improved varieties with appropriate spacing and timing and good control of weeds, insect pests and diseases. Vigorous crop growth is associated with an extensive and vigorous root system capable of efficient uptake of soil nutrients and water. The full benefits of ISFM may be achieved in a stepwise fashion as farmers learn to best adapt and integrate potential components and gain access to financial resources for higher levels of management (Figure 3.1). Potential organic soil fertility practices vary by AEZ and may include

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Table 3.1: Amount of N, P and K removed in plant parts

	Nutrient uptake kg/t					
	Grain/produce			Plant residue		
	N	P	K	N	P	K
Maize	13	2.4	2.7	5.4	1.8	11
Sorghum	15	2.6	3.1	3.5	0.7	3.7
Wheat	9	1.7	1.8	5.1	1.8	8.3
Soybean	55	5.5	13	5.2	1.8	16
Rice	12	2.8	5.0	6.4	0.7	13
Bean	46	5.4	27	7.8	1.0	7.7
Groundnut	43	3.5	6	15	1.3	13
Irish potato	16	2.5	21	11	1.0	20

agroforestry such as fallows with fast-growing leguminous trees, leguminous annual cover or green manure crops for BNF, biomass transfer from plants growing outside the production area, manure and compost application, managing crop residue for soil maintenance and improvement, non-legume with legume rotations and intercropping, and rotation with well managed grass or grass-legume leys. While ISFM as a term and its definition are relatively recent creations, the underlying principles have been long recognized in soil fertility research, teaching and management. Many studies have addressed components of ISFM and their integration (Bationo et al., 2007). It is not the intent of this chapter to review all or any of these. Rather the chapter gives an interpretation of a synthesis of results with reference to a few key synthesis publications done for SSA. While good agronomic practices are key to ISFM and nutrient use efficiency generally, only practices with implications for soil nutrient supply and soil productivity will be addressed.

3.3 Common ISFM practices for sub-Saharan Africa

3.3.1 Land application of organic resources

The value of land application of organic resources is widely recognized by African smallholders and the resources are widely used. Inadequate supply often constrains greater use. Organic resources can supply soil nutrients but nutrient contents range widely. Manure nutrient concentrations range from 0.5 to 2.5% N, 0.4 to 3.9% P_2O_5, 1.2 to 8.4% K_2O and 0.3 to 5.4% CaO (Table 3.2). Green leaves of legumes range from 2.9 to 4.4% N, 0.13 to 0.30% P and <1 to 2.8% K (Table 3.3). Crop residues, including residues of legume pulse and oil seed crops, typically have <1% N and K and <0.1% P content. Nutrient contents should not be interpreted as fertilizer nutrient substitution values, with the exception of K which is readily released from dead organic materials. High carbon to nitrogen ratio (C:N) and high contents of lignin and polyphenols delay decomposition and organic nutrient mineralization of lower quality resources. Large quantities of most organic materials may be needed to equal the nutrient uptake associated with much increased crop yield. Transport of such huge amounts of low quality biomass and its capacity to immobilize soil mineral N due to high C:N limits the feasibility of using some organic resources. Available organic resources often have alternative uses such as livestock feed, fuel and construction material which further limits availability for land application.

The soil amendment effect of applied organic resources may exceed and certainly complement the nutrient supply effect. The amendment effect can be especially great on soils with low available water holding and nutrient supply capacity such as sandy soils of low soil organic matter (Chivenge et al., 2011). The amendment effect may also be great in cases of weak soil aggregation if susceptibility to

Table 3.2: Typical nutrient concentrations (%) for animal manures (Kaola, 2001)

Manure	Water	N	P_2O_5	K_2O	CaO
Farmyard manure	38 – 54	0.5 – 2.0	0.4 –1.5	1.2 – 8.4	0.3 – 2.7
Cattle dung	34 – 40	1.7 – 2.0	0.5 – 3.7	1.3 – 2.5	0.9 – 1.1
Sheep and goat droppings	40 – 52	1.5 – 1.8	0.9 – 1.0	1.4 – 1.7	0.9 – 1.0
Pig manure	35 – 50	1.5 – 2.4	0.9 – 1.0	1.4 – 3.8	1.3 – 1.5
Poultry manure	10 – 13	2.3 – 2.5	2.3 – 3.9	1.0 – 3.7	0.6 – 4.0
Compost manure	49 – 52	0.5 – 1.7	0.3 – 0.5	5.0 – 7.4	4.6 – 5.4

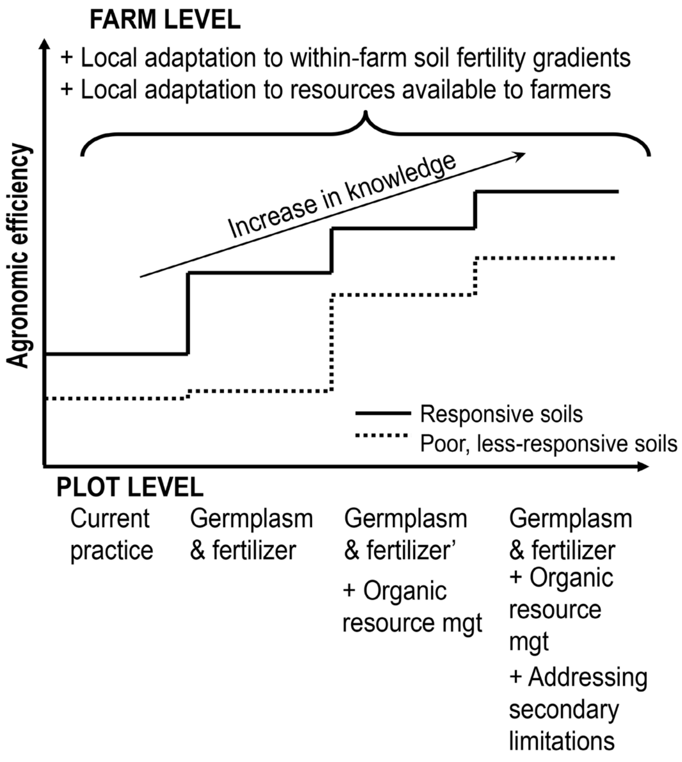

Figure 3.1: Conceptual relationship between agronomic efficiency (AE) of fertilizers and organic resource and the implementation of various components of ISFM culminating in complete ISFM towards the right side of the graph. Soils that are responsive to NPK based fertilizer and those that are poor and less responsive are distinguished. Source: Vanlauwe et al., 2010.

erosion and crusting is reduced. With such soils, there may be little response to fertilizer nutrients applied alone, but a much greater response to fertilizer when an organic resource is also applied (Figure 3.1).

3.3.2 Organic resources complemented with fertilizer application

Chivenge et al., (2011) compiled and analysed the results of 52 research studies conducted in SSA to evaluate the effects on maize yield of combined application of organic resources and fertilizer N compared with using either alone.

The synergist effects varied with properties of soil and the organic resource. The effect of the applied organic resources alone increased with rate and the capacity to supply N. High quality organic resources applied in sufficient quantities could fully meet maize N requirements, including sandy soil. Organic resources with <2.5% N concentration were considered low quality as were some high N plant materials with high lignin and polyphenol concentration. Application of organic materials alone resulted in more yield increase in situations of <5 t/ha maize yield compared with fertilizer N alone. The percent yield increase was greater with the combination of fertilizer N and low compared with high quality organic resource but this was not necessarily true for the quantity of yield increase. The benefit of the combination was greater with <600 compared with >1000 mm/yr rainfall. With loam soils and >600 mm/yr rainfall and therefore of relatively high productivity, there was little yield benefit with the combination compared to fertilizer N alone. The residual effect of the organic resources on the subsequent crop was, however, greater for loam compared with sandy soils.

The effect of 25 years of continuous cropping was determined in Central Kenya where the initial soil organic C was 2%. Soil organic C declined with all soil management practices. The soil organic C decline was 37% for a combination of fertilizer N and P and 10 t/yr of farmyard manure applied plus retention of crop residues in the field, but 54% with another treatment (Kibunja et al., 2012).

3.3.3 Crop residue management and tillage

The value of crop residues in soil management has been long recognized, especially in densely populated areas. Allan (1965) described several examples such as use as mulch for banana and

Table 3.3: Elemental nutrient concentration of above ground biomass of various plant materials (Zingore et al., 2014; Kaizzi and Wortmann 2001)

Organic Source	Species	Plant part	%N	%P	%K
Tree or shrub	*Calliandra calothyrsus*	Leaves	3.3	0.17	0.8
	Leucaena leococephala	Leaves	3.9	0.19	2.1
	Tephrosia vogelii	Leaves	2.9	0.18	1.1
	Fleminga macrophylla	Leaves	2.7	0.16	0.7
	Lantana camara	Prunings	2.7	0.16	2.7
Herbaceous legume	*Crotalaria grahamiana*	Leaves	3.0	0.13	0.8
	Crotaralia juncea	Leaves	3.8	0.16	1.3
	Mucuna pruriens	Leaves	4.4	0.30	1.6
Herbaceous, other	*Senna hirusta*	Plants	3.0	0.18	4.6
	Aspilia kotschyi	Plants	1.3	0.11	4.0
Grain legume	Pigeonpea	Leaves	3.3	0.19	1.3
	Groundnut	Leaves	3.0	0.17	2.4
	Soybean	Leaves	3.6	0.15	2.4
	Beans	Leaves	2.9	0.30	2.8
	Cowpea	Leaves	2.9	0.10	2.1
Cereals	Maize	Leaves/husks	0.9	0.07	0.7
	Rice	Leaves/husks	1.0	0.07	0.7

coffee in Eastern Africa, the Matengo pit system of southwestern Tanzania, the Mambwe mound system of northeastern Zambia and the Dagomba system of the Guinea Savanna in Ghana. With the exception of mulching, each of these systems aims to fully use crop residue as a nutrient source with an enhanced rate of decomposition and nutrient cycling.

While there are competing uses for the crop residues, much burning of residues continues. Crop residues are low quality organic resources in regards to nutrient supply as indicated by low N concentrations (Table 3.3). Incorporation compared with removing soybean crop residue was found in the Guinea Savanna of Nigeria to have a fertilizer N value of about 15 kg/ha for maize that received no fertilizer N (Figure 3.2). However, crop residues left in the field and not consumed by termites and ruminants contributes to soil organic matter which regulates numerous soil properties and processes. It has been most common to incorporate plant residues before planting the next crop but there is potential advantage in avoiding tillage and leaving the crop residues on the soil surface.

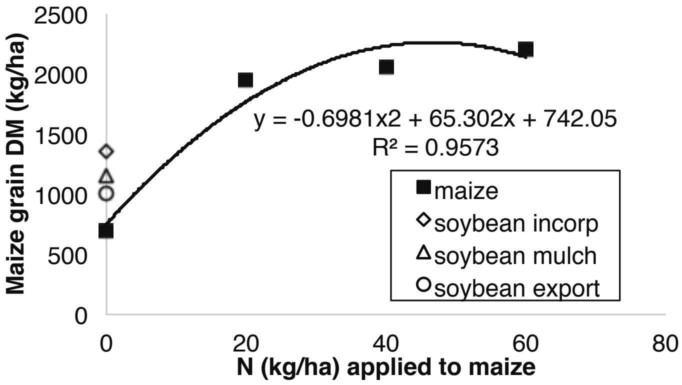

Figure 3.2: Effect of management of soybean residues on soybean rotation effect (Singh et al., 2001).

Conservation agriculture (CA) integrates reduced or no tillage, ground cover by plants and plant residues, and crop rotation. Pittelkow et al. (2015) did a globally comprehensive analysis of 610 studies with 5463 comparisons of CA with some other management system. In considering the tillage component alone, mean yields were 11.9% less with no pre-plant tillage compared with the conventional tillage practice but the reduction was less in drier compared with humid production situations. However, under semi-arid rainfed conditions, there was a 7.3% mean yield increase when all three components of CA were applied with residue retention and crop rotation contributing equally to overcome the negative effect of no tillage. The benefit of residue retention plus rotation with tillage compared with no tillage was not reported. The results did not show that CA became more effective over time.

These results are largely supported by an earlier and smaller analysis of numerous studies conducted for SSA and South Asia where annual crop yields were typically less with no-tillage compared with conventional tillage and the negative effect was lessened if combined with crop rotation and crop residue retention (Brouder and Gomez-Macpherson 2014). In each study, good targeting of CA is emphasized. For example, mean sorghum yield over 7 yr at two locations in Uganda was 11% more with direct planting without tillage compared with conventional inversion tillage (Nansamba et al. 2016). In a review for sorghum production systems, mostly of the Sudan Savanna, Mason et al. (2015) found yields with no-till to be 12% less on average compared with shallow tillage. Yields were increased with crop residue left on the soil surface compared with residue removal. Sorghum yield in rotation with cowpea was consistently higher compared with sorghum monoculture. The Nansamba and Mason works demonstrate that one or more components of CA are often beneficial to yield on their own and additively without much evidence of synergy.

In a review of over 100 published studies with a focus on SSA and South Asia, Palm et al. (2014) found that both crop residue retention and reduced tillage resulted in the improvement of several soil properties in the surface 10-cm soil depth but there was a lack of evidence for synergistic effects and generally there was little or no effect below 10-cm depth. Overall for the surface 10-cm soil depth, with both no-till compared to conventional tillage and crop residual retention compared with removal, there were increases in total and particulate soil organic matter, soil microbial biomass and diversity, earthworms, aggregate stability and plant available water. No-till and residue retention compared with the management alternatives resulted in reduced runoff, erosion and evaporation. Soil porosity was generally reduced with no-till and increased with residual retention.

3.3.4 Intercropping with legumes

Legume integration into cropping systems is an important component of ISFM. Legume production in intercrop association with maize, sorghum, pearl millet, banana, cassava and other non-legumes is widely practised and more common in SSA than legume rotation with these crops. Intercropping benefits include increased land productivity and reduced risk compared with sole crop production. Much bean production in SSA is by intercropping with maize, but also with sorghum, banana, cassava and other crops. In the Sahel, pearl millet/cowpea, pearl millet/groundnut and sorghum/groundnut are the most common intercropping systems. In higher rainfall AEZ of West Africa, maize intercropped with cowpea, groundnut or soybean is common. Pigeonpea is commonly produced by intercropping with maize.

When crops are complementary in terms of growth pattern, aboveground canopy, rooting system and/or periods of high water and nutrient demand, intercropping enables more efficient use of photosynthetically active radiation, water and nutrients. Intercropping may provide better soil cover compared to sole crop for weed suppression and reduced soil erosion and crusting. The legume intercrop may suppress Striga infestation of the cereal crop but probably less effectively than with rotation. The intercrop complementarity is often achieved through differences in maturity times with legumes often making much of their growth and nutrient and water uptake before the associated crop forms a full canopy and maturing earlier than the non-legume. In such cases, fallen legume leaves may decompose enough to release nutrients to the associated crop. In other cases, such as with long season pigeonpea or relay intercropping of cowpea, the legume makes much of its growth after the maize or other associated crop matures.

The intercropped legumes can fix atmospheric N but are also likely to compete with the non-legume for available soil N. Given the amount and timing of soil N availability, soil N depletion by the non-legume may stimulate BNF. Most fertilizer N should therefore be applied in-season when the non-legume has a high rate of N uptake. Significant BNF may occur, such as with long duration pigeonpea or with relay intercropping legumes into the cereal where the legume makes much of its growth after the cereal crop matures and has depleted soil mineral N. In cases of cereal-legume intercrop that is fertilized to meet the N need of the cereal, BNF may be very little as the legume will be competitive for uptake of the applied N while legume suppression by the vigorously growing cereal will also suppress BNF. It is not likely that significant transfer of N from the living legume to the cereal occurs although the later maturing non-legume may access N mineralized from decomposing leaves and nodules following senescence. More BNF as well as transfer of N from the legume to the grass is likely with a perennial grass-legume ley compared with annual cereal-legume intercropping.

The associated crops do compete for all essential soil nutrients and water but differences in timing of their high uptake rates reduces this competition. Most legume pulse and oil seed crops have tap roots. When the legume has extensive root development, it may tap deep immobile nutrients and leached nutrients such as nitrate-N, use these for growth and return some to the soil through decomposition of crop residue. Long season and perennially growing pigeonpea can be especially effective in taking up deep soil nutrients and cycling some to the topsoil through decay of roots and above ground crop residues. With a good legume grain harvest, however, N removed in the harvest commonly exceeds the atmospheric N that is fixed.

It is common that yield of both associated crops is less with intercropping compared with sole crop but the total of the intercrop yields relative to their sole crop yields commonly exceeds sole crop yield. This is assessed by land equivalent ratio (LER); if LER is greater than one, productivity has been improved by intercropping. Intercropping can be managed to favour one associated crop relative to the other. Planting the legume after the associated cereal has emerged will enhance the relative competitiveness of the cereal compared with planting both on the same day. A basal application of little or no N and withholding most N application until six weeks or longer after planting is expected to increase the relative competitiveness of the legume compared with applying 50% or more of the fertilizer N at or before planting.

Intercrop planting pattern varies including planting all crops in the same row, alternative rows or pairs of rows, and alternating strips of more than two rows which may include rotation of crops across these strips. The planting pattern variation also has temporal aspects with both or all crops planted on the same day or on different days. Planting pattern is expected to affect the relative competitiveness of the component crops.

An innovative intercropping system, named MBILI (Kiswahili for two, and an acronym for 'Managing Beneficial Interactions in Legume Intercrops') consists of two maize rows alternated with two rows of bean, groundnut and/or another legume which allows more light penetration for the under-storey legume component and reduces legume access to N applied for the maize component. In the Sahel, alternating four rows each of cowpea and pearl millet combined with crop rotation has resulted in similar pearl millet yield and increased cowpea yield compared with the respective sole crops.

Relay intercropping of maize and cowpea is common in the Guinea Savanna of Nigeria. One planting pattern is to plant on the same day two rows of medium maturity maize alternated with four rows of a 65 days maturity cowpea variety. After cowpea harvest, the entire field is weeded and a medium maturity cowpea variety is planted in the rows of harvested legumes and also inter-planted between the maize rows. After the harvest of the maize, the entire field becomes a cowpea sole crop that matures during the dry season (Photo 1).

Photo 1: Cowpea was relay intercrop planted into maize and continues to grow following maize harvest.

‘Doubled-up legume’ intercropping refers to intercropping of two legumes and is practised in Malawi. Species complementarity is improved with differing growing habits and maturity periods such as with tall growing and late maturing pigeonpea intercropped with groundnuts or soybean. Doubled-up legume intercropping has been observed to result in more BNF compared with the sole crops. The earlier maturing legume makes much of its growth before the tall legume intercepts much radiation. The tall late maturity legume uses water of late rains and residual soil water following maturity of the associated crop. Soybean and cowpea have been observed to lack complementarity in doubled-up legume intercropping.

The implications of intercropping for nutrient application rates have generally not been well determined. An exception is for maize-bean intercropping in Kenya where the optimal rate of N and P is higher with intercropping compared with soil crop maize (see Chapter 6).

3.3.5 Green manure

Legumes can add much to the N balance of a farm operation through BNF. Giller and Wilson (2001) estimated the BNF capacity of various legumes at 105 to 206 kg/ha N for pulses, 110 to 280 kg/ha for green manure crops and 162 to 1063 kg/ha over several years for tree legumes Some species-specific annual BNF rates are presented in Table 3.4.

A green manure crop is a legume that is grown for BNF to supply N to following crops and organic matter for soil property improvement. It is often terminated before maturity although may be allowed to grow to maturity when maximized production of a relatively higher C:N biomass is desired such as for ground cover or increasing soil organic C. It is commonly incorporated into the soil but may be left on the soil surface as a mulch. Green manure crops are cover crops but not all cover crops are green manure crops in that cover crops often are not legumes and may be grown for other purposes than N supply, such as protection against erosion or for weed suppression. Green manure and other cover crops are by definition not harvested although a farmer may decide in the end to instead harvest it as a forage or grain crop.

Much research on green manure and cover crops has been done in SSA and the results were well synthesized by Eilitta et al. (2004). Common green manure species include mucuna *Mucuna pruriens*, several crotalaria species, *Canavalia ensiformis, Dolichos lablab* and cowpea. The green manure may be a sole crop, especially during the minor rainy season where bimodal rainfall occurs. It may also be relay intercropped with another species, such as planting of the green manure crop at second weeding of the main crop with the green manure crop continuing to grow after harvest.

There is ample evidence of increased yield of the following non-legume crop, even in some cases with fertilizer N applied. Depending on the C:N of the biomass of the green manure crop and the time since termination of the crop before planting the next non-legume crop, some fertilizer N might be applied to support the early growth of the non-legume crop while organic N in the green manure biomass becomes crop available. For example, application of up to 30 kg/ha of fertilizer N is recommended in Tanzania for rice production following the incorporation of mucuna green manure biomass.

Table 3.4: Potential biological N fixation rates of various leguminous species (Giller and Wilson, 2001)

Species	Potential BNF rate (N/ha/yr)	References
Acacia mangium	50-100	Atangana et al., 2014
Casuarina equisetifolia	360	Atangana et al., 2014
Gliricidia sepium	86-309	Liyanage et al., 1994
Tephrosia vogelii	100	Werner 2005, FAO 2010
Pigeonpea	90	Werner 2005, FAO 2010
Crotalaria grahamiana	142	Werner 2005
Crotalaria juncea	130	Becker 1995, FAO 2010
Mucunapruriens	130	Werner 2005, FAO 2010

Despite much study of green manure in SSA with promising results, there is little green manure production practised. Farmers have not been able to justify to themselves the value of producing a crop that they will not harvest.

3.3.6 Cereal-legume rotation

Studies across SSA and elsewhere have found rotation benefits of increased yield both for the cereal following the legume and the legume following the cereal in rotation compared to cereal or legume continuous production. These rotation benefits commonly are 5 to 15% yield increases, although cases of much lower and others of much greater benefit have been reported, as by Mason et al. (2015). The percent but less so the magnitude of yield increases due to rotation are often greater with low compared with adequate soil fertility situations. Some of the rotation benefit to the following cereal crop may be due to increased N availability but the benefit can occur even when adequate fertilizer N is applied. Breaking disease and insect cycles likely contributes much to rotation benefits. Soil microbial communities are affected by the previous crop and the type and quantity of crop residues produced as well as the type and quantity of organic materials applied (Kamaa et al., 2011); these shifts may contribute to the rotation effect such as more effective colonization of roots by vesicular arbuscular mycorrhiza that contribute to improved nutrient and water uptake.

Legumes in rotation can add much to the N balance of a farm operation through BNF (Table 3.4). However, harvest of forage and grain legumes typically removes more than the equivalent of the N derived from BNF. Legumes prefer to use available soil N as BNF requires plant energy. Soil mineral N is often observed to be more depleted following a pulse compared with a cereal harvest. Even so, fertilizer N need for the cereal following a legume in rotation is commonly less, even with the increased yield due to the rotation effect, compared with continuous cereal production. This N benefit is likely due to factors other than a direct contribution from the legume crop to the cereal crop that may include: relatively quick decomposition of the legume leaf residue compared with cereal crop residue; less crop residue of lower C:N ratio for the legume compared with the cereal crop and therefore less immobilization of soil and fertilizer N following the legume crop; and generally healthier and more vigorous root systems for more effective nutrient uptake for cereals following legumes compared with following a cereal.

Soil organic matter during the legume compared with the cereal phase of the rotation typically shows some decline as photosynthesis and biomass production is typically less during the legume phase while plant and soil respiration are similar for both phases. This decline is at least partly if not fully compensated for by increased productivity of the rotation compared with cereal monoculture. However, rotation of a cereal with an annual leguminous pulse or oil seed crop, with its numerous benefits, should not be seen as a means to increasing soil organic matter.

Fertilizer P use may differ for cereal-legume rotations compared with continuous production of a single crop with evidence that the cereal is less responsive to applied P following a legume compared with a cereal. Application of fertilizer P often results in increased BNF by legumes. Some therefore advise that rather than applying fertilizer P every year, all fertilizer P be applied to the legume and to produce the cereal on the residual P. However, other evidence contradicts this in that the legume such as soybean is less sensitive to low soil test P than maize, resulting in a preference to apply all fertilizer P to maize and producing soybean on the residual P. In cases of high P fixation by the soil and where fertilizer use is constrained by inadequate finance, application of some fertilizer P each year may be most profitable and preferred. The OFRA approach to optimizing fertilizer use is to maximize profit. With poor farmers, this profit needs to be gained within a short time and they cannot afford to wait for more than a year for production to benefit from the residual effect of a fertilizer application. Therefore fertilizer use decisions need to be based on the expected net returns with the next crop. As seen from the country chapters of this book, net returns for P application to legumes compared to non-legumes are overall relatively good.

3.3.7 Adding perennials to the annual crop rotation

Based on research begun in the 1930s, Uganda has a rarely used recommended rotation of three to four years in annual crop rotated with three years of well managed perennial ley. The ley could be established from natural revegetation or planting, such as with Napier grass. The effectiveness of ley in the rotation in maintaining soil productivity was greater than planting of green manure crops. The forage could be grazed or harvested for animal feeding. The benefit appeared to be due to the increase in active soil organic matter, improved soil physical properties and improved soil P availability. The greatest benefit may be on sandy soils of low organic matter that are not very responsive to fertilizer use. An added advantage on erodible land is the protection from erosion throughout the rotation by having good vegetative ground cover for the ley, the improved resistance to erosion because of improved soil aggregation and the enhanced productivity and ground cover of the annual crops. Perennial ley in rotation is similar to fallow but the ley needs to be well managed to be effective.

Fallowed lands are commonly abused by unregulated overgrazing, giving the plants little opportunity to develop good root systems and achieve high productivity. The rotation can be profitable not only because of the increased annual crop yields but also through use of the forage produced for profit-oriented intensive ruminant production. The system cannot work well where farmers have no control of grazing as even severe overgrazing during the dry season is likely to delay perennial recovery and reduce productivity and soil improvement.

Another means of adding perennials to annual crops is with short duration treelots. The treelots may be solely as a form of improved fallow and a green manure crop. More often the trees will have a harvested product such as high protein forage for dairy or producing wood products. Leguminous trees add N to the system and cycle deep nutrients but such trees are likely to be less effective in increasing soil organic matter and improving soil aggregation compared with perennial grass.

3.3.8 Parkland agriculture

Parkland agriculture is a term used in the Sahel and Sudan Savannas and refers to annual crop production under and around generally large, erect trees (Depommier 1996). It is practised elsewhere in some semi-arid parts of eastern and southern Africa, often on sandy soils of low productivity and with low soil organic matter, but the term parkland agriculture is commonly used only in west Africa.

The trees add organic material to the soil and improve soil water holding capacity and nutrient availability. The most recognized parkland tree is *Faidherbia (Acacia) albida* (Photo 2). It is unique for its reverse phenology in that it sheds its leaves during the rainy season reducing direct competition for water, light and nutrients. In the hot and dry season it produces leaves which can be used as fodder. The dry season shade leads to ruminant livestock gathering under the trees where more excretion of faeces and urine occurs compared with open areas. Faidherbia is a legume adding N to the farming system. Compared with open fields, the N and P availability under trees have been determined to be 200 and 30% more, respectively, and crop performance is noticeably better with measured yield increases of greater than 100%.

Other trees such as the shea-tree (*Vittelaria paradoxa*) are also effective, although less so compared with Faidherbia, in improving annual crop productivity while providing its own economically valuable yield. *Parkia biglobosa* is

Photo 2: Pearl millet production is commonly greater under Faidherbia trees. These trees do not have leaves during the rainy season and are leafy during the dry season (reverse phenology).

another important parkland species. Farmers recognize the value of parkland agriculture but establishment of trees is difficult due to unrestricted overgrazing during the dry season.

3.3.9 Biochar

Biochar is charcoal or pyrogenic carbon that is applied in small pieces to amend soil (Guo et al., 2016). The major advantage of adding biochar compared with the original organic material is that the biochar C is much more persistent in the soil compared to the C applied in organic resources. The half-life in soil of C applied in organic materials is typically less than a year as decomposition occurs through soil microbial activity with C released to the atmosphere through microbial respiration. In comparison, the half-life of biochar C in the soil may be longer than 100 years.

Biochar application increases cation exchange capacity, water holding capacity, soil aggregation and soil porosity. The amendment effect is expected to be greatest with soils of low nutrient supply and low water holding capacity. Such soils amended with biochar can have much improved response to applied nutrients. The benefit of biochar is expected to be less with soils that are relatively good for these properties and more where there is greater opportunity for improvement of these soil properties. The biochar is not a good C and energy source for soil microbes but can enhance microbial habitat. The magnitude of effects varies with the rate of application. Biochar in most cases will be a very limited resource as are organic resources for soil management, but what is potentially available could often be used to great benefit.

There is some traditional 'biochar' practice with smallholders of SSA although it has not been recognized as such. In Madagascar, there is a tradition of 'burning' low productivity Ferralsols and Andosols, the latter with very high P fixation capacity. At the end of a fallow period, they do not pile and do combustion burning of the bush and grass plant material. Instead, furrows of approximately 20 cm depth are dug, the dried plant material arranged in the furrows, and then covered using the excavated soil. The furrow ends are left open and the material ignited. Once ignited, pyrolysis slowly progresses down the covered furrow for a week or more with little oxygen supply, charring the covered plant materials. Subsequent production over these burn furrows is much greater than for unburnt soil. The combined benefit of heating the soil, ash deposition and biochar has not been well differentiated but it is expected that the biochar effect will be long term. It is likely that even with slash and burn systems, significant amounts of existing soil C is pyrogenic C due to incomplete combustion of some of the vegetative material.

The feasibility of biochar depends on the availability of plant materials and of the potential of improving a soil such as a sandy soil of low nutrient supply and water holding capacity. Crop residues that are not consumed by termites or someone else's livestock can be valuable to the farmer for diverse reasons if left in the field, including for reduced evaporation and erosion, and improvement of surface soil aggregation. However, often the residues are consumed with little in-field value. There is also much combustion burning of plant materials by smallholders, e.g. following fallow, rice straw and hulls, strong stalks of tall traditional sorghums and even maize stover. Very often the burning of plant materials is associated with low productivity soils that could benefit from increased stable soil C supplied as biochar.

Numerous simple and inexpensive kiln options are available that are appropriate for smallholder use including some consisting of little more than a 200-litre drum (http://www.appropedia.org/Simple_Biochar_Kilns). A small kiln that can be easily moved to accumulations of plant materials in the field greatly reduces the labour of transporting the plant material, especially if the biochar is used *in situ*. The biochar will be most effective if crushed into small bits. Biochar has low density and should be incorporated into the soil to prevent removal by runoff.

3.3.10 Good fertilizer use practices

Good fertilizer use practices have been encapsulated in the term '4Rs of nutrient stewardship' including the right fertilizer source (or type) applied at the right rate, at the right time and in the right place (Johnson and Bruulsema 2014). In the case of poor smallholders, potential profit from fertilizer use needs to be of primary concern. Profit also needs to be a concern of well financed crop production but needs to be balanced with concerns about effects on soil, ground and surface waters, and the atmosphere.

The right fertilizer. The right fertilizer source or type means matching the fertilizer to the crop's need for applied nutrients. Therefore, the fertilizer needs to supply one or more nutrients which are inadequately available in the soil to meet crop needs. Fertilizer formulations differ in cost per nutrient supplied with added complexity and processing adding to cost. The effect of the fertilizer type on the soil needs to be considered. For example, some fertilizers have a greater soil acidifying effect than others which is a consideration for soils with or nearing problematic low soil pH. However, economics needs to be considered. While nitrate, unlike urea and ammonium, in fertilizer does not contribute to soil acidity, nitrate production requires more fossil fuel consumption and production costs. The more economical approach may be to use a less expensive source of N with an acidification effect and to manage soil acidification with lime application as compared to using a more costly N source of less acidifying effect.

The right rate. The rate of fertilizer nutrient application is overall the most important of the 4Rs for profitability and environmental consequences. Fertilizer N rates are especially of concern in good nutrient stewardship as much N is applied but it is a nutrient that is at risk of loss due to leaching, volatilization, denitrification, runoff and nitrous oxide emission. Excessive N application contributes unnecessarily to soil acidification, and the acidification effect is greater for N lost to leaching compared with that recovered by the crop. The rate of application should not normally exceed the economically optimal rate (EOR), that is, the rate expected to maximize net returns to fertilizer use per hectare. Often the rate should be less than EOR. Smallholders who are financially constrained in fertilizer use are expected to get better returns on their constrained fertilizer use by applying at a rate where the yield increase per kg/ha of applied nutrient is relatively great compared to the increase near EOR. An environmental concern, such as risk of nitrate leaching to groundwater, may result in a regulation for applying N at some rate less than EOR. In reality, EOR varies greatly by field and year and is not well predicted. Essential to approximating EOR are representative crop nutrient responses functions such as have been determined by OFRA for food crops in 67 AEZ (see Chapter 1). Estimation of EOR can be improved by considering soil test information, rotation effects, organic resource application and other practices as addressed in this chapter and in Chapters 4-16. Some low productivity soils require amendment such as with lime or organic resources to have good crop response to fertilizer (Figures 3.3 and 3.4). Biotic constraints, such as severe Striga infestation, may reduce the potential of crop response to applied fertilizer. Due to low predictability of N EOR in a given season, in-season N application with adjustment of rates according to canopy colour has gained practice globally.

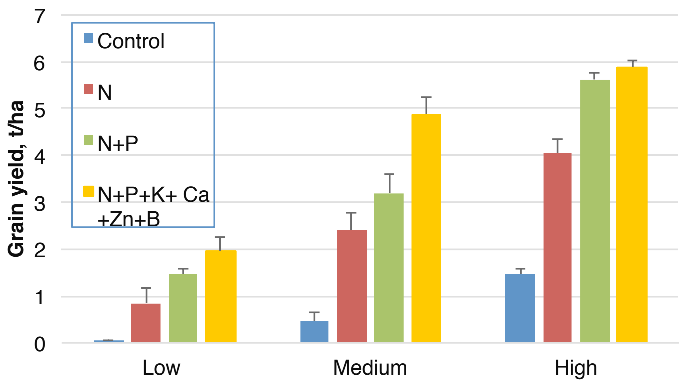

Figure 3.3: Maize response to applied nutrients for low, intermediate and high productivity soils in southern Malawi (Zingore et al., 2011).

Fertilizer micro-dosing is point application of fertilizer nutrients at low rates at planting, post

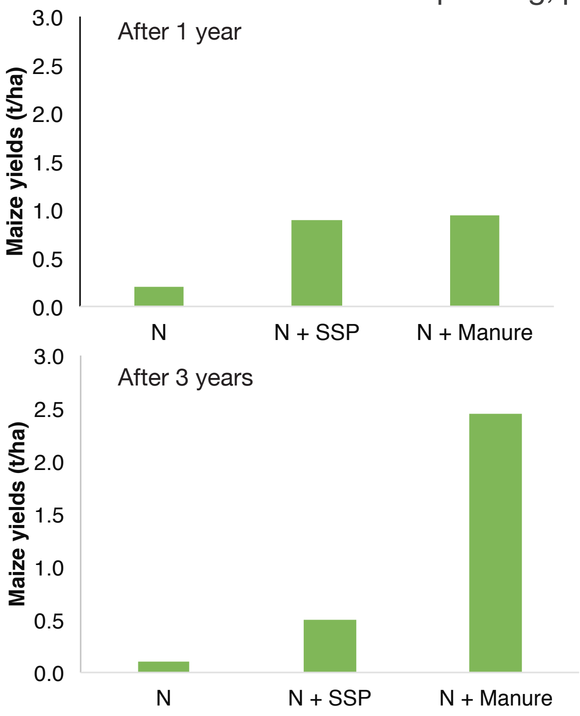

Figure 3.4: Effect of manure on crop response to fertilizer in non-responsive sites (Zingore et al., 2007).

Table 3.5: Average maize grain in relation to micro-dosing and banding application methods in Hawasa, Ziway and Melkassa regions in Ethiopia (Sime and Aune 2014)

	Fertilizer rate		Location	
Method	**DAP+Urea kg ha**	**Hawassa**	**Ziway**	**Melkassa**
Control	0	6334b[1]	4054b	3649b
Microdosing	27+27	7539a	5864a	5320a
	53+53	7222a	6042a	5542a
	80+80	7086a	5743a	5221a
Banding	100+100	7636a	5815a	5226a

[1]Means sharing the same letter are not significantly different from each other

emergence or several weeks after emergence, as appropriate, for low productivity soils in low rainfall areas such as the Sahel. Sorghum and pearl millet yield increases of 44 to 120% due to micro-dosing have been reported which were comparable to yield increases with the higher recommended rates (Bagayoko et al., 2011; Tabo et al., 2011). Micro-dosing was evaluated with maize in Ethiopia with a mean grain yield with no fertilizer applied of 4.7 t/ha; yield increases were similar with all rates of N and P application which ranged from 17 and 5 kg/ha of N and P to 64 and 20 kg/ha of N and P, respectively (Table 3.5) (Sime and Aune 2014).

The right time. The time of fertilizer application is important. It is very common to apply P, some N and maybe K and/or other nutrients before or at planting as often there is a pop-up effect to stimulate early growth and root development. Delay in basal fertilizer application can result in yield loss as found by Sakala (1998) in Zambia. In cases of risk of poor crop establishment, however, this basal application may be more wisely done shortly after crop emergence and maybe with a rate adjustment according to establishment success. In-season application of some N is a common practice globally and in SSA, and is especially beneficial on sandy soils and where much rainfall occurs during the season (Zingore et al., 2014). An important advantage of in-season N application, in addition to reduced risk of N loss to leaching, is that the farmer can judge the condition of the crop and may decide in cases of poor crop condition, due to biotic or abiotic problems or to management, to apply no or a reduced rate of N. This adaptive management is expected to increase in importance as the frequency of extreme weather events increases. In-season N application should

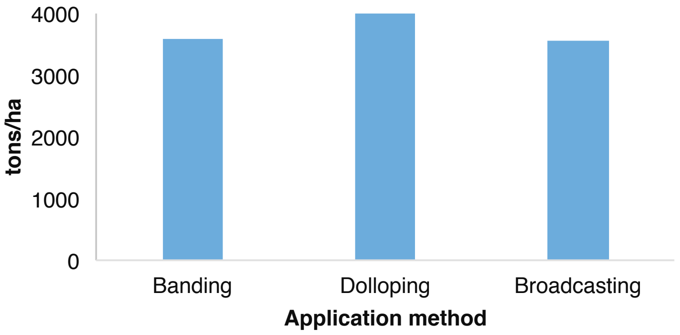

Figure 3.5: Effect of fertilizer application method on maize yield in Malawi. (Adapted from a presentation by Benson T.D.) http://www.slideshare.net/IFPRIMaSSP/maximizing-returns-to-fertilizer-use-on-maize-in-malawi-lessons-from-onfarm-agronomic-research-by-todd-benson-ifpri.

correspond to near the beginning of very rapid N uptake by the crop, such as at the 8-leaf stage of maize.

The right place. Placement of fertilizer is important. Placing the fertilizer at a point under or very near the seed or plant creates the risk of fertilizer salt damage. Legumes with tap roots are especially vulnerable to high salt fertilizers, such as KCl placed under the seed, even if well covered with soil. Point or band placement of basal fertilizer, at least 5 cm from the seed or plant, is often more efficient than broadcast application for maize and other crops with widely spaced planting when fertilizer application rates are low but there are exceptions (Figure 3.5).

Deep placement of urea super granules (USG) may add to N use efficiency in lowland rice production. The USG are oval compacted pellets, commonly of 1.8 or 2.7 g, produced using briquetting machines. One USG is placed at 5-7 cm depth in puddled transplanted rice fields at one week after transplanting between four rice plant stands spaced at 20 × 20 cm. No additional fertilizer N is applied. Benefits to the use of USG

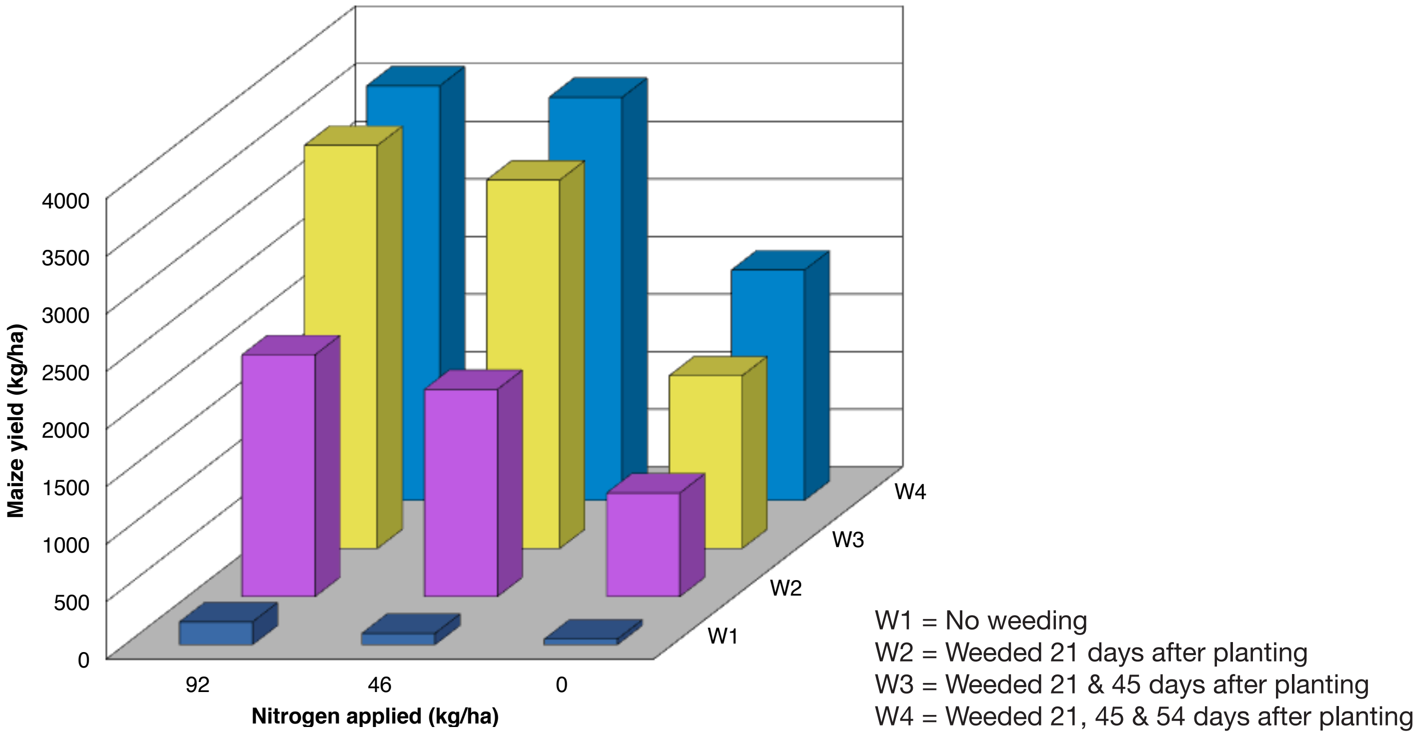

Figure 3.6: Effect of different weeding levels on maize yield.

deep placement include reduced N rate, fewer N applications, increased yield, less weeding and better applied N recovery with less denitrification and runoff loss of N.

3.3.11 Water availability

Water is the direct source of the essential nutrient hydrogen and is necessary for plant uptake of nutrients as well as for plant metabolism and growth generally. Soil water deficits may be prevented with timely irrigation. Mason et al. (2015) reviewed 21 papers addressing tillage and water conservation in the Sahel and found generally higher yields by planting pearl millet into tilled compared with untilled soil because of improved water infiltration with tillage, a large positive effect of water conservation with tied-ridges and zai, and that there was often a positive interaction of combining nutrient application with water conservation.

Zougmoré et al. (2004) found that water harvesting and conservation alone did not improve crop productivity in Burkina Faso but was effective when organic material and fertilizer were added. They found that combining compost with stone bunds or grass strips resulted in 180% more sorghum grain yield, while the same soil conservation measures used jointly with fertilizer N only increased yield about 70%. Sorghum yield was more with zai half-moon micro-catchments combined with compost or animal manure application compared with fertilizer application.

Weed control is important to water and nutrient availability. Inadequate control may reduce maize yields by more than 50% and two weeding cycles of maize are often needed (Kabambe and Kumwenda 1995) (Figure 3.6).

3.4 Conclusion

Improved soil nutrient availability is essential for much increased crop productivity in SSA. Smallholder farmers are typically very poor and need to get high net returns on their use of money such as for fertilizer use. Therefore, cost effectiveness of improved soil nutrient supply is very important. This chapter has explored alternatives of nutrient supply and management for high nutrient use efficiency.

Potential synergies of combining different alternatives sometimes exist, especially for situations of low soil productivity and little response to fertilizer application, but more often effects are mostly additive. Increases and improved use of organic resources, increased integration of legumes in rotations, crop rotation, increasing soil organic matter and improvement in associated soil properties such as through rotation of perennial with annual crops and use of biochar, better use of fertilizer and reducing soil water deficits, are addressed.

Most practices have trade-offs. No single practice may be universally appropriate. Practices need to be well targeted for greatest effectiveness.

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