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Pedosphere **27**(4): 662–680, 2017
doi:10.1016/S1002-0160(17)60382-5
ISSN 1002-0160/CN 32-1315/P
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Published by Elsevier B.V. and Science Press

PEDOSPHERE

www.elsevier.com/locate/pedosphere

Integrated Soil Fertility and Plant Nutrient Management in Tropical Agro-Ecosystems: A Review

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(Received April 14, 2017; revised July 12, 2017)

ABSTRACT

The greatest challenge for tropical agriculture is land degradation and reduction in soil fertility for sustainable crop and livestock production. Associated problems include soil erosion, nutrient mining, competition for biomass for multiple uses, limited application of inorganic fertilizers, and limited capacity of farmers to recognize the decline in soil quality and its consequences on productivity. Integrated soil fertility management (ISFM) is an approach to improve crop yields, while preserving sustainable and long-term soil fertility through the combined judicious use of fertilizers, recycled organic resources, responsive crop varieties, and improved agronomic practices, which minimize nutrient losses and improve the nutrient-use efficiency of crops. Soil fertility and nutrient management studies in Ethiopia under on-station and on-farm conditions showed that the combined application of inorganic and organic fertilizers significantly increased crop yields compared to either alone in tropical agro-ecosystems. Yield benefits were more apparent when fertilizer application was accompanied by crop rotation, green manuring, or crop residue management. The combination of manure and NP fertilizer could increase wheat and faba bean grain yields by 50%–100%, whereas crop rotation with grain legumes could increase cereal grain yields by up to 200%. Although organic residues are key inputs for soil fertility management, about 85% of these residues is used for livestock feed and energy; thus, there is a need for increasing crop biomass. The main incentive for farmers to adopt ISFM practices is economic benefits. The success of ISFM also depends on research and development institutions to provide technical support, technology adoption, information dissemination, and creation of market incentives for farmers in tropical agro-ecosystems.

Key Words: crop rotation, crop yield, food security, integrated soil fertility management, organic sources, nutrient-use efficiency, sustainability

Citation: Agegnehu G, Amede T. 2017. Integrated soil fertility and plant nutrient management in tropical agro-ecosystems: A review. *Pedosphere*. **27**(4): 662–680.

INTRODUCTION

The adoption of climate-smart agriculture would enhance productivity and the income of farmers, while contributing to the amelioration of the negative effects of climate change (FAO, 2016). Food insecurity is becoming a recurrent challenge affecting livelihoods and socio-economic developments in Ethiopia. Increasing climate variability, accompanied with declining soil fertility, decreasing land holdings, and decreasing crop and livestock productivity have amplified national concerns about the ability of the Ethiopian agricultural sector to feed the ever-growing population. Land degradation and associated soil fertility declines are considered the major bio-physical root causes for the decline in per-capita food production in sub-Saharan Africa (SSA) in general (Gruhn *et al.*, 2000; Sanchez, 2002; Farouque and Tekeya, 2008) and in Ethiopia in particular (Zeleke *et al.*, 2010; Agegnehu *et al.*, 2014a, b). Traditional soil fertility management practices, including long-term fallows and crop rotations, have been diminishing over time because of population pressure and other external drivers. The amount of N and P applied in Ethiopia has been one of the lowest (below 20 kg ha^{-1}) in SSA (FAO, 2013), and hence the traditional agriculture has been mining the inherent soil fertility over centuries. Inherent soil fertility is commonly the major source of N for crops in the region until the labile soil organic fraction (N capital) is depleted (Sanchez *et al.*, 1997). The consequence is decline in crop yield: the average yield of major cereals in Ethiopia is about 2.0 t ha^{-1} (CSA, 2013), whereas the global average is greater than 3.5 t ha^{-1} (FAO, 2013). Low crop productivity, even in relatively high rainfall areas, has also prompted farmers to expand their farming into marginal, non-cultivable lands, including steep lands-

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capes and semi-arid rangelands. Conversely, crop yield in research fields within Ethiopia reach up to 3 times more than that of farmers' fields, among others, because of improved agronomic practices and application of organic and inorganic fertilizers.

The major causes of soil fertility decline include nutrient removal through entire crop harvests, uncontrolled soil erosion, low soil organic matter, inherent soil fertility, limited application of appropriate types of fertilizers, and inappropriate land management practices (Zeleke *et al.*, 2010; Agegnehu *et al.*, 2016a, b). Although there is broad recognition that soil fertility decline is a major production constraint in Ethiopia, application of inorganic fertilizers has not been given their due attention for various reasons (Amede, 2006; Zeleke *et al.*, 2010). The high probability of nutrients being washed away by soil erosion commonly discourages farmers to apply fertilizers, particularly in poorly managed watersheds and on hill sides. Farmers are selective in applying nutrients to crops and commonly prioritize crops that have a higher and immediate benefit in terms of income and food security than perennial crops with long-term benefits. The high cost of chemical fertilizers and strong competition for organic fertilizers (biomass) among soil fertility, livestock feed, and household energy, discourages farmers from applying the required amount of fertilizer to crops. Soil organic matter depletion has been a critical problem across Ethiopia, particularly in the highlands of the country, where population and livestock pressure is high (Fig. 1).

In addition to the very low soil fertility status of Ethiopian soils, in part caused by the removal of nutrients through harvested products and losses through erosion and leaching, phosphorus (P) fixation and aluminum toxicity are two major constraints for most Ethiopian soils (Agegnehu *et al.*, 2006). This is particularly apparent in soils with pH less than 5.5, which enhances nutrient deficiency and toxicity. In such soils, phosphate is unavailable to plant roots because of fixation unless it is applied in large amounts (Marschner, 2012). Another challenge for Ethiopian soils is the de-

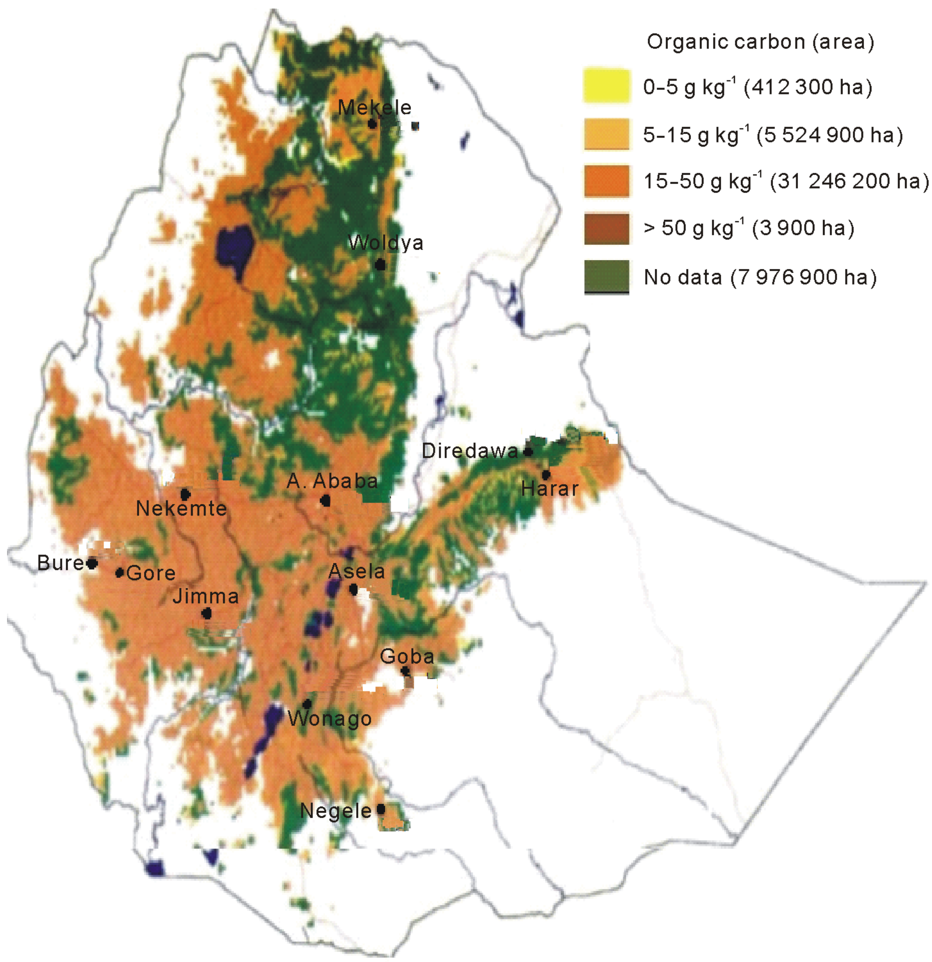

Fig. 1 Status of soil organic carbon in Ethiopia (sources: FAO (1986), Hurni (1988), and Zeleke *et al.* (2010)).

cline in soil organic matter and the resultant loss in soil productivity. Organic amendments, such as animal manure, green manure, and crop residue, if returned to the soil, could maintain or enhance soil quality, improve the nutrient pool, and enhance crop productivity through favorable effects on soil properties in the rhizosphere. The addition of organic materials also plays a key role in nutrient availability, soil water content, nutrient recycling, and addition of nutrients to the stock (Amede *et al.*, 2003). They influence mineralization-immobilization patterns as an energy source for microbial activities (Burger and Jackson, 2003; Cookson *et al.*, 2005; Zavalloni *et al.*, 2011). Organic amendments can also act as precursors to soil organic matter (Agegnehu *et al.*, 2012), reduce the P sorption of the soil (Pizzeghello *et al.*, 2011) and leaching of nutrients, and make them available to crops over a longer period of time (Zeleke *et al.*, 2010).

Integrated soil fertility management (ISFM) approaches have proven to be viable options for improving land productivity and increasing yield (Tian *et al.*, 2001; Mponela *et al.*, 2016). In most developing countries, the amounts of nutrients applied as organic fertilizers are generally higher than the quantities applied as chemical fertilizers (IAEA, 2003). However, surveys in the central highlands of Ethiopia showed that more than 80% of the manure was used as a cooking fuel (Melesse, 2011). The use of dung cake accounts for about 50% of total household energy sources, especially in the cereal zones of the northern and central Ethiopian highlands (Zeleke *et al.*, 2010). The use of dung as fuel instead of fertilizer is estimated to reduce Ethiopia's agricultural gross domestic product by 7% (Gebreegziabher, 2007), necessitating the introduction of alternative energy sources in rural systems. There is also a strong competition for crop residues between soil fertility, animal feed, and cooking fuel, and little is allocated to soil fertility. Although legumes are known to add nitrogen (N) and improve soil fertility, the frequency of legumes in the cropping systems in Ethiopian highlands is less than 10% (Bationo, 2004; Agegnehu *et al.*, 2014a, b), which implies that the probability of legumes being grown on the same land is only once in 10 years. Previous studies have suggested that future strategies for increasing crop productivity should focus on agricultural intensification through increased use of external inputs and managing the available nutrient resources more efficiently and effectively and in a sustainable way (Gruhn *et al.*, 2000; Tilman *et al.*, 2002). Moreover, reversing land degradation and improving soil fertility demands integrated landscape management, which would positively influence overall agricultural productivity and ecosystem services (Lal, 2008; Lichtfouse *et al.*, 2009; Melesse, 2011; Tscharntke *et al.*, 2012; Kassam *et al.*, 2013).

The objectives of this review are to summarize past and present research results from within Ethiopia regarding soil fertility and nutrient management over the last three decades, identify key soil fertility management technologies and practices for scaling-up, highlight research gaps, and recommend lessons for improved policy formulation and actions in tropical agroecosystems. This review also highlights the key lessons in biological N-fixation and its implication in crop yields and discusses experiences in integrating various soil fertility management interventions through employing integrated soil fertility management approaches at various scales in tropical agro-ecosystems.

LITERATURE SEARCH AND DATA PROCESSING

A literature search was conducted through the Web of Science (apps.webofknowledge.com), Google Scholar (scholar.google.com), AGRIS (agris.fao.org), Research Gate (https://www.researchgate.net), and the Ethiopian Society of Soil Science (www.esss.org.et). We searched the literature published up to 2016, using "integrated soil fertility and plant nutrient management" as key words. Although over 1 000 papers were retrieved, we focused on those reporting empirical results about Ethiopia. Over 100 publications were used to develop this review paper.

Individual articles from the collected literature were grouped with respect to research objectives and experimental types. Research objectives were further sub-categorized into articles focusing on organic and inorganic nutrient sources, including compost, manure, and crop residues, crop rotation, and agroforestry systems. Crops tested in the field were cereals (grain crops, such as wheat, maize, and barley), legumes (faba bean, field peas, and leguminous trees), and oil crops (rapeseed). The information gleaned from the published literature was organized into an archived database. Statistical analysis was performed using SAS-STAT software and graphical presentations were constructed using Microsoft Excel 2010.

NUTRIENT FLOW AND BALANCE

Many tropical soils are poor in inorganic nutrients and rely on the recycling of nutrients from soil organic matter to maintain fertility. More than half of all African areas are affected by land degradation, making this one of the continent's most urgent developmental issues. For example, an estimated US $42 billion in income and 6 million ha of productive land are lost every year because of land degradation and declining agricultural productivity (Bationo *et al.*, 2006). Moreover, Africa is saddled with a US $9.3 billion annual cost of desertification. Assessments have shown that nutrient losses are only partially compensated by natural and synthetic inputs, thus the nutrient balance for the total of SSA appearing to be negative (−26 kg N, −3 kg P, and −19 kg potassium (K) ha^{-1} $year^{-1}$) (Drechsel *et al.*, 2001), whereas in Ethiopia the losses were larger, amounting to 122 kg N, 13 kg P, and 82 kg K ha^{-1} $year^{-1}$ (Haileslassie *et al.*, 2005). In addition to the limited use of fertilizers among smallholder farmers, the nutrient loss caused by erosion, leaching, and crop residue removal depletes nutrients from the agricultural systems at over 60–100 kg ha^{-1} $year^{-1}$ of N, P, and K in Eastern Africa and is commonly reflected by low crop and livestock productivity (Stoorvogel *et al.*, 1993). Similarly, the Ethiopian farming systems are operating under an imbalanced nutrient status.

Farmers commonly set priorities in applying fertilizers in terms of crop types, market opportunities, farm locations, distance from homesteads, and other socio-economic conditions. The differential application of organic and chemical fertilizers within a farm over years, aggravated by erosion, commonly creates a clear soil fertility gradient from the homestead to the outfield. For instance, in southern Ethiopian farming systems, where perennial crops are grown around the homesteads, soil nutrient status commonly decreases from the homestead to the outfield, regardless of resource endowment categories (Bationo *et al.*, 2007). A detailed nutrient flow analysis in southern Ethiopia (Eyasu, 1998) has revealed that nutrient distribution also varied among landscapes, households, farms, and farm subunits in tropical agro-ecosystems. In these systems, high concentrations of nutrients in the homestead were created because nutrients were transferred from the house to the home garden in the form of household refuse, chemical fertilizers, animal manure, and others. Nutrients were also transferred from the distant fields to the homestead fields in the form of grain, crop residue for feed, mulch, fuel wood, and other uses. In general, the home garden fields have positive nutrient balance, whereas the outfields have a strong negative nutrient balance (Table I).

TABLE I

Nutrient balance at the farm level in relatively rich or poor households in Areka, south Ethiopia[a]

Farm unit	Rich farmers		Poor farmers	
	N	P	N	P
	kg ha^{-1}			
Enset (*Ensete ventricosum* garden)	12	11	−12	6
Midfield	−3	8	−5	4
Outfield	−95	7	−54	3

[a]Source: Amede (2006).

The soil fertility gradient has been partly created by preferential management for food security crops (*e.g.*, enset, *Enset ventricosum*) and market crops (*e.g.*, coffee). This is particularly apparent in women-led households and elderly families where the shortage of labor affects their ability to transport manure and household waste to distant fields. Shortage of organic waste and manure also limits the application to home garden crops as the distant fields are commonly exposed to heavy erosion losses and theft of high-value crops (Bationo *et al.*, 2007). The nutrient imbalance can also be seen at the country scale. Countrywide, nutrient losses under cereals and other annual crops are predominantly caused by erosion (Table II). Of the total nutrients removed from cereal cropping, approximately 70% of N, 80% of P, and 63% of K are removed by erosion. A countrywide analysis of nutrient balance indicated a depletion rate of 122 kg N, 13 kg P, and 82 kg K ha^{-1} $year^{-1}$ (Haileslassie *et al.*, 2005).

TABLE II

Determinants of total nutrients removed under different cropping systems in Ethiopian smallholder mixed farming[a]

Cropping system	Harvested products			Residue removal			Leaching		Denitrification	Erosion		
	N	P	K	N	P	K	N	K	N	N	P	K
	%											
Cereal	10.0	19.4	6.0	4.0	5.0	11.0	9.0	17.0	3.0	74.0	80.0	66.0
Pulse	14.0	16.8	13.0	4.0	3.0	8.0	8.0	17.0	2.0	72.0	84.0	62.0
Oilseed	1.0	1.0	2.0	1.0	4.0	5.0	8.0	20.0	2.0	88.0	96.0	73.0
Vegetable	21.0	30.4	25.0	19.0	31.0	34.0	22.0	22.0	12.0	24.0	44.0	19.0
Permanent	16.0	24.9	14.0	40.0	67.0	70.0	27.0	13.0	14.0	3.0	10.0	2.0

[a]Source: Haileslassie *et al.* (2005).

INTEGRATED SOIL FERTILITY MANAGEMENT (ISFM)

Application of inorganic and organic fertilizers

World average grain yields have almost doubled since the early 1960s. It is estimated that approximately 70%–80% of future increases in crop production in developing countries will have to come from intensification, *i.e.*, higher yields (FAO, 2006). The use of fertilizers is indispensable for alleviation of existing crop nutrient deficiencies, as was also recognized by the African heads of states and governments (Africa Fertilizer Summit, 2006). In June 2006 in Abuja, Nigeria, the African Union (AU) Special Summit of the Heads of State and Government adopted the 12-resolution Abuja Declaration on Fertilizer for African Green Revolution. At the end of the Summit, the AU Member States resolved to increase fertilizer use from 8.0 to 50 kg ha^{-1} by 2015, which was coincidentally the International Year of Soils. African leaders declared fertilizer, from both inorganic and organic sources, "a strategic commodity without borders" and resolved that "the AU Member States will accelerate the timely access of farmers to fertilizers." Reports as of March 2015 showed that the average fertilizer use in Africa was still only 11 kg ha^{-1} in 2014, equivalent to one tenth of the world average. At the same time, the recent Status of the World's Soil Resources Report stated that 40% of the African soils are subjected to moderate to severe degradation (FAO, 2015). Despite the recognition for the need to increase fertilizer use in Ethiopia, fertilizer consumption is still below 20 kg NPK ha^{-1} (FAO, 2013). Several studies have examined the responses of various crops to applied fertilizer in Africa. Results from the FAO fertilizer program, for instance, have indicated an average increase in yield of 64% after application of NPK fertilizer across SSA (FAO, 2006). Other experiences with the African Millennium Villages Project also showed an average threefold increase in maize yield with fertilizer application (Sanchez *et al.*, 2007). Moreover, because of the inconsistent use of chemical fertilizers and the limited return of crop residue to the soil, most of the internal N cycling in smallholder systems results from mineralization of soil organic N.

Although N, P, and K are the three major nutrient elements required by plants in large quantities for normal growth and development, some of them are rarely applied for crop production in Ethiopia. For instance, K fertilizer is barely available in the Ethiopian fertilizer market. This is merely because of the historical generalization that Ethiopian soils are believed to contain sufficient quantities of K (Murphy, 1968). On the other hand, soil analysis and site-specific studies indicate that elements, such as K, S, Ca, and Mg, and micronutrients (Cu, Mn, B, Mo, and Zn) are becoming depleted, and deficiency symptoms are being observed on major crops in different parts of the country (Dibabe *et al.*, 2007; Tulema *et al.*, 2007). Results from field trials in Ethiopian soils showed positive crop responses to K application. For example, coffee yield increased from 1 038 kg ha^{-1} in the control without K to 1 311 kg ha^{-1} when K was applied at 62 kg ha^{-1} in Jimma (Melke and Ittana, 2015). Haile and Boke (2011) also reported that increasing the level of K application to 150 kg ha^{-1} increased tuber yield from 18 t ha^{-1} in the control (no application) to 53 t ha^{-1}. Likewise, application of K sulfate on a highland Vertisol in central Ethiopia resulted in a wheat yield increase of approximately 1.0 t ha^{-1} compared to that of untreated plots (Astatke *et al.*, 2004).

Various experiments have also been conducted to determine responses of crops to applications of organic and inorganic nutrient sources in different parts of the country. The addition of farmyard manure (FYM) at 4 and 8 t ha^{-1} and 50% of the recommended NP fertilizer on dila (medium fertile soil) and dimile (less fertile soil) resulted in wheat yield similar to that of the recommended rate of 60/20 kg N/P ha^{-1} (Table III). The economic analysis showed that treatments with applications of 64/20 kg N/P ha^{-1} and 32/10/4 000 kg N/P/FYM ha^{-1} were above the minimum rate of economic return, which was assumed to be 100% (Agegnehu and Bekele, 2005). Organic amendments and N fertilizer also had additive effects on yield and nutrient uptake of barley. Grain yields respond synergistically to the combined application of organic amendments and N fertilizer. The findings of Agegnehu *et al.* (2016a, b) indicated that addition of 10 t ha^{-1} compost with 2 t ha^{-1} biochar and 69 kg N ha^{-1} more than tripled barley grain yield (5 381 kg ha^{-1}) compared to that of the control (1 560 kg ha^{-1}) and that of the highest N fertilizer rate of 92 kg N ha^{-1} alone (4, 270 kg ha^{-1}). Application of 60/20 kg N/P ha^{-1} and 6.5 t FYM ha^{-1} also increased tef grain yield by 141% compared to that of the control (Agegnehu *et al.*, 2014a, b).

In another attempt to establish optimum rates of P and FYM combinations, the applications of FYM at 4 and 8 t ha^{-1} increased faba bean seed yield by 34% and 53%, respectively, compared to that of the control. Phosphorus and FYM interaction significantly increased faba bean seed yield. The highest mean faba

TABLE III

Effects of N and P fertilizers and farmyard manure (FYM) on wheat yield on highland Nitisols, central Ethiopian[a)]

N/P/FYM rate	Medium fertile soil (dila)		Less fertile soil (dimile)	
	Wheat grain yield	Wheat total biomass	Wheat grain yield	Wheat total biomass
$kg\ ha^{-1}/kg\ ha^{-1}/t\ ha^{-1}$	$t\ ha^{-1}$			
9/10/0	2.63c[b)]	7.10c	1.63c	5.06c
9/10/8	3.05b	8.56b	2.15b	6.23b
32/10/4	3.27ab	9.18ab	2.29b	6.37b
32/10/8	3.44a	9.77ab	2.59a	7.45a
64/20/0	3.46a	10.06a	2.78a	8.18a
$LSD^{c)}_{0.05}$	0.34	1.38	0.23	0.96

a) Source: Agegnehu and Bekele (2005).
b) Values followed by the same letter(s) in a column are not significantly different at $P < 0.05$.
c) Least significant difference at $P < 0.05$.

bean seed yield was recorded with application of 8 t FYM ha^{-1} and 39 kg P ha^{-1}. Based on the economic analysis, applications of 8 t FYM ha^{-1} alone and 4 t FYM ha^{-1} and 13 kg P ha^{-1} were above the minimum acceptable rates of return of 2 027% and 134%, respectively (Agegnehu *et al.*, 2005).

There are significant differences in P sorption among the Ethiopian soils, whereby most soils are known to be non-responsive to P supply at lower application rates. Mamo and Haque (1987) reported four categories of P sorption isotherms in Ethiopia, with significant differences in sorption capacity. The volcanic ash-based soils (*e.g.*, Andosols) required approximately 100 times more P compared to the Fluvisols or Regosols. Efficient P fertilization may require the development of guidelines for P requirements in various categories of Ethiopian soils, which would also increase the economic returns and enhance the confidence of farmers to apply P in their farms and systems. In general, farmers rarely apply the recommended fertilizer rates even for major food crops for various reasons, including limited awareness of fertilizer use and management, low rate of economic return from chemical fertilizers, such as urea and di-ammonium phosphate (DAP), increasing cost of fertilizers, and poor input-output markets. The lack of fertilizer options in the market beyond DAP and urea has also been a repellent to the wider use of fertilizer because it causes unbalanced fertilizer application and low fertilizer-use efficiency. In view of this, it is necessary to increase the fertilizer-use efficiency through the application of balanced and appropriate fertilizer mixes, which could increase crop yield, improve the physical, chemical, and biological properties of soils, and increase revenue from fertilizer application. Moreover, the balanced use of fertilizers in tropical ago-ecosystems should be promoted following soil test-based recommendations.

Organic resource use and management

Organic resources are the major nutrient sources for smallholder agriculture. However, the nutrient contents of organic materials, ranging from crop residues through manure to agro-industrial wastes, vary widely. Table IV compares the nutrient contents of a variety of organic materials with the nutrients required to produce a modest 2 t ha $^{-1}$ crop of maize grain. Although all the nutrients in organic sources will not be available for crops, the information could be used to design a soil fertility management strategy that would consider organic resources as part of the nutrient budget in a given cropping system and yield goal. These estimates could be adjusted, based on the fact that crop recovery of N supplied by high-quality organic resources (*e.g.*, green manure) is rarely more than 20%, whereas that recovered from lower-quality cereal stover is generally even much lower (Giller and Cadisch, 1995). Some organic matter, such as poultry manure, contains sufficient nutrients, with approximately 2 t of manure sufficient to fertilize a 2-t maize crop, whereas other organic resources, such as crop residues, may require up to 10 t ha^{-1} to match the requirements of a 2-t maize crop. Cattle manure also tremendously varies in its quality and fertilizer value. Nutrient contents of commercial dairy farms have been significantly higher than those of smallholder farms (Probert *et al.*, 1995; Agegnehu *et al.*, 2005).

On the other hand, many leguminous trees and cover crops contain sufficient N in 2 to 3 t of leafy material (Buresh *et al.*, 1997). As a general rule, many organic materials when applied in modest amounts, *i.e.*, about 5 t dry matter ha^{-1}, contain sufficient N to match that of a 2-t maize crop, but they cannot meet P requirements and must be supplemented by inorganic P (Palm *et al.*, 1997). Moreover, stubble is one of the major sou-

TABLE IV

Average nutrient contents on a dry matter basis of selected plant materials and manure and nutrient required by 2-t maize grain + 3-t stover[a)]

Item	Plant material or manure	N	P	K
		kg t^{-1}		
Nutrient content	Crop residues			
	Maize stover	6	1	7
	Bean trash	7	1	14
	Banana leaves	19	2	22
	Sweet potato leaves	23	3.6	–
	Sugarcane trash	8	1	10
	Coffee husks	16	4	–
	Refuse compost	20	7	20
	Animal manure			
	Cattle			
	High quality	23	11	6
	Low quality	7	1	8
	Chicken	48	18	18
	Farmyard chicken	24	7	14
	Leguminous tree species (leaves)			
	Calliandra calothyrsus	34	2	11
	Gliricidia sepium	33	15	21
	Leucaena leucocephala	34	15	21
	Sesbania sesban	34	15	11
	Senna spectabilis (non-N_2 fixing)	33	2	16
	Non-leguminous trees and shrubs (leaves)			
	Chromolaena odorata	38	2.4	15
	Grevillea robusta	14	1	6
	Lantana camara	27	2.4	21
	Tithonia diversifolia	36	2.7	43
	Leguminous cover crops			
	Crotalaria ochroleuca	42	16	9
	Dolichos lablab	41	2.2	13
	Mucuna pruriens	35	2.0	7
Nutrient required by 2-t maize grain + 3-t stover		80	8	60

[a)] Sources: Khasawneh *et al.* (1980), Mugwira and Mukurumbira (1984), Palm *et al.* (1997), and Agegnehu *et al.* (2005).

rces of nutrients in the Ethiopian farming systems though the quantity and quality are low. The quality is commonly a function of biomass production and translocation, but is also dictated by the genetic-environment interaction (Nordblom, 1988). The removal of crop residues without replacement of sufficient external inputs is a major reason for nutrient mining, which causes nutrient deficiency, imbalance, and low productivity of crops, particularly in erosion-prone regions.

Most farmers have focused on cattle feeding at the expense of soil fertility. There are few studies in Ethiopia that have assessed the effect of crop residue management on soil properties, crop growth, and yield under field conditions. However, there is enough information indicating that the annual production of crop residues in Ethiopia has significantly increased, from 6.3 million tons in 1980 to approximately 31.5 million tons, mainly because of the expansion of cultivated land (Tsigie *et al.*, 2011) (Table V). On the other hand, there is a strong competition for biomass in Ethiopia, with approximately 63%, 20%, 10%, and 7% of cereal straws used for feed, fuel, construction, and bedding purposes, respectively (Zeleke *et al.*, 2010). Castellanos-Navarrete *et al.* (2015) have also reported that farmers in Kenya feed 73% of maize residues to cattle given their vital role for livelihoods. According to Mesfine *et al.* (2005), the application of 3 t ha^{-1} of tef straw increased grain yield of sorghum by 70% under conventional tillage and by 46% under zero tillage (Table VI), probably through reducing unproductive water losses. In their experiment, mean soil water content throughout the season was 16% higher with 3 t ha^{-1} application of straw compared to that of plots without straw application. They concluded that ground cover with crop residues is necessary to achieve acceptable yields along with minimum tillage, especially in low moisture-stressed areas of the country.

TABLE V

National estimates of crop residues produced per annum based on grain yield of August 2007 in Ethiopia[a)]

Crop	Grain production	Conversion factor	Crop residues
	$\times 10^6$ t		$\times 10^6$ t
Tef	3.0	3.0	9.0
Maize	3.75	2.0	7.5
Wheat	2.38	0.8	1.9
Barley	1.36	1.2	1.63
Sorghum	2.67	3.0	8.0
Millet	0.54	3.0	1.61
Oats	0.04	1.2	0.043
Rice	0.07	0.8	0.057
Pulse	1.78	1.0	1.78
Total	15.6		31.5

[a)] Sources: Nordblom (1988) and Tsigie *et al.* (2011).

TABLE VI

Effects of tef crop residue application on sorghum grain and biomass yields, total seasonal water use, and water-use efficiency for grain production at Melkassa, Ethiopia[a)]

Residue mulch rate	Grain yield	Biomass yield	Water use	Water-use efficiency efficiency
t ha^{-1}	kg ha^{-1}		mm	kg ha^{-1} mm^{-1}
0	2 916	9 614	595	4.85
3	3 591	14 322	618	5.73
6	4 138	14 710	614	6.55
$LSD^{b)}_{0.05}$	924	1 241	16.9	1.32

[a)] Source: Mesfine *et al.* (2005).
[b)] Least significant difference at $P < 0.05$.

Reduced tillage and maintenance of ground cover with crop residues commonly improve soil water availability and increase grain and straw yields in semiarid areas. Bationo *et al.* (1993) noted that incorporating crop residues, particularly along with the use of inorganic fertilizers, improved rainwater-use efficiency and soil tilth and minimized soil erosion rates. Over the duration of the study, grain yield in control plots (no fertilizer, no crop residue) was lower and steadily declined. However, although most farmers have been convinced to use farm-based organic fertilizers, they are challenged by questions such as which kind of organic residue is good for soil fertility, how to identify the quality of organic resource, how much to apply, when to apply, and what ratio of organic soil amendment to mineral fertilizer should be applied. This shows the need for the development of decision support guides to support farmers' decision making on resource allocation and management.

Nitrogen-fixing legumes and crop yields

Integration of multipurpose N-fixing legumes into farming systems commonly improves soil fertility and agricultural productivity through symbiotic associations between leguminous crops and *Rhizobium* spp. However, the contribution of N fixation to soil fertility varies with the types of legumes grown, characteristics of soils, availability of key micronutrients in soil to facilitate fixation, and frequency of growing legumes in the cropping system (Giller, 2001). Although perennial legumes are known to fix more N than annual legumes (Amede *et al.*, 2003), the most prominent ones contributing to N enrichment of soils in Ethiopia are annual legumes, including faba beans, peas, and chick peas. Some food legumes (*e.g.*, *Phaseolus vulgaris*) are known to fix N below their own N demands and may not contribute much to replenish the soil with additional nutrients. On the other hand, perennial legumes, including those referred to as legume cover crops, could produce up to 10 t ha^{-1} dry matter and fix up to 120 kg N ha^{-1} per season (Amede *et al.*, 2003). Other studies conducted to evaluate effective rhizobial isolates and strains for different agro-ecologies in Ethiopia indicated that biological N fixation (BNF) could play an important role in increasing food production through increasing yields of crops and forages (Hailemariam and Tsige, 2006). Crop yields on Nitisols at Holleta, Ethiopia increased by 51%–158% with the combined application of 20 kg P ha^{-1} and *Rhizobium* strain inoculation, as compared to no inoculation (Table VII) (Hailemariam and Tsige, 2006).

Research results from the Kulumsa Research Station in Ethiopia also indicated that wheat grain yield was enhanced by dicot rotations compared to cereal rotations (Amanuel and Feyisa, 2006). Results of a long-term experiment indicated that faba bean, as a precursor crop, increased the mean grain yield of wheat by 660–1 210 kg ha^{-1} at Kulumsa and 350–970 kg ha^{-1} at Asassa, compared to continuous wheat (Table VIII). The highest wheat grain yield was recorded after faba bean in a two-year rotation and in the first wheat crop after faba bean in a three-year rotation. From an economic point of view, a three-year rotation with either faba bean or rapeseed was an appropriate cropping sequence in a wheat-based cropping system. In addition, a study at Holetta showed that incorporation of vetch in the crop rotation significantly increased wheat grain yield after vetch by 98%–202% compared to wheat after wheat (Woldeab, 1990). The efficiency of applied NP fertilizer was also enhanced in the wheat field rotated with vetch. In an experiment conducted to determine N_2 fixation at three sites of the Arsi highlands, the amount of N fixed by faba bean ranged from 139 to 210 kg ha^{-1} (Amanuel *et al.*, 2000). This, in turn, resulted in a substantial mean soil N balance that ranged from 12 to 58 kg N ha^{-1} after the seed had been removed, but all faba bean residues were incorporated in the soil. In contrast, the mean soil N balance in wheat after wheat was at deficit (−9 to −44 kg N ha^{-1}), indicating nutrient mining and hence the need for higher rates of fertilizer N application in a continuous wheat production system (Amanuel *et al.*, 2000).

TABLE VII

Grain yields and plant heights of faba bean as influenced by P application and *Rhizobium* strain inoculation at Holetta, Ethiopia[a)]

Treatment	Plant height	Grain yield
	cm	kg ha^{-1}
Control	42.5	680
20 kg P ha^{-1}	51.0	1 540
Strain #18 + 20 kg P ha^{-1}	88.6	3 980
Strain #64 + 20 kg P ha^{-1}	56.5	2 320
Strain #51 + 20 kg P ha^{-1}	57.5	2 740
23 kg N ha^{-1} + 20 kg P ha^{-1}	61.7	2 050
20 kg N ha^{-1} + 20 kg P ha^{-1}	66.9	2 240
$LSD_{0.05}$[b)]	10.8	2 980

a)Source: Hailemariam and Tsige (2006).
b)Least significant difference at $P < 0.05$.

In Ethiopia, where demographic and economic pressures are intense, monocropping is a common practice, soil fertility depletion is severe, and use of external inputs is very low. Rotating barley with different crops resulted in higher grain yields than continuous cropping of barley (Agegnehu *et al.*, 2014a, b). Planting barley after faba bean, field pea, and rapeseed increased barley grain yield by 93%, 67%, and 78%, respectively, at Holetta and 47%, 26%, and 34%, respectively, at Jeldu, compared to continuous barley

(Fig. 2). Jones and Singh (1995) reported that barley-legume rotations out-yielded barley-fallow and barley-barley rotations. The highest yield increase because of break crops at Holetta in comparison to Jeldu is an indication of the low fertility status of soils at Holetta, which was verified by soil analysis. A review by Agegnehu *et al.* (2006) also indicated that field pea and faba bean significantly increased grain and straw yields of barley by approximately 20%–117% and 34%–102% at different locations in the highlands of Ethiopia, respectively, compared to continuous barley. Generally, higher barley grain yields after faba bean and field pea could be the result of additional N release from the residues of the preceding crops. Crop rotations have the ability to provide succeeding crops with N and reduce disease incidence and weed populations (Harker *et al.*, 2009; Turkington *et al.*, 2012). Inclusion of legumes in rotation can also bring about changes in soil fertility, soil microorganisms, soil organic matter, soil water, and crop responses (Lupwayi *et al.*, 1998; Taa *et al.*, 2004; Johnston *et al.*, 2005). Results of rotation trials elsewhere also indicated higher yields of cereals following food legumes compared to continuous cereal, or even after a fallow (Osman *et al.*, 1990; Hamilton *et al.*, 2015). Nitrogen fixation was largely responsible for the yield increment. Barley after legume, without any N fertilization, yielded as much as continuously cropped barley supplied with 60 kg N ha^{-1} (Papastylianou, 1990).

In addition to food legumes, other N-fixing forage legumes and cover crops that could be integrated into the Ethiopian highlands include *Tephrosia*, *Mucuna*, *Crotalaria*, *Canavalia*, and vetch (Bationo, 2004). A study conducted in western Ethiopia showed that the

TABLE VIII

Mean yield increments of wheat with two-year and three-year rotations and higher rates of N and P as affected by crop rotation at Kulumsa and Asassa in Ethiopia[a)]

Cropping sequence	Yield increment due to rotation over continuous wheat		Yield increment due to higher N or P rate			
	Kulumsa	Asassa	N		P	
			Kulumsa	Asassa	Kulumsa	Asassa
	kg ha^{-1}					
Wheat after faba bean	1 370	860	40	−60	380	580
First wheat after faba bean	1 300	1 050	250	0	140	360
First wheat after faba bean	620	380	310	260	160	420
Wheat after rapeseed	670	600	730	240	650	320
First wheat after rapeseed	640	470	850	420	550	280
First wheat after rapeseed	310	80	780	390	−30	610
Wheat after barley	200	230	850	140	270	460
First wheat after barley	120	220	660	390	0	330
First wheat after barley	100	10	550	610	110	250
Continuous wheat			620	450	150	230

[a)]Source: Amanuel and Feyisa (2006).

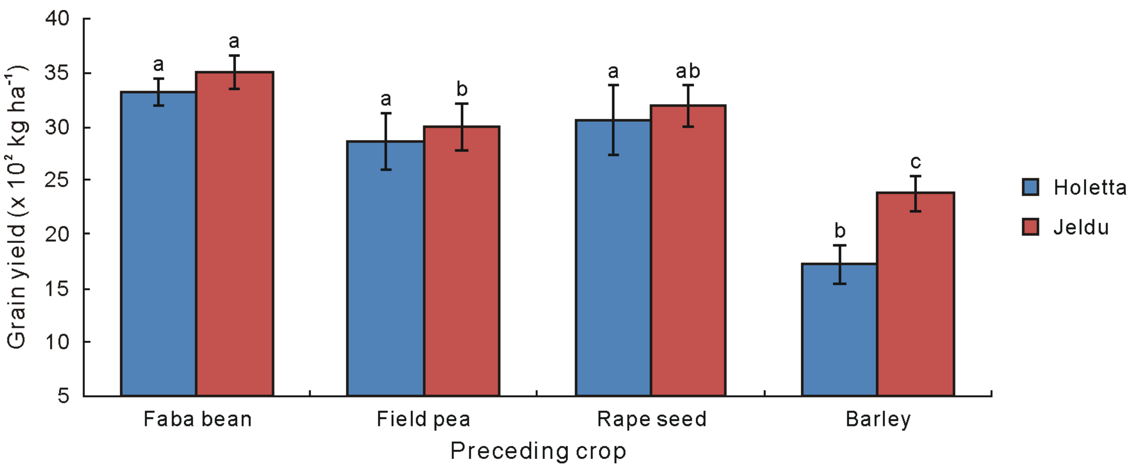

Fig. 2 Preceding crop effects on grain yields of barley at Holetta and Jeldu in Ethiopia (sources: Agegnehu *et al.* (2014a, b)). Values are means with standard deviations shown by vertical bars. Bars with the same letter(s) for each site are not significantly different at $P < 0.05$.

integrated use of improved fallow using *Mucuna* with a low dose of NP fertilizer or FYM significantly increased maize grain yield (Negassa *et al.*, 2007). The three-year average maize grain yield indicated that *Mucuna* fallow doubled maize yield compared to that of the control without improved follow and fertilizer (Fig. 3). Supplementing the improved fallow with a low dose of NP fertilizer or FYM further increased grain yield, ranging between 5.9 and 6.1 t ha^{-1}. Another study conducted at Melkassa, central Rift Valley of Ethiopia on selected leguminous shrubs and their suitability for alley cropping with food crops, such as sorghum and maize, indicated that grain yield increased by 4.2% and 13% for maize and 38.3% and 8% for sorghum, when maize and sorghum were alley cropped with *Sesbania*, *Leucaena*, and *Cajanus* spp., respectively, compared to maize and sorghum alone (Kidane and Reddy, 1993). Nitrogen fixation could increase with improved agronomic and nutritional management of the host plant. For instance, P nutrition increased symbiotic N fixation in legumes by stimulating host plant growth (Agegnehu and Tsige, 2007). Application of micronutrients, such as Mo, Mn, Fe, and Zn, could stimulate symbiotic N fixation. In some cases, the contribution of legumes could be beyond N fixation. For example, some legumes (*e.g.*, chickpeas) could modify soil climate and increase the availability of major nutrients, such as P and K, particularly in acidic soils where P fixation occurs (Betencourt *et al.*, 2012; Rose *et al.*, 2016).

MANAGEMENT OF PROBLEMATIC SOILS

The degree of soil acidity or alkalinity, expressed as soil pH, is a principal factor that affects a wide range of chemical and biological properties of soils (Brady and Weil, 2014). Although the extent and distribution as well as the causes and management of problematic soils of Ethiopia is not well documented, soil acidity in high rainfall areas, which comprises about 41% of the cultivated land (Schlede, 1989), and soil salinity in the drought-prone Rift Valley and lowland plains (Abrol *et al.*, 1988) of the country are becoming major production constraints. According to Schlede (1989), acidic soils occur in Ethiopian highlands where the rainfall intensity is high, proper crop rotation with deep-rooted crops is not practiced, and very limited fertilizers, particularly cation-based fertilizers, are applied. Nitisols are the main soil classes dominated by acidity, and more than 80% of the landmasses originated from Nitisols could be acidic in nature, partly because of leaching of cations. Some of the well-known areas severely affected by soil acidity in Ethiopia are Gimbi, Nedjo, Hossana, Sodo, Chencha, Hagere-Mariam, and the Awi Zone (Sertsu and Ali, 1983). Solubility and availability of plant nutrients is closely related to the pH of the soil because it affects the availability of plant nutrients through P fixation and shortage of available cations (*e.g.*, K and Ca), and also through release of soluble Al, Mn, and other metallic ions, which could be toxic to plants (Somani, 1996; Marschner, 2012; Brady and Weil, 2014). Wakene and Heluf (2003) also reported that Fe and Mn in Nitisols were at toxic levels to most crop plants, whereas Zn, B, and Mo were commonly deficient in Alfisols under various land-use systems in western Ethiopia. Deficiencies of micronutrients could

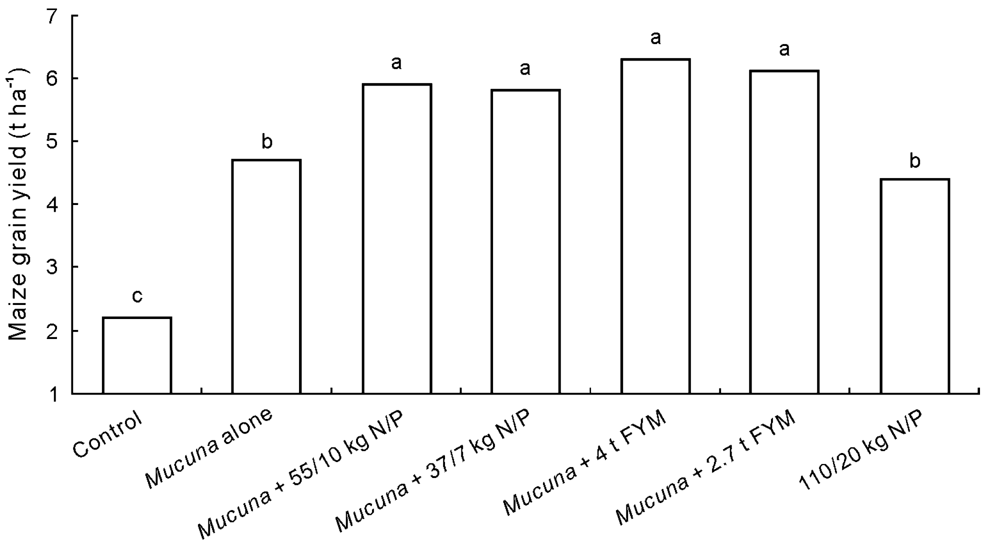

Fig. 3 Effects of improved fallow with *Mucuna* alone, *Mucuna* + 55/10 kg N/P ha^{-1}, *Mucuna* + 37/7 kg N/P ha^{-1}, *Mucuna* + 4 t FYM ha^{-1}, *Mucuna* + 2.7 t FYM ha^{-1}, and 110/20 kg N/P ha^{-1} on maize grain yield over the control without improved fallow and fertilizer in western Ethiopia (source: Negassa *et al.* (2007)). Bars with the same letter are not significantly different at $P < 0.05$. FYM = farmyard manure.

be aggravated by low pH or waterlogging, particularly in Vertisols (Dibabe *et al.*, 2007).

Crops differ in their susceptibility to soil acidity. Cotton, alfalfa, oat, and cabbage cannot tolerate acidic soils, but neutral soils with a pH range of 7–8 are suitable, whereas crops such as wheat, barley, maize, clover, and bean grow well on neutral to mildly acidic soils with a pH range of 5.5–7. Among crops tolerant to acidic soils are millet, sorghum, sweet potato, potato, tomato, flax, tea, rye, carrot, and lupine. The negative effect of toxicity and deficiency of Fe and Mn on crop yield would be avoided if the soil was held within a soil pH range of 5.5–7 that would promote the availability of plant nutrients (Somani, 1996). Management of acidic soils should emphasize strategic research, integrating soil and water management with improved crop varieties and agronomic management. Such intervention may need to focus on organic matter enrichment in acidic soils, erosion control, and increased supply of cations. Moreover, acidic soil research is needed to provide complete information on the magnitude and extent of soil acidity.

Salt-affected soils are prevalent in the Rift Valley and the lowland plains of Ethiopia, including the Awash Valley and the Afar plains because of the increase and expansion of irrigated agriculture in the country. Unlike in humid regions of the world, minimal weathering in Ethiopia allows several weatherable and relatively soluble minerals to remain in the soil, and in some cases they do not contribute adequate levels of certain elements to the soil-plant-animal system (Brady and Weil, 2014). Salt-affected soils reduce plant growth by causing nutritional disorders and decreasing or increasing the availability of essential plant nutrients (Jenks *et al.*, 2007). Moreover, these soils experience excessive accumulations of certain ions, such as Na^+, HCO_3^-, CO_3^{2-}, SiO_3^{2-}, NaCl, and Na_2SO_4. Uptake of many specific ions (Na^+ and/or Cl^-, sometimes Mg^{2+}, or others) in saline or saline-sodic soil could cause toxicity to plants that consequently results in deficiencies of nutrients (*e.g.*, K^+) and plant water stress. For instance, Fe decreases by 1 000-fold for each unit increase of soil pH in the range of 4–9, whereas it is 100-fold for Mn, Cu, and Zn (Lindsay and Norvell, 1978). Consequently, deficiencies of these micronutrients mostly occur on calcareous soils, such as those in the Rift Valley with a pH value of up to 9.0. The concentrations of Zn and Cu were found deficient in 65% and 89%, respectively, of soil samples collected all over Ethiopia. Over 75% of the Vertisols, Cambisols, and Fluvisols analyzed were also reported to be deficient in Zn (Dibabe *et al.*, 2007).

ISFM AND ITS APPLICATIONS

Combined application of organic and mineral inputs

Soil management practices for sustainable use can be best practiced through the adoption of an ISFM practice. Sanginga and Woomer (2009) defined ISFM as an integrated approach that seeks to enhance agricultural productivity and improve ecosystem services for sustainable future use through combined application of soil fertility management practices with the knowledge of how to adapt these to local conditions to maximize fertilizer- and water-use efficiency. Vanlauwe *et al.* (2010) further stated the ISFM definition as a set of soil fertility management practices that necessarily include use of chemical fertilizer, organic inputs, and improved crop varieties, combined with the knowledge of how to adapt these practices to local conditions, aimed at maximizing agronomic efficiency of the applied nutrients and improving crop productivity. All inputs need to be managed in line with sound agronomic principles. The ISFM practices incorporate both organic and inorganic nutrient sources to attain higher yields, prevents soil degradation, and improves soil water infiltration, thereby helping to meet future food supply needs and also promoting the dissemination of knowledge among farmers, extension personnel, and researchers.

Building sustainable soil fertility management is a long-term process that requires a systematic approach integrating various components, including judicious use of inorganic fertilizers, improved organic residue management through composting and application of FYM, deliberate crop rotations, cereal-legume intercropping, and integration of green manure. It also demands building a strong local capacity and market incentives for farmers to experiment, innovate, and adopt suitable ISFM practices. As the current use of inorganic fertilizers in Ethiopia is one of the lowest, and it is also neither crop nor soil specific, the limited availability of fertilizers may considerably affect the application of ISFM in the country.

The other key component of ISFM is to develop strategies to enhance fertilizer-use efficiency, which must focus on factors affecting nutrient availability and use, including choices of crop varieties, soil moisture status, and appropriate agronomic practices. In most Ethiopian farming systems, the nutrient-use efficiency (kg yield per kg nutrient applied) is remarkably low compared to other African countries, which is probably caused by interactions between soil erosion, improper crop management, and limited use of inputs. For instance, the N-use efficiency of maize in Ethiopia, Kenya, and Tanzania is 9–17, 7–36, and 18–43 kg grain kg^{-1} N applied, respectively (Heisey and Mwangi, 1996). This may partly be because nutrients applied to the soil are exposed not only to complex chemical and biological interactions, but also to competition between erosion, soil microorganisms, and plant roots. In contrast, Vanlauwe *et al.* (2011) reported that mixing fertilizer with manure or compost resulted in the highest agronomic efficiency of N (36 kg maize grain kg^{-1} N applied), whereas organic inputs of medium quality also showed significantly higher agronomic efficiency of N compared with fertilizer alone, but only at low organic input application rates (40 and 23 kg maize grain kg N^{-1} applied, respectively).

Agricultural soils could be divided into two groups based on their responses to management: 1) soils that are highly responsive to application of external inputs of fertilizers and 2) soils that are poorly responsive to external inputs because of other constraints in addition to the nutrients contained in the fertilizer (Fig. 4). According to Vanlauwe *et al.* (2010), the above soils are termed responsive soils and poor, less responsive soils, respectively. For instance, Zingore *et al.* (2007) reported that N-use efficiency by maize varied from > 50 kg grain kg^{-1} of N applied on the fertile fields close to homesteads to less than 5 kg grain kg^{-1} N applied on the degraded outfields. In some cases, where fields were close to homesteads and received large amounts of organic inputs each year, or where land was newly opened, a third class of soils where crops responded little to fertilizer existed (Fig. 4) because the soils were already fertile (Vanlauwe *et al.*, 2010). These soils require only maintenance fertilization and are termed fertile, less responsive soils. On the other hand, soils become non-responsive when other inputs, beyond the supplied nutrients, are limiting plant growth and productivity following the well-established ecological principle of the Law of the Minimum.

According to Vanlauwe *et al.* (2010), the use of fertilizers and improved seeds on responsive soils will enhance yields and improve the agronomic efficiency relative to current farming practices, characterized by local cultivars receiving very little and sub-optimally managed nutrient inputs (Fig. 4). For example, recent experiences with the Millennium Villages Project showed an average threefold increase in maize yield with fertilizer application (Sanchez *et al.*, 2007). On the other hand, the return from low-yielding local crop cultivars was expected to be modest compared to high-yielding improved varieties even under favorable conditions, although the level of risk of crop failure because of extreme conditions is less with local cultivars. Major requirements for achieving production gains on responsive fields include 1) the use of high-yielding crop varieties, 2) appropriate soil fertility and plant nutrient management practices, with appropriate fertilizer formulation and rates, and 3) suitable crop management practices. However, gains from combined use of improved seeds and soil fertility management could be reversed unless other constraints, including disease and

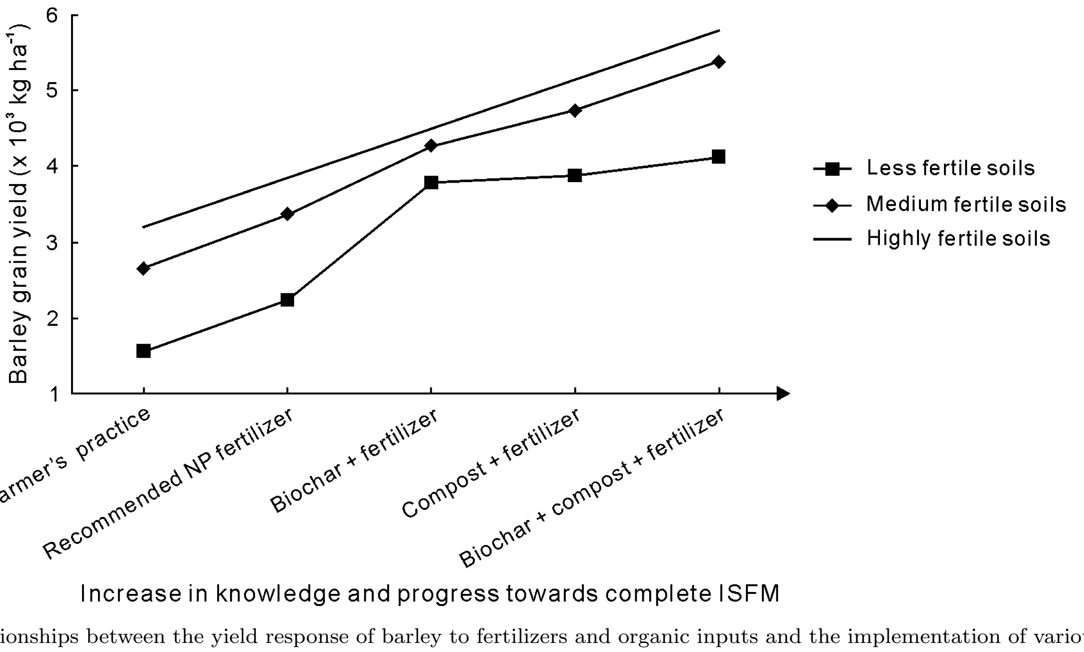

Fig. 4 Relationships between the yield response of barley to fertilizers and organic inputs and the implementation of various components of integrated soil fertility management (ISFM) developing into complete ISFM (sources: Vanlauwe *et al.* (2010) and Agegnehu *et al.* (2016a, b)). Soils that are medium in fertility and responsive to NP fertilizer and those that are low in fertility and less responsive are clearly observed in field research.

pest management practices, are in place (Sanginga and Woomer, 2009).

Farmers in the central highlands of Ethiopia classify soils of their farmland based on color, fertility status, slope, soil depth, suitability to various crops, drainage, workability, and resistance to erosion (Yirga *et al.*, 2002). Based on the degree of soil fertility, farmers in the area identify three groups of soils: 1) kosi, highly fertile soils, 2) dila, medium fertile soils, and 3) dimile, poor, less fertile soils (Fig. 4). In terms of area coverage, the poor soils are the most important soils followed by medium fertile soils. These soil categories are drained Nitisols. Highly fertile soils, mostly located around homesteads, are the most fertile soils because of the accumulation of organic matter and nutrients as a result of continuous application of household waste and manure, but represent the smallest part of total cultivated area. Wheat and barley can be grown on highly fertile soils without fertilizer and on medium fertile soils with a modest rate of fertilizer. However, less fertile soils are characterized by low soil fertility as a result of continuous cultivation and soil erosion, and thus higher rates of NP fertilizer and organic amendments are required to attain optimum yield.

Although organic inputs applied at reasonable rates seldom release sufficient nutrients for optimum crop yields, they contain nutrients that are released at a rate determined in part by their biochemical characteristics or quality of organic amendments (Kirchmann and Bergström, 2008). The combined application of organic and inorganic inputs has been advocated as a sound management practice for smallholder farming in the tropics because neither of the two inputs is highly accessible in sufficient quantities. In addition, positive interactions between both inputs have often been observed, and they are needed in the long term to sustain soil fertility and crop production (Place *et al.*, 2003; Agegnehu *et al.*, 2016a, b). Major issues within the context of ISFM are as follows. 1) Does the fertilizer and organic input application generate the required crop residues that are needed to optimize the agronomic efficiency of fertilizer for a specific situation? 2) Can application of organic inputs restore poor, less responsive soils (Fig. 4) and make them responsive to fertilizer? Where inorganic and organic fertilizer sources were applied to barley, sufficient residues were produced to meet both the farm household demands for food and feed and management needs of the soil in terms of crop residues and surface protection from erosion (Agegnehu *et al.*, 2016). Evidence also supports that application of FYM on Nitisols at relatively modest rates assisted in a clear response to fertilizer, whereas such a response was not visible before amelioration (Agegnehu *et al.*, 2014a, b). Application of FYM also reduced acidification of Nitisols in the central highlands of Ethiopia (Agegnehu *et al.*, 2005). To apply the ISFM approach to maximize yield and agronomic efficiency, adaptation is required to the prevailing soil fertility status and other site-specific improvers of crop growth.

Adapting ISFM to local conditions

Because farming systems are highly variable at different scales, adaptation of site-specific fertilizer recommendation is a challenge. First, soil fertility status can vary considerably within short distances, resulting in three general soil fertility classes (Fig. 4), as explained above. Soil organic matter content is often a good indicator of soil fertility status if this parameter is not extrapolated across different soils. Soil organic matter contributes positively to specific soil properties promoting crop growth, such as soil cation exchange capacity, moisture, aeration, and nutrient stocks. On fields where these constraints limit crop growth, a higher soil organic matter content may enhance the crop demand for N and consequently increase the fertilizer N-use efficiency. On the other hand, soil organic matter also releases available N that may be synchronized with the plant demand for N better than fertilizer N. Thus, a larger soil organic matter pool may result in lower N fertilizer agronomic efficiency. According to Vanlauwe *et al.* (2010), for fertile soils, agronomic efficiency for plant nutrients is less than that for less intensively managed outfields in western Kenya. Adapting to local conditions also includes accompanying measures that are needed to address constraints that are unlikely to be resolved by fertilizer and organic inputs. These adjustments include application of lime on acidic soils, water management practices in soil moisture-deficit conditions, and soil erosion control practices to curtail soil loss. The ISFM approach should readily be integrated into field practices for it to remain a practical approach to better soil management for farmers that are dictated by these local conditions (Vanlauwe *et al.*, 2015).

Some intermediate steps that assist in the progress towards comprehensive ISFM from the current very low fertilizer application with local cultivars are identified. Each step is expected to provide the management skills that result in improvements in yield and agronomic efficiency (Fig. 4). Complete ISFM comprises the use of improved seeds, fertilizer, appropriate organic resource management and local adaptation. Trends in Fig. 4 are not necessarily intended to prioritize interventions, but rather indicate the need for progress towards complete ISFM. They denote key components that lead to better soil fertility management. For instance, in areas where FYM is targeted towards specific fields within a farm, local adaptation is already taking place, even if no fertilizer is used, as is the case in much of Central Africa (Vanlauwe *et al.*, 2010). For less fertile soils, investment in soil fertility restoration will be required before agronomic efficiency of fertilizer is enhanced. It is important to note that the different steps are part of ISFM, but maximal agronomic efficiency or complete ISFM can be expected only when all steps are implemented. For instance, a farmer adopting good agronomic practices for applied fertilizer will improve the agronomic efficiency of those inputs, thus implementing one component of ISFM. However, ISFM can be considered complete only when organic inputs are also recycled and improved crop varieties and the required associated measures are used. Finally, the above evidence for the different steps is fragmented and derived from different cropping systems and agroecological zones, and thus a concerted effort with a standardized multi-locational design, including the existing variability in soil fertility, is needed to determine which circumstances are most crucial in the stepwise improvement of agronomic efficiency of fertilizer and organic input.

The ISFM practices interact with environmental quality by minimizing nutrient losses to the environment and maximizing crop yield per unit of nutrient applied. In this way, agricultural production is intensified and pressure to convert additional lands to agriculture is reduced. Although soil fertility is most often defined as the capacity of a soil to grow crops, soil health is usually defined in broader terms and encompasses the potential of soils to provide a full range of ecosystem services. According to the Millennium Ecosystem Assessment (2005), healthy soils are those soils which are capable of delivering essential provisioning, regulating, and supporting ecosystem services on a sustained basis. Examples of the latter are nutrient cycling, water flow regulation, and maintenance of soil biological diversity. Many of these services are directly or indirectly related to the soil organic matter pool, although knowledge of how much soil organic matter and of which quality is required to retain specific service functions is currently limited. Thus, ISFM is a viable option for improved soil health, and more so when ISFM practices increase the soil organic matter pool over time. Recycling of organic inputs is likely to result in increased soil organic matter and restoration of degraded soils. Whether the seed and fertilizer strategy is able to produce sufficient crop residues to positively influence the soil organic matter pool is uncertain and ultimately regulated by soil microclimate, texture, and structure, organic input strategies, and soil tillage regimes (Vanlauwe *et al.*, 2015).

The ISFM approach in existing cropping systems can be illustrated as: 1) legume-cereal rotations with P fertilizer targeted at the legume phase and N fertilizer at rates below the recommended rates targeted at the cereal phase and 2) modest fertilizer applications with FYM and compost in cereal-based cropping systems (Vanlauwe *et al.*, 2010). Application of appropriate amounts of P to the legume phase ensures good grain and biomass production, and the latter in turn benefits a subsequent cereal crop, thus reducing the need for external N fertilizer application (Agegnehu *et al.*, 2014a, b). Use of a proper legume variety with a low harvest index may aid in the accumulation of organic matter and N in the non-harvested plant parts, and use of adapted maize variety may favor the corresponding requirement for nutrients by the maize. Selection of fertilizer application rates based on local knowledge of the initial soil fertility status within these systems would qualify the soil management practices as complete ISFM. Localized application of appropriate amounts of fertilizer with compost as depot to crops, such as maize, markedly improves its use efficiency (Agegnehu and Sommer, 2000). Recycling of crop residues can reduce erosion and thus further benefit growth and nutrient demand of a subsequent cereal crop (Tsigie *et al.*, 2011). Rotating a legume with cereals has proven to increase cereal yields further (Aune and Bationo, 2008; Agegnehu *et al.*, 2014a, b). Although both systems are good examples of complete ISFM, the selection of management priorities should be in line with the overall economic conditions and the resource capability of farmers.

Scaling up of ISFM

Despite the production of substantial quantities of crop residues and manure in Ethiobia as a source of organic soil amendments, they are not returned to soil because of competing utilizations. Thus, what farmers do with the crop biomass and manure and the proposal to recycle these resources to soil fertility are illustrated in Fig. 5. At present, farmers use the crop residues as livestock feed because of their higher value as feed than as soil improver. Manure is used as an energy source instead of using it as a soil amendment owing to lack of alternative energy sources (Fig. 5). With the use of compost and biochar, the organic resource can be recycled back to the farm (Fig. 5). Composting of both

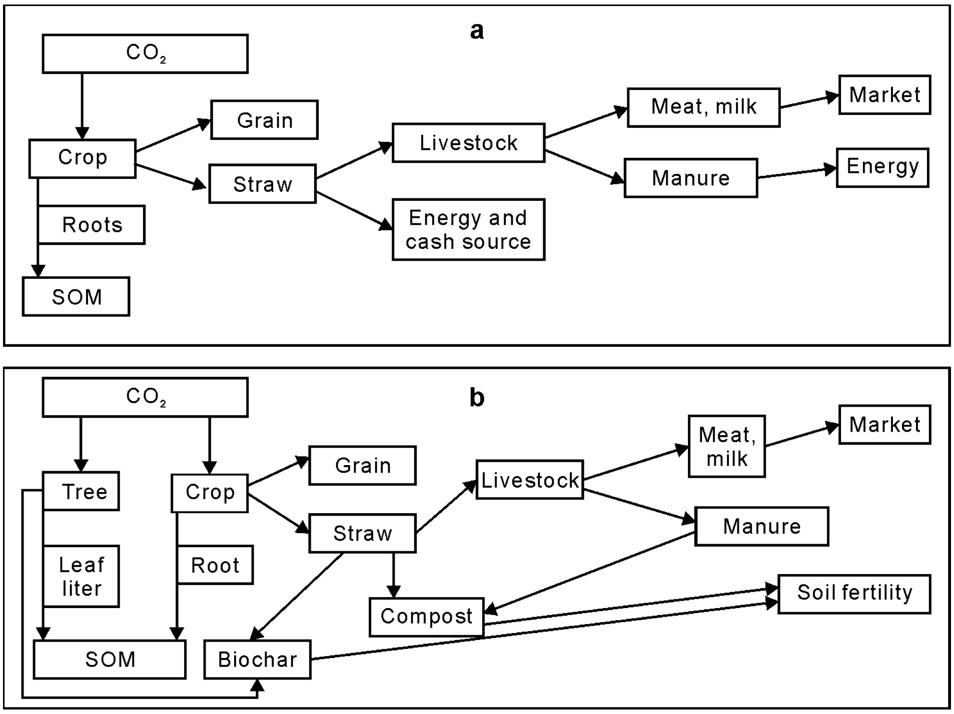

Fig. 5 Current carbon recycling practices (a) and proposed carbon recycling strategies (all carbon pools increase in size due to the recycling of manure and crop residues) (b) in Ethiopia farms. SOM = soil organic matter.

crop residues and manures together or carbonization of part of them to biochar can reduce the volume of organic resources, which means less labor/cost to transport them back to the field. Application of compost to the soil may enable farmers to get the benefit of fairly resistant organic matter and nutrients, provided that they have not been leached out or denitrified during the composting process, but the labile carbon may be lost to the atmosphere. The labile carbon would benefit the soil because it can feed soil organisms, which are responsible for several beneficial processes in the soil.

The level of knowledge increases as we progress to complete ISFM, which has implications for the strategies in adapting for widespread dissemination of ISFM. Moreover, a set of enabling conditions can favor the application of ISFM. The operations of every farm are strongly influenced by the rural communities, policies, markets, and supporting institutions. Since ISFM is a set of principles and practices to intensify land use in a sustainable way, adoption of ISFM is facilitated in areas with greater pressure on land resources. Recognizing the need for fertilizer, improved varieties is the first step towards ISFM. Access to farm inputs, markets for produces, and financial resources are essential for early adoption of ISFM, which is largely market-driven as product sales provide incentives and finance to invest in soil fertility management technologies. Appropriate policies towards sustainable land use intensification and the necessary institutions and mechanisms to implement and evaluate these are also important to facilitate the adoption of ISFM. Specific policies addressing the restoration of degraded soils may also be required as investments to achieve this may be too high to be met by farmers alone.

Considerable improvements in production can be made by promoting use of farm inputs and improved seeds within market-oriented farm enterprises although dissemination and adoption of complete ISFM is the ultimate goal. Such dissemination strategies should include means to facilitate access to the required inputs, dissemination of simple information leaflets through extension networks, and knowledge of how to improve poor and less responsive soils. Although the utilization of improved seeds and fertilizers has significantly increased the productivity of major crops, application of ISFM could considerably increase low agronomic efficiency (Vanlauwe *et al.*, 2011; Agegnehu *et al.*, 2016a, b), with all the consequent economic benefits to farmers. As efforts to promote the seed and fertilizer technology has been under way, activities such as development of site-specific decision guides that enable tackling more complex issues can be initiated to guide farming communities towards complete ISFM, including suitable organic matter management and adaptation of technologies to be achieved at the local level. Farmer adoption of ISFM may further be enhanced through implementation of balanced rural promotions that combine all of these considerations by offering farmers information, technology demonstrations, product samples, financial incentives, and opportunities to develop their skills within their own farms. Overall, in the face of climate change, adoption of ISFM has the potential not only to improve farm productivity and farmers' income, but also to result in environmental benefits in tropical agro-ecosystems.

CONCLUSIONS

Large-scale dissemination of ISFM practices will strategically help to intensify agriculture in tropical agro-ecosystems. Although ISFM is an important strategy, its implementation demands the deliberate integration of various soil fertility management interventions along with incentives for farmers to adopt and implement these strategies. Moreover, for ISFM to be adopted, there is a need to understand the flow of nutrients within the landscape and the farm, as well as a need for combined use of organic and inorganic sources of fertilizers reflecting the socio-economic realities of farmers and facilitating the integration of N_2-fixing legumes into the farming systems. There is the need for improved agronomic practices to combine these various interventions over time and space. In facilitating proper management and use of nutrient resources in tropical agro-ecosystems, there is also a need to create strong collective action at national, regional, and local levels that may address the following challenges: 1) minimizing major agents of nutrient movement, mainly soil erosion through improved management of upper-watersheds, for which there could be a need for integrated application of soil and water conservation, afforestation, establishment of waterways, and other practices through enhancing collective action and farmer innovation; 2) producing sufficient organic matter within the cropping systems that would satisfy the competing demands of animal feed, household energy, and soil fertility management, which may require solutions that could be beyond soil management practices while increasing biomass through application of chemical fertilizers to crop and forage fields is possible, for instance, introducing fuel-efficient stoves and introducing alternatives energy sources that would minimize competition and spare more organic matter for soil fertility improvement; 3) enabling effective policy strategies that would induce communities to recycle organic resources to valuable nutrients in homesteads and farm niches at household and community levels, which may also demand collective action to collect, process, and market organic resources, particularly in peri-urban settings; 4) sustaining crop yields by soil ameliorating materials, particularly on highly weathered acidic soils, which is the best approach for achieving higher crop yields, higher fertilizer-use efficiency and economic feasibility; 5) establishing crops to fertilizer responses that would consider economic returns and socio-economic requirements because sound soil-test crop responses and balanced use of fertilizers based on soil test fertilization are essential for successful fertilizer promotion and increased crop production, which will also help to inform farmers on the use of correct and balanced use of fertilizers for maximum efficiency and profitability; 6) facilitating by various associated measures the adoption of ISFM practices in priority farming systems, as widespread adoption of ISFM has the potential not only to improve farm productivity and farmers' livelihoods, but also to bring about environmental benefits; and 7) engaging agricultural development personnel with the training of farmers to grow more grain and forage legumes and trees in watersheds, to make compost, and to recycle nutrients, thus creating an opportunity for farmers to learn and adopt these practices.

ACKNOWLEDGEMENTS

The Australian Agency for International Development (AusAID) is highly acknowledged for funding this review as part of the study of the first author in Australia. We are also grateful to the anonymous reviewers whose comments and suggestions improved this manuscript.

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