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Section 2

Crop response to fertilizer application in Ethiopia: a review[3]

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1. Introduction

Enhancing agricultural productivity is one of the central challenges to achieving food security and poverty reduction in Ethiopia. Considering the fact that soil fertility is one of the biggest challenges, an obvious strategy is to increase fertilizer application and promote good agronomic practices to enhance productivity. As a result, national annual fertilizer use grew from 3,500 t to about 140,000 t by the early 1990s, and reached about 200,000, 400,000, 550,000 t in 1994, 2005, and 2010, respectively. The total amount of fertilizer available for application will exceed one million tons in the 2012/13 cropping year (Tefera et al., 2012).

In Ethiopia, demonstrations about fertilizer effects on major cereal crops started in the 1960s through programs such as the Freedom from Hunger Campaign. The results from these programs showed the positive benefits of fertilizer addition, and most of the focus was on N and P. Despite the recognition for the need to increase fertilizer use in Ethiopia, fertilizer consumption was still below 20 kg ha^{-1} (Croppenstedt et al., 2003; FAO, 2004; Yirga and Hassan, 2013), which is related to several factors such as: education, land tenure, access to credit, and livestock ownership (Yirga and Hassan, 2013). A survey conducted in the Central Highlands of Ethiopia showed that fertilizer use was low but more fertilizer was used in the wheat/teff cropping systems in the Mid Highlands compared to the Upper Highlands (Yirga and Hassan, 2013). Only 30 to 40% of Ethiopian smallholder farmers use fertilizer, and those that do only apply 37 to 40 kg on average per hectare, which is significantly below the recommended rates (MoA, 2012). This is due to multiple factors including: input supply, transportation, price, and absence of site-specific recommendations that affected adoption.

Traditionally, Diammonium phosphate and urea (supplying nitrogen and phosphorus) were the major fertilizers used by farmers in Ethiopia, creating nutrient imbalances in soils (Nandwa and Bekunda, 1998). However, there are significant differences in P sorption among Ethiopian soils, and most soils are nonresponsive to P supply at lower application rates.

3 This is based on contributions related to the 'Crop response to fertilizer response' Workshop organized by CIAT and ICRISAT on 1–2 December 2016. Details and reports for other crops will be reported in a Special Issue of the Ethiopian Journal of Natural Resources (EJNR), Vol. 16, Number 1 and 2, 2017.
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Mamo and Haque (1987) reported that there are four categories of P-sorption isotherms in Ethiopia, with significant differences in sorption capacity. The volcanic ash-based soils (e.g. andosols) needed about 100 times more P compared to fluvisols or regosols. Efficient P fertilization may require the development of guidelines on P requirements of the various categories of Ethiopian soils, which would also increase the economic returns and enhance the confidence of farmers in applying P in their farms and systems.

Potassium fertilizer is not readily available in the Ethiopian fertilizer market. This is because of the historical generalization that Ethiopian soils contain a sufficient quantity of potassium (Murphy, 1959). Recent studies in Ethiopia showed positive crop responses to potassium (K) application. For instance, Ayalew et al. (2010) showed that coffee yield increased when the K level was increased from zero to 62 kg ha^{-1} at Melko. Haile et al. (2009) reported significant increases of Irish potato yield following application of K fertilizer on acidic soils of Chencha, southern Ethiopia. The authors also showed that increasing the rate of K application to 150 kg ha^{-1} increased tuber yield from 15 t ha^{-1} in the control (no application) to 57.2 t ha^{-1}. Gizaw (2010) also reported a significant difference in potato tuber number per plant due to K fertilizer application on acrisols of Wonjella in Banja Woreda, western Amhara region of Ethiopia. Soil analyses and site-specific studies also indicated that elements such as K, S, Ca, Mg, and micronutrients (e.g. Cu, Mn, B, Mo, and Zn) were becoming depleted and deficiency symptoms were observed in major crops in different parts of the country (Asgelil et al., 2007; Ayalew et al., 2010).

In general, farmers rarely apply the recommended fertilizer rates, even for their major food crops (Nandwa and Bekunda, 1998; Abegaz et al., 2007) for various reasons including: limited awareness of fertilizer use and management; low rate of economic return from mineral fertilizers (DAP and urea); increasing cost of fertilizers; and poor input-output markets. The lack of fertilizer options in the market beyond DAP and urea has reduced wider fertilizer use as farmers mostly applied unbalanced fertilizers which caused low fertilizer efficiency. Fertilizer use efficiency should be improved through the application of a balanced and appropriate fertilizer mix, which could increase crop yield, improve the physical, chemical and biological condition of the soil, and increase the revenue from fertilizer application. Moreover, a balanced use of mineral fertilizers should be promoted following soil test-based recommendations. Against this background, the EthioSIS project under the coordination of the Agricultural Transformation Agency (ATA), has collected soil samples from 250 districts to map soil fertility status, among others. Its aim was to understand the spatial variability of soil properties and design fertilizer recommendations for the major agricultural areas of the country.

Designing site- and context-specific fertilizer recommendations requires an understanding of the effects of fertilizer application on crop yield. The main aim of this section is to document existing information on the response of major crops to inorganic fertilizer application in Ethiopia. A comprehensive review of existing information over the last three decades on crop response to application of chemical fertilizers across soil types, agroecologies and cropping systems was conducted for various crops. Below we present the major findings of a review of the response to fertilizer application of major crops in Ethiopia. The use of fertilizers to alleviate existing crop nutrient deficiencies is indispensable; this has been recognized by the African heads of States (African Fertilizer Summit, 2006).

2. Crop response to fertilizer application

2.1. Wheat response to fertilizer application

Ethiopia is one of the largest wheat producers in SSA (White et al., 2001; Minot et al., 2015) with an estimated area of 1.66 million ha and production of 4.3 million tones (CSA, 2016). The area suitable for wheat production falls between 1,900 and 2,700 m above sea level and is produced exclusively under rain-fed conditions (Simane et al., 1999; White et al., 2001). Mean wheat yields increased from 1.3 t ha^{-1} in 1994 (CSA, 1995) to 2.54 t ha^{-1} in 2015 (CSA, 2016), which is well below experimental yields of over 5 t ha^{-1} (Tadesse et al., 2000; Zeleke et al., 2010; Mann and Warner, 2015). However, Ethiopia's current wheat production is insufficient to meet domestic needs, forcing the country to import 30 to 50% of its wheat to fill the gap (Okalebo et al., 2007; Dixon et al., 2009; Minot et al., 2015). The yield gap of over 3 t ha^{-1} suggests that there is potential for increasing production through improved soil and crop management practices, particularly increased use of fertilizers and an adequate soil fertility maintenance program. With this background, soil fertility management studies began in Ethiopia with an emphasis on inorganic fertilizers application (mainly urea and DAP) some five decades ago.

Wheat soil fertility research achievements before the 1990s were documented by Asnakew et al. (1991) and Tanner et al. (1991). Since the 1990s, substantial wheat soil fertility research efforts have been made. However, crop response information could not be accessed easily for different users. This review collates wheat response to soil fertility research-based evidence generated over the last two to three decades. The data were gathered from federal and regional agricultural research centers, higher learning institutes and extracted from various published and unpublished research outputs.

Review and summary results based on experiments conducted across the major wheat production belts of the Ethiopian highlands indicated that N and P are the two major plant nutrients that limit wheat productivity, although there is growing evidence that other nutrients such as K and some micronutrients also constrain wheat production. The recommendation rates for N and P fertilizers vary from 30 to 138 N kg ha^{-1} and 0 to 115 P_2O_5 kg ha^{-1}, respectively (Abdulkadir et al., in press). These huge differences in NP fertilizer responses across the test locations highlight the need to target the right fertilizer and application rates to the location to improve the efficiency of fertilizer use and to prevent negative environmental consequences. In addition, wheat response to K is observed in some test locations contrary to long-standing assumptions that Ethiopian soils are rich in K (Abdulkadir et al., in press). The application of potassium sulphate on highland vertisols in central Ethiopia resulted in about 1 t of wheat yield advantage compared to untreated plots (Astatke et al., 2004).

Multi-location bread wheat fertilizer response trials conducted on farmers' fields on poorly drained vertisols of Bichena in northwestern Ethiopia indicated an extremely high grain yield response to N and a lesser, but significant response to P (Minale et al., 1999). The highest grain yield, 3,317 kg ha^{-1} was obtained with the application of 138–92 kg N–P_2O_5 ha^{-1}, representing a yield increase of 2,336 kg ha^{-1} over the control, but 138–46 kg N–P_2O_5 ha^{-1} was the most economical NP combination for Bichena (Minale et al., 1999). Generally, there was linear increase in all parameters as N and P rates increased. Similarly, fertilizer rates of 138–46 kg N–P_2O_5 ha^{-1} at Farta and 123–46 kg N–P_2O_5 ha^{-1} at Laie-Gaient of northwestern Ethiopia were also found economically feasible and bread wheat grain yield consistently increased as the rate of applied NP increased to the highest levels (Minale et al., 2006). Similar on-farm experiments conducted in mid-highland vertisol districts of Arsi zone revealed that the application of 92–46 N–P_2O_5 kg ha^{-1} gave optimum bread wheat yield with the agronomic efficiency (AE) of 13.3 kg grain per kg N applied (Dawit et al., 2015). Additional recommendations of 138–69 and 115–46 N–P_2O_5 kg ha^{-1} were also set for resourceful farmers to attain a long-term high yield goal.

Different combinations of N/P fertilizer 9/10/0, 32/10/4, 32/10/8, 9/10/8 and 64/20/0 kg ha^{-1} N/P and FYM t ha^{-1}, respectively, were studied in Wolmera, Ethiopia to determine their effects on the growth and yield of wheat. Results showed that on Dila (moderately fertile soil), significantly higher grain and biomass yields were obtained from the application of 64/20/0, 32/10/8 and 32/10/4 kg N/P and FYM t ha^{-1}, while on Dimile (poorly fertile soil), 64/20/0 and 32/10/8 kg N/P and FYM t ha^{-1} resulted in significantly higher wheat grain yield (Table 2.1). Similarly, the application of manure significantly increased nutrient uptake and grain yield of wheat (Sharma and Behera, 1990; Prasad et al., 2012). Based on economic analysis, the treatments with application of 64/20/0 and 32/10/4 were above the minimum economical rate of return, which was assumed to be 100% for this experiment (Agegnehu and Chilot, 2009).

Table 2.1 Inorganic N/P fertilizers and FYM effects on wheat grain yield (GY) and total biomass (TBY) on nitisols of Welmera area. *Means followed by the same letter within a column are not significantly different.*

Treatment	Moderately fertile soil (Dila)		Poor soil (Dimile)	
	GY (t ha^{-1})	TBY (t ha^{-1})	GY (t ha^{-1})	TBY (t ha^{-1})
N/P kg ha^{-1}/FYM (t ha^{-1})				
9/10/0	2.63c†	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 (0.05)	0.34	1.38	0.23	0.96
CV (%)	8.79	12.77	8.43	11.93

Source: Agegnehu and Chilot (2009).

Results from experiment conducted on two soil types in the central highlands of Ethiopia indicated that wheat grain yield increased by 83, 156, 233, and 288% on vertisols and by 45, 62, 98, and 150% on nitosols in response to the application of 20.5, 41, 82, and 164 kg N ha^{-1}, respectively. In similar trends, application of 23, 46, and 92 kg P_2O_5 ha^{-1} resulted in a grain yield increment of 171, 196, and 203% on vertisols, and 71, 90, and 104% on nitosols, respectively (Table 2.2). The mean grain yield response to fertilizer application was 163% on vertisols and 76% on nitosols, compared to the unfertilized control (Amsal et al., 2000b; Amsal and Tanner, 2001). Adamu (2013) also reported that the application of 101–10 kg N–P ha^{-1} and 130–30 kg N–P ha^{-1} are recommended for optimum grain yield on relatively fertile and infertile black soils, respectively, around Debre Birhan in central Ethiopia. Another NP fertilizer rate study at Melka Werer under irrigation indicated that wheat yield significantly increased with the application of 30 kg N ha^{-1}, but did not respond to P application, indicating high available P in the soil of the area (Kassahun, 1996).

Table 2.2 The effects of N and P application rates on wheat grain yield grown on nitisols and vertisols in central Ethiopia.

Fertilizer rates	Grain yield (t ha^{-1})	
	Nitosols	Vertisols
N rates (kg N ha^{-1})		
20.5	2.54	1.32
41	2.83	1.84
82	3.46	2.4
164	4.37	2.79
P rates (kg P_2O_5 ha^{-1})		
23	3.00	1.95
46	3.32	2.13
92	3.57	2.18
Control	1.75	0.72
Mean	3.08	1.89
CV%	16.0	12.8

Source: Amsal et al. (2000b).

Nitrogen is a highly mobile nutrient and can easily be lost through leaching, volatilization, and denitrification (Abdulkadir et al., in press). As a result, the efficiency of applied N in the form of urea is usually less than 50% (Amanuel, 1998). Nitrogen fertilizer rate by timing trials conducted in southeastern Ethiopia exhibited that the highest grain yields were obtained by applying all of the N at sowing or splitting it between sowing and tillering than delaying all N application until mid-tillering or later. The grain yield advantages were 13 to 27% for the N application at sowing or split between sowing and tillering (Zewdu and Tanner, 1994). The response to N was highest for early application timings; grain yield responses were 8.5 and 7.4 kg grain per kg of N over the 0 to 41 kg N ha^{-1} interval, respectively.

Another study examined the effects of three N sources (large granular urea (LGU), ammonium sulfate (AS) and standard urea (prills), three rates [0, 60, and 120 kg N ha^{-1}]), and three different application timings [$^{1}/_{3}$ at planting and $^{2}/_{3}$ at tillering]) at Akaki and Robe (Tilahun et al., 1996). The N sources were ammonium sulfate (AS, 21% N), and large granular urea (LGU) and urea (both 46% N). The results revealed that bread wheat responded more to the high rate of N from LGU or AS than from urea; the maximum grain yield (3.3 t ha^{-1}) was obtained with 120 kg N from LGU (vs. 2.1 and 2.4 t ha^{-1} with 120 kg N from urea and AS, respectively). At the low N rate, there was no AE difference among the three N sources, but at 120 kg N ha^{-1}, the agronomic efficiency (AE) of LGU was superior to those of urea and AS, which did not differ from each other. Apparent N recovery (AR) followed the same trend: at 60 kg N ha^{-1}, N sources exhibited the same level of recovery in grain, but, at 120 kg N ha^{-1}, the apparent recovery (AR) of LGU was superior to those of urea and AS (Tilahun et al., 1996).

Many researchers noted that micronutrients such as Zn and Cu (unlike Fe and Mn) are severely deficient in many test locations. Asgelil et al. (2007) documented the status of some micronutrients in agriculturally important soil types of the country. In their work, Fe and Mn were above critical limits and in some cases, Mn surpassed the sufficiency level. Zn and Cu were deficient in most of the zones studied. The frequency of Zn deficiency was highest in vertisols and cambisHaiols (78%) and the lowest in nitisols; Cu deficiency was the highest in fluvisols and nitisols with a value of 75 and 69%, respectively. In the same study, wheat tissue analysis revealed no deficiency of Fe and Mn, whereas the deficiency of Zn and Cu were severe, ranging from 43 to 87% of the total samples analyzed. Teklu et al. (2007) also reported that the status of Mn, Zn and B were sufficient in andosols in the Rift Valley of Ethiopia. Wheat flag leaves micronutrient analysis from ten sites in central highland vertisols of Ethiopia showed that Cu, Fe, Mn and Cl concentrations were sufficient, while Zn was deficient in all the samples (Amsal et al., 2000a; Hailu et al., 2015). In addition, recent nutrient survey conducted by EthioSIS exhibited widespread B and Zn deficiency across the country.

Research results from Kulumsa Research Station in Ethiopia have indicated that wheat grain yield was enhanced by dicot rotations compared to continuous cereal (Tanner et al., 1999; Amanuel et al., 2000; Amanuel and Daba, 2003). The results of a long-term experiment indicated that faba bean as a precursor crop increased mean grain yield of wheat by 660–1210 kg ha^{-1} at Kulumsa and 35–970 kg ha^{-1} at Asassa, compared to continuous wheat (Table 1.7). The highest wheat grain yield was recorded after faba bean in a two-course rotation (FbW) and in first wheat after faba bean in a three-course rotation (FbWW). From an economic point of view, a three-course rotation with either faba bean or rapeseed was found to be an appropriate cropping sequence in a wheat-based cropping system.

Moreover, results from a study at Holetta showed that the incorporation of vetch in the crop rotation increased wheat grain yield considerably compared to wheat after wheat. Grain yield of wheat after vetch increased from 98–202% compared to wheat after wheat (Woldeab, 1990). The efficiency of applied NP fertilizer was also enhanced in a field rotated with vetch.

Long-term crop rotation trials in different parts of the country had a marked effect on sustainable wheat productivity (Table 2.3). Faba bean, field pea, lupine, rapeseed, vetch, lentil, and chickpea were the most favorable break crops in most of the wheat-growing areas of Ethiopia. Wheat after legume break crops (particularly faba bean, field pea and lupine) produced higher grain yields and soil NO_3 than cereal-based rotations and reduced 60–100% of inorganic N fertilizer requirement, levels of root diseases and weed infestations compared to wheat monoculture.

Table 2.3 Wheat grain yield (kg ha^{-1}) as affected by crop rotation across 5 years at Bekoji and Asasa, southeastern Ethiopia.

Cropping sequences	Grain yield (kg ha^{-1})	
	Bekoji	Asasa
FbW	4,500	3,260
FbWW	4,430	3,450
FbWW	3,750	2,780
RpW	3,800	3,000
RpWW	3,770	2,870
RpWW	3,440	2,480
BaW	3,330	2,630
BaWW	3,250	2,620
BaWW	3,230	2,410
WWW	3,130	2,400
Mean	3,660	2,790
CV (%)	10.9	14.5
LSD (0.005)	389	491

Source: Amanuel et al. (2000). *Fb-faba bean, W-wheat, Rp-rapeseed, Ba-Barley.*

2.2. Barley response to fertilizer

In Ethiopia, barley is the fifth most important cultivated crop after teff, maize, wheat and sorghum and is used as food, in local beverages and beer. However, its productivity (1.965 t ha^{-1}) is low compared to the global average of 3.095 t ha^{-1}. In response to this, numerous research efforts have been undertaken (Fana, in press).

Agronomic trials on barley started in the late 1960s under the then Institute of Agricultural Research (IAR) (Adamu et al., 1993). The highest response of barley to 40–18 kg ha^{-1} N-P_2O_5 applications was obtained in 1968 at Holetta on red soils with optimum sowing dates. The cropping system trial at Bedi in 1972 recommended fallow in the 1st year followed by unfertilized local barley in the 2nd year, fodder oats in the 3rd year, barley with 27–30 kg ha^{-1} N-P_2O_5 in the 4th year, wheat with 48–15 kg ha^{-1} N-P_2O_5 in the 5th year and rape seed with 23–10 kg ha^{-1} N-P_2O_5 or linseed with 46 kg N ha^{-1} in the 6th year.

Acidity is a major constraint for barley production in Ethiopia. Hailu and Getachew (2006) reported a triple yield increase by application of 3 t ha^{-1} of lime compared to no lime at Adadi, southwest Shewa. Shiferaw and Anteneh (2014) reported highest barley grain yield (2,792 and 3,279.3 kg ha^{-1}) was recorded from combined application of NPK at the rate of 46/40/50 kg ha^{-1} and half the recommended lime rate (3.84 and 0.85 t ha^{-1} at Chencha and Hagerselam, respectively). A pot experiment conducted on soils collected from different land use systems in West Oromia revealed that maximum mean barley yield for both 50 and 100 mesh lime particle sizes (LPS) were obtained at 6 t ha^{-1} of lime rate on the forest land, followed by 8 and 10 t ha^{-1} on grazing and cultivated lands, respectively (Chimdi et al., 2012). Liming of acid soils at Dera (Sheme kebele) and Jabitehenan (Mana kebele) in northwestern Amhara region based on regional soil laboratory recommendation (Asresie Hassen et al., 2015) increased food barley productivity by 50% by application of 2 t ha^{-1} of lime (3.65 t ha^{-1} as compared to 2.43 t ha^{-1} grain yield without liming). Temesgen et al. (2017) reported 133% grain yield advantage by combined application of 1.65 t ha^{-1} lime and 30 kg ha^{-1} P as compared to control (no lime and fertilizer) in the central highlands of Ethiopia.

Fertilizer recommendation for barley was revised in 1988 based on soil types where the Arsi, Shewa and Bale regions had different range of recommendations from other regions. For the three regions, N/P_2O_5 was recommended as 25/45 kg ha^{-1} for the nitisols, 20/55 kg ha^{-1} for the black soils, 20/45 kg ha^{-1} for the red soils and 30/35 kg ha^{-1} for the brown soils, respectively (Fana, in press). For the other regions across the country, a general recommendation was made in which N/P_2O_5 of 30/45 kg ha^{-1} was recommended for nitisols, 20/40 kg ha^{-1} for black soils, 20/45 kg ha^{-1} for red soils and 25/30 kg ha^{-1} for brown soils (Fana, in press).

Soil test-based barley response to phosphorus calibration studies on nitisols were conducted in Walmera district in 2012 and 2013 (Table 2.4). The results indicated significant ($P \leq 0.05$) yields of food barley due to application of P, showing a linear trend of increase ((Fana, in press). Grain yield consistently increased as P rate increased with a very slight decrease at the rate of 20 kg ha^{-1} P in 2013. Soil P values analyzed for samples taken 3 weeks after planting have been significantly ($P \leq 0.05$) affected by P fertilizer application (Fana, in press).

Table 2.4 Response of barley grain yield to P application on nitisols, Welmera in 2012 and 2013. *Means followed by the same letter within a column are not significantly different.*

P rate (kg/ha)	Grain yield (kg ha)	
	2012	2013
0	4339.6[c]	1420.8[c]
10	4813.9[b]	1796.7[b]
20	5008.7[b]	1764.8[b]
30	5204.1[b]	2080.6[a]
40	5613.0[a]	2106.6[a]
50	5778.5[a]	2292.2[a]
LSD (0.05)	393.4	252.2
CV (%)	12.6	18.2

Source: Holetta Agricultural Research Center.

Table 2.5 shows the performances of barley in different agro-ecological zones (for different time periods). Based on the observed results, there was yield increase of over 200% with 69/30 kg ha^{-1} N/P application as observed by Getachew and Tekalign (2003). Based on the results in Table 2.5, fertilizer recommendation rates and the corresponding crop responses showed variability across different sites. Similar observations were made by different studies where crop response to input use varied across soil types (e.g. Mulatu and Grando, 2011). This clearly signifies the need for a detailed, site-specific study to develop appropriate and economical recommendations.

Up to 2002, there was a common belief that K is not a constraint for barley production in Ethiopia. However, recent developments under ATA have indicated a yield increase of barley by 14% due to the application of K (Mulugeta Demiss et al., 2015). Trials are also being conducted to evaluate the response of barley for micronutrients in different sites (e.g. Fana, in press).

Nitrogen, phosphorus and FYM rates were evaluated on the vertisols of South Tigray in the period 2013–2014 on grain yield of barley (Assefa, 2015). It was recommended that application of 46/46 N/P_2O_5 kg ha^{-1} with 8 t ha^{-1} gave 18% and 100% yield more than the blanket fertilizer recommendation in the area (46/46 N/P_2O_5 kg ha^{-1}) and the control. Barley grain yield was investigated for a response to bio-slurry compost and chemical fertilizer in the Tigray region from 2001–2005 (Edwards et al., 2007). Application of bio-slurry compost produced the highest yield of 3,535 kg ha^{-1} with an advantage of 67.2% over the control. However, the use of chemical fertilizer produced a barley grain yield of 1,832 kg ha^{-1} with a yield advantage of 36.7% over the control. Another study in 2010 in the same region indicated that the use of compost had a yield increment of 72% over the control. At Waza, Hintalo Wejerat, a 45.5% yield advantage of barley grain yield was obtained using bio-slurry compost over the control, whereas the advantage of using chemical fertilizer over no input was 42%.

Studies are also being conducted to assess the response to malt barley fertilizer (e.g. Amsal et al., 1993; Kemelew Muhe, 2006; Getachew et al., 2014; Yemane et al., 2015; Biruk and Demelash, 2016; Fana, in press). For details please refer the corresponding publications in the workshop proceeding (Fana, in press).

Table 2.5 Summary of recommended fertilizer rates across different regions of Ethiopia.

Location	Period	Recommended rate	Output result	Reference
Highlands of Wollo	2001–2002	50 kg ha^{-1} urea 100 kg ha^{-1} DAP	78% yield increment over the control	Legesse et al. (2006)
Shambu Arjo Gedo	1998–2000	23 kg ha^{-1} N with hand weeding 20/30 kg ha^{-1} N/P 10/30 kg ha^{-1} N/P 10/30 kg ha^{-1} N/P	1677 kg/ha (double over control)	Bako Agricultural Research Center (2000)
Holetta Annokere, Holetta	1987–1988	57/25 kg ha^{-1} N/P	double yield compared to the control	Amsal et al. (1997)
		69 kg ha^{-1} N 30 kg ha^{-1} P	120% yield increment over the control 110% yield increment over the control	Woldeyesus S. (unpublished)
Farta, NW Ethiopia	1996–1997	69/10 kg ha^{-1} N/P	150% over the control	Minale Liben et al. (2001)
Huleteju-Enebssie	1996–1997	46/10 kg ha^{-1} N/P	131% over the control	"
Laie-Gaient	1996–1997	92/20 kg ha^{-1} N/P	98% over the control	Adet ARC (2001)
Enarge-Enawga, Machakel and Debay-Tilatgin	2000-2003	46/20 kg ha^{-1} N/P	Recommended for higher yield	Adet Agricultural Research Center. (2002)
Gozamen and Chillga	2000-2003	69/30 kg ha^{-1} N/P	Recommended for optimum yield	"
Estie	2000-2003	69/10 kg ha^{-1} N/P	Recommended for optimum yield	"
Wogera	2000-2003	69/20 kg ha^{-1} N/P	Recommended for optimum yield	"
Estayish, N Wollo	1996–1999	69/30 kg ha^{-1} N/P	202% over the control	Getachew and Tekalign (2003)
		46/10 kg ha^{-1} N/P	Highest MRR	"
Hosana, SNNP	1998–2000	69/20 kg ha^{-1} N/P, 23/20 kg ha^{-1} N/P	Highest grain yield Recommended N/P rate	Areka Agricultural Research Center (2000)
Kokate, SNNP	1997	41/20 kg ha^{-1} NP	Highest yield obtained	"
Tarmaber, N Showa	1996–1997	41/20 kg ha^{-1} N/P manured 3–5 years 41/20 kg ha^{-1} N/P on non-manured plot	28% over unfertilized plot 82% over unfertilized plot	Sheno Agricultural Research Center (1997)

Source: Mulatu and Grando (2011).

An experiment was conducted over a period of 3 years (2007–2010) on integrated fertility management options at Fereze in Gurage zone (Abay and Tesfaye, 2012). The result showed that the highest barley grain yield of 4,896 kg ha^{-1} was produced by application of 46/40/50 kg ha^{-1} of N/P/K with 20 t ha^{-1} of FYM, giving a yield advantage of 3,146 kg or 62% over the control. Application of 46/40/50 kg ha^{-1} of N/P/K alone produced a 2,150-kg ha^{-1} grain yield advantage over the control. Half of the NPK rate (23/20/25 kg ha^{-1}) alone produced a yield advantage of 1,300 kg ha^{-1} over the control treatment, whereas the use of FYM alone had a yield advantage of 750–920 kg ha^{-1} over the control. Economic analysis also showed that a net return of ETB 1600 and a marginal rate of return of 300% were obtained from the integrated application of 46–40–50 kg ha^{-1} NPK with 20 t ha^{-1} FYM. Application of 46/40 kg ha^{-1} N/P with 20 t ha^{-1} of FYM could also produce a net return of ETB 1,500 with a 252% marginal rate of return.

The effects of organic amendments and nitrogen fertilizer on yield and N use efficiency of barley were investigated on a nitisol of the Central Ethiopian Highlands in 2014 (Agegnehu et al., 2016). The application of organic amendment and N fertilizer significantly improved grain yield, with yield advantages of 60% from compost + biochar + 69 kg N ha^{-1} at Holetta with the highest total N uptake of 138 kg ha^{-1} and 54% from compost + 92 kg N ha^{-1} at Robgebeya with the highest total N uptake of 101 kg ha^{-1}, compared to the yield from the maximum N rate alone.

A study conducted in North Shewa, Ethiopia to identify the best precursor crops for barley production indicated that field pea and faba bean significantly increased grain and straw yields of barley by about 20–117% and 34–102% at different locations, respectively, compared to continuous barley (Figure 1.1). Similarly, Gebre et al. (1989) reported that the yield of wheat after faba bean was higher by 69% than the yield of wheat after wheat. The results of rotation trials elsewhere also indicated higher yields of cereals following food legumes compared to cereals after cereals, or even after a fallow (Buddenhagen, 1990; Blair et al., 2005). It is assumed that N fixation is largely responsible for the yield increment compared to cereal after cereal. Barley after legume, without any N fertilization, yielded as much as continuously cropped barley supplied with 60 kg N ha^{-1} (Papastylianou, 1990).

2.3. Maize response to fertilizer

Maize (*Zea mays L.*) is the most widely cultivated cereal crop in terms of area coverage (16%) and production (26%) with about 6.5 million t of production in Ethiopia (CSA, 2014). It is also the major staple food crop and source of cash in the country (Abera, 2013). Although maize is one of the most productive crops in Ethiopia, it cannot play a significant role in ensuring food security because of various factors (Abera, 2013). The estimated average yields of maize for smallholder farmers in Ethiopia are about 3.2 t ha^{-1} (CSA, 2014), which is much lower than the yield recorded under demonstration plots of 5 to 6 t ha^{-1} (Dagne et al., 2008). Thus, the potential maize productivity in the country has not yet been exploited. To alleviate the soil fertility problems of maize, different research activities have been undertaken using various fertilizer sources in different parts of the country.

The response of both hybrid and open pollinated maize varieties in different periods to chemical fertilizer (NP) in different parts of the country was reviewed and summarized in Kelsa et al. (1993), Tolessa et al. (2002) and Negassa et al. (2012). The application of 75/33 kg N/P ha^{-1} around Bako and Didessa, 46/33 kg N/P ha^{-1} in Jimma area, 92/44 kg N/P ha^{-1} in Hawassa area and 69/30 kg N/P ha^{-1} in the Rift Valley were recommended for maize production (Kelsa et al., 1993). Hybrids and improved composites showed higher response to N and P application than local varieties (Tolessa et al., 2007). Similarly, Tolera et al. (2016) reported that hybrid maize varieties produced higher grain yield compared to open pollinated varieties. Hence, hybrid highland maize varieties (Jibat and Wenchi) were recommended for sustainable maize production in highland areas of Toke Kutaye. Accordingly, the combined application of 90/15 kg N/P ha^{-1} fertilizers had improved maize grain yield (5.36 t ha^{-1}) and yield components recommended for vertisols of around Aykel, Chilga district in North Gondar zone (Habtamu, 2015). Similarly, Zelalem (2013) found that a combined application of NP gave a better grain yield of hybrid maize (BH-140) and improved P content of the soil. Higher grain yield of maize variety (Melkassa I), 3,868 and 5,069 kg ha^{-1} in Babile and Dire Dawa area were obtained with the combined application of 64/20 kg NP ha^{-1} (Hassen et al., 2006). The application of 69–20–75 kg N–P–K ha^{-1} for maize gave significantly higher yields compared to another recommended NP at Areka (Wassie et al., 2009). The minimum (4,687 kg ha^{-1}) and maximum (4,905 kg ha^{-1}) maize yield at Dangla in 2009 cropping season were obtained from control and 100 kg K_2O ha^{-1}, respectively (Tadele et al., 2010). Similarly, at Mota, Tadele et al. (2010) found that the minimum (2,951 kg ha^{-1}) and maximum (3,929 kg ha^{-1}) yield of maize in the 2008 cropping season were recorded from the control and application of 100 kg K_2O ha^{-1}, respectively. The mean grain yield of maize at both locations responded non-significantly to the applied K rates (Tadele et al., 2010).

Recent attempts have been made to provide N and P fertilizer recommendations based on the results of soil test and crop responses. Accordingly, experiments have been conducted since 2010 through 2014 on P calibration for maize on different agroecology and soil types. The critical N levels beyond which application of N fertilizers becomes non-responsive to maize were identified as 9.01% and 0.594% and 55.54 mg kg^{-1} for organic matter and total N and NO3-N, respectively, measured at planting for West Amhara (Yihenew et al., 2003a, 2006). Furthermore, the critical P concentration beyond which applied P fertilizer becomes non-responsive to maize was identified as 11.6 and 14.6 mg kg^{-1} for Olsen and Bray-2 methods, respectively, taking 98% as optimum relative yield goal on nitisols/luvisols for West Amhara (Yihenew et al., 2003b, 2006). Additional studies were also carried out to investigate the response of maize grain yield to the methods and timing of applications (Tolessa et al., 1994; Negassa et al., 2012; Kidist, 2013). Higher grain yield and net benefits (49,433 EB ha^{-1}) was obtained with an application of 130 kg N ha^{-1} with a split application of ½ at sowing and ½ at knee height (Kidist, 2013). A three-way split application (¼ at planting, ½ at knee height, and ¼ at tasseling) gave higher N use efficiency of maize variety (BH-660) in Haramaya district of eastern Ethiopia (Kidist, 2013).

The N use efficiency (grain kg per applied N) of open-pollinated and hybrid maize genotypes at Bako was high (20.8 to 16 kg ha^{-1} for 46 to 92 kg ha^{-1} of N) for the hybrids compared to open-pollinated varieties (OPVs) (15 to 10 kg ha^{-1}) for the same rate of N application (Tolessa et al., 2007). Similarly, higher agronomic efficiency, N-use efficiency, nitrogen physiological efficiency and fertilizer N (recovery)-use efficiency of maize varieties with application of 55 kg N ha^{-1} following faba bean and soybean precursor crops were responsible for increasing maize yields (Tolera, 2016). Likewise, Tolera et al. (2016) found a higher agronomic efficiency of 35 to 46 compared to Horra (OPV), and 5–16 compared to Wenchi (hybrid) from Jibat variety followed by Wenchi and Webii varieties of maize planted with half the recommended N rate. In addition, higher N uptake efficiency and N use efficiency were obtained from Jibat followed by Webii and Wenchi varieties of maize planted with half the recommended N fertilizer applied. Significantly higher N fertilizer (recovery) use efficiency of 80% was obtained from maize varieties planted with half N fertilizer application compared to the recommended rate (Tolera et al., 2016). Thus, hybrid highland maize varieties were more N use efficient compared to open-pollinated varieties. Higher nitrogen use efficiency of maize was obtained at lower rates of NS fertilizer application in and around Aykel, Chilga district, North Gondar zone (Habtamu, 2015). Similarly, improved N use efficiency of maize variety (BH-660) was obtained with 130 kg N ha^{-1} application in Haramaya district of eastern Ethiopia (Kidist, 2013). Higher physiological efficiencies of 79 and 9 kg grain kg N uptake of maize variety (Melkassa I) at Dire Dawa and Babile were obtained with 41 and 64 kg N ha^{-1} application (Hassen et al., 2006). Higher agronomic efficiency and nitrogen use efficiencies of all maize varieties was obtained from maize planted with application half recommended nitrogen fertilizer compared to full recommend. Agronomic efficiency ranged from 18 to 33 in five maize varieties (Tolera, 2016). Thus, BH-661 followed by BH-660 and BH-543, had higher nitrogen uptake efficiency and physiological nitrogen use efficiency and were recommended for wide production in the region. Generally, the results show the significance of planting of maize varieties with optimum N application for sustainable maize production (Tolera, 2017).

The integrated use of NP and FYM gave higher yields than application of either NP or FYM alone for maize production (Negassa et al., 2004a). Similarly, the sole application of FYM at the rates of 4–12 t ha^{-1} is also encouraging for resource poor farmers on relatively fertile soils (Negassa et al., 2004a). Accordingly, the application of FYM every 3 years at a rate of 16 t ha^{-1} supplemented by NP fertilizer annually at a rate of 20–46 Kg N–P_2O_5 ha^{-1} was recommended for sustainable OPV maize production around Bako area (Tolessa, 1999). Furthermore, the integrated use of coffee by-products and N fertilizer increased N uptake and grain yield of maize in Hawassa, southern Ethiopia. Coffee residues and N fertilizer positively influenced soil moisture, soil nitrogen and organic matter, grain and water use efficiency of maize (Tenaw, 2006). The application of 4 t FYM ha^{-1} incorporated with 75/60 kg of N/P ha^{-1} was an economical and profitable combination in boosting hybrid maize (BH-140) yield in West Hararghe zone, eastern Ethiopia (Zelalem, 2014). Furthermore, the integrated use of 5 t ha^{-1} of compost either with 55/10 or 25/11 kg of N/P ha^{-1} was economical for maize production in Bako Tibe district (Negassa et al., 2004b). Similarly, applications of the full recommended doses of NP fertilizers integrated with 5 t per hectare crop residue were advised to improve the fertility of these soils for sustainable maize production in Haramaya area (Heluf et al., 1999). The integration of biogas slurry and NP fertilizer produced significantly higher grain yield of maize and improved soil physico-chemical properties. Biogas slurry at 8 t ha^{-1} with 50% recommended N/P kg ha^{-1} (100/50 kg ha^{-1} of urea/DAP) or 12 t biogas slurry ha^{-1} alone was recommended for maize production (Tolera et al., 2005a, 2005b).

In terms of integrating cropping sequence with NP and FYM, studies show that intercropping of maize with climbing bean with integrated application of 69/10 kg NP ha^{-1} with 4–8 t FYM ha^{-1} gave better grain yields and is recommended for sustainable production of component crops (Abera, 2013). N, P and organic matter content of the soil was improved with integrated use of NP and FYM in intercropping maize climbing beans (Tolera et al., 2010).

Accordingly, maize following Niger seed and haricot bean with recommended N–P fertilizer application is recommended for enhanced maize production in Bako area (Table 2.6). The production of maize following Niger seed precursor crop with 46/5 Kg N-P and 8 t FYM ha^{-1} or recommended fertilizer (110/20 Kg N-P ha^{-1}) is recommended for Bako area (Tolera et al., 2009;Tesfa et al., 2012). The production of maize following sole haricot bean with the recommended fertilizer rate gave higher mean grain yield and is recommended for sustainable production of maize in the region (Tolera, 2012). Similarly, improved grain yield of maize was obtained from maize planted with application of half and full recommended rate of nitrogen fertilizer following soil incorporated soybean and faba bean precursor crop biomass, highlighting the importance of additional nitrogen application in the cropping sequence (Tolera, 2016). Therefore, the use of legume precursor crop significantly reduced the application of N fertilizers for different cereal production.

Table 2.6 Integrated use of precursor crops, N/P fertilizers and FYM on maize grain yield on West Showa ultisol.

Precursor crop	Maize variety	N/P/FYMa	t ha^{-1}	Location	Sources
Maize-haricot bean	BH-543	110/20/0	6.36	Bako	Bako Agricultural Research Center (2007)
Maize-climbing bean	,,	110/20/0	7.80	,,	,, ,,
Haricot bean	,,	110/20/0	6.74	,,	,, ,,
Climbing bean	,,	110/20/0	8.11	,,	,, ,,
Maize	,,	110/20/0	6.72	,,	,, ,,
Mucuna pruriens	BH-660	0/0/0	4.74	,,	Negassa et al. (2007)
Mucuna pruriens	,,	55/10/0	5.91	,,	,, ,, ,,
Mucuna pruriens	,,	37/7/0	5.78	,,	,, ,, ,,
Mucuna pruriens	,,	0/0/4	6.25	,,	,, ,, ,,
Maize	,,	110/20/0	4.41	,,	,, ,, ,,
Mucuna pruriens	BH-660	0/0/ 0	5.11	,,	Tolera et al. (2005a)
Mucuna pruriens	,,	46/5/8	7.53	,,	,, ,, ,,
Maize	,,	110/20/0	8.55	,,	,, ,, ,,
Niger seed	BH-660	110/20/0	7.24	,,	Tolera et al. (2009)
Haricot bean	,,	110/20/0	6.28	,,	,, ,, ,,
Teff	,,	110/20/0	5.71	,,	,, ,, ,,
Maize	,,	110/20/0	4.47	,,	,, ,, ,,
Niger seed	,,	0/0/0	5.85	,,	,, ,, ,,

Precursor crop	Maize variety	N/P/FYMa	t ha-1	Location	Sources
Niger seed	BH-660	46/5/8	8.97	Bako	Tolera et al. (2009)
Soybean	BH-543 and BH-661	55/20/0	6-7	„	Tolera et al. (2005a, 2005b)
Haricot bean, Niger seed and soybean	BH-660	89/15/0 or 12 FYM	9.3	„	Zerihun et al. (2013)
Faba bean	Jibat and Wenchi	55/20	5-7	Toke Kutaye	Tolera (2016)

N/P: kg ha-1; FYM: t ha-1; Negassa et al. (2012).

Green manure legumes such as *Dolichose lablab, Mucuna pruriens, Crotalaria ochralueca* and *Sesbania sesban* enhanced soil fertility and resulted in grain yield increases of 30–40% over plots that received 92 kg N ha-1 from a urea source. Green manure of sole legumes could substitute for more than 70 kg urea N ha-1 at Jimma. Moreover, the application of *Sesbania sesban's* biomass and dry FYM above 5 t ha-1 gave comparable or greater mean maize yield of up to 69 kg N ha-1 from urea fertilizer (Tesfa et al., 2012). Green manure of intercropped legumes could at least offset the cost of 46 kg N ha-1 from urea for smallholder farmers who did not have sufficient land. N fixed by soybean, *S. sesban* and *C. ochralueca* had a 50% yield advantage over a plot of continuous maize without N application and produced a yield comparable to plots of continuous maize with recommended N (Abera, in press). In addition, the mean yield advantage of biomass N from 5 t ha-1 dry biomass of *Sesbania*, soybean and *Crotalaria* was increased by 49% over the control and it rendered comparable yield to plots of continuous maize with recommended N (Tesfa et al., 2009). Similarly, the integrated use of 5 t of Tithonia with 30 kg P ha-1 gave comparable maize yield with the recommended NP fertilizers of 69/20 kg NP ha-1 and could be advised for low cost and sustainable maize production in Areka area (Wassie et al., 2009). A similar study conducted at Melkassa, Central Rift Valley of Ethiopia, to determine the adoption of 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* compared to sole maize and sorghum, respectively.

3. Organic resources use and management

The declining productivity of Ethiopian soils has been associated with loss of soil organic matter (Solomon et al., 2002; Gelaw et al., 2014). The addition of organic amendments such as animal dung, green manures and crop residues could maintain or enhance soil quality, improve the nutrient pool and enhance crop productivity (Bationo et al., 2007). The addition of organic matter also plays a key role in nutrient availability, soil water content and nutrient recycling by adding nutrients to the soil, influencing mineralization-immobilization patterns, serving as an energy source for microbial activities and as precursors to soil organic matter, reducing the P absorption of the soil, and reducing leaching of nutrients and making them available to crops over a longer period of time (Amede et al., 2002).

Smallholder farmers in most developing countries commonly use organic fertilizers as their main source of nutrients (IAEA, 2001). However, a recent survey in the Upper Central Highlands of Ethiopia showed that more than 80% of the manure is used as a cooking fuel (Amede et al., 2011). Similarly, Bojö and Cassells (1995) reported that dung cake accounts for about 50% of total household energy source especially in the highland cereal zones of the north and central Ethiopian highlands. The use of dung as a fuel instead of as a fertilizer has reduced Ethiopia's agricultural GDP by 7% (Zenebe, 2007). There is also strong competition for crop residues for use as animal feed and cooking fuel and little is remaining for the soil. Although legumes are known to add nitrogen and improve soil fertility, the frequency of legumes in the cropping sequence in the Ethiopian highlands is less than 10% (Amede and Kirkby, 2004), which implies that the probability of growing legume on the same land is only usually once every 10 years. Thus with the limited use of mineral and organic fertilizers in Ethiopia, we need to explore efficient utilization of external inputs (Gruhn et al., 2000). The combined addition of organic and mineral fertilizers, which forms the basis of integrated soil fertility management (ISFM), can improve crop yields and soil fertility (Vanlauwe et al., 2001; Chivenge et al., 2011).

Organic resources are the major nutrient sources for Ethiopian agriculture, but the quality of the resources available is usually low, affecting their effectiveness to supply nutrients (Yirga and Hassan, 2013). The nutrient content of organic materials, ranging from crop residues, to manure, to agro-industrial wastes widely vary (Palm et al., 2001; Vanlauwe et al., 2005). Table 2.7 compares the nutrient content of a variety of organic materials with the nutrients required to produce a modest 2 t ha^{-1} crop of maize grain. Although only a proportion of the nutrients in the organic source is available for crop uptake in the year of application, the information could be used for designing a soil fertility management strategy that would consider organic resources as part of the nutrient budget in each cropping system and yield goal. These estimates could be adjusted, as crop recovery of N supplied by high-quality organic resources (e.g. green manures) is rarely more than 20% (Giller and Cadisch, 1995), while that recovered from lower quality cereal stovers is even lower.

Some organic materials, such as poultry manure, contain sufficient nutrients, with about 2 t of manure being sufficient to fertilize a 2 t maize crop per hectare, while other organic resources such as crop residues may require up to 10 t to match the requirements of a 2 t maize crop. Cattle manure also varies in its quality and fertilizer value tremendously. Extremes are found in the manure obtained from commercial dairy farms compared with that from smallholder farmers' fields (Mugwira and Mukurumbira, 1984; Mugwira and Murwira, 1997; Murwira et al., 2002). The latter, which are predominantly produced on smallholder farms in SSA (Probert et al., 1995) are low-quality manures mainly because the livestock feed is of poor quality. Many leguminous trees and cover crops contain sufficient N in 2 to 3 t of leafy material (Giller et al., 1997). As a rule, many organic materials, when applied in modest amounts of 5 t dry matter ha^{-1}, can contain sufficient N to match that of a 2 t crop of maize, but they cannot meet P requirements and must be supplemented by inorganic P (Palm, 1997).

Table 2.7 Average nutrient contents on a dry matter basis of selected plant materials and manures.

Material+	N (Kg t^{-1})	P (Kg t^{-1})	K (Kg t^{-1})
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 manures			
Cattle§			
High quality	23	11	6
Low quality	7	1	8
Chicken	48	18	18
Farmyard chicken	24	7	14
Leguminous trees (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
Nonleguminous trees and shrubs (leaves)			
Chromolaena ordorata	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
Nutrients required by 2 t maize grain + 3 t stover	80	18	60

The TSBF database is the source of all data unless otherwise noted.
Source: Palm et al. (1997); Sommers and Suttona (1980); Mugwira and Mukurumbira (1984).

Stubble is one of the major sources of nutrients in the Ethiopian farming systems, although its quantity and quality is low. The quality is commonly a function of biomass production and translocation, and is dictated by the genetic-environment interaction (Nordblom, 1988). The removal of crop residues without sufficient replacement is a major reason for nutrient mining, causing nutrient deficiency and imbalance and low productivity of crops, particularly in erosion-prone regions.

There are several studies in Ethiopia that assessed the effect of crop residue management on soil properties, crop growth and yield under field conditions. The information indicates that the annual production of crop residues in Ethiopia has significantly increased, from 6.3 million t in 1980 to about 19 million t, mainly due to the expansion of cultivated land (CSA, 2008). There is strong competition for biomass in Ethiopia, with about 63, 20, 10 and 7% of cereal straws being used for feed, fuel, construction and bedding purposes, respectively. According to Mesfine et al. (2005), the application of 3 t ha^{-1} of teff straw increased grain yield of sorghum by 70% in conventional tillage and by 46% in zero tillage treatments (Table 2.8), probably through reducing unproductive water losses. In their experiment, mean soil water content throughout the season was 16% more with 3 t ha^{-1} application of straw compared to plots without straw application. They concluded that surface cover with crop residues was necessary to achieve acceptable yield along with minimum tillage, particularly in low moisture stress areas. Reduced tillage and maintenance of surface cover with crop residues commonly improved soil water availability and increased grain and straw yields in semiarid areas. Similarly, Bationo et al. (1993) noted that incorporating crop residues had a positive effect, particularly when using inorganic fertilizers in improving rainwater use efficiency and soil tilth, and in minimizing the rate of soil erosion. Bationo et al. (1993) also reported a large positive and additive effect of crop residue and mineral fertilizer application on millet yield in the Sahel because of higher organic matter accumulation.

Table 2.8 Effect of teff crop residue application on sorghum grain, stover and biomass yields, harvest index and seasonal water use at Melkassa, Ethiopia.

Mulch rate (t ha^{-1})	Grain yield kg ha^{-1})	Biomass yield (kg ha^{-1})	Seasonal water use (mm)	WUE for grain yield (kg $ha^{-1}mm^{-1}$)
0	2916	9614	595	4.85
3	3591	14322	618	5.73
6	4138	14710	614	6.55

Source: Mesfine et al. (2005).

The addition of organic fertilizers, although mainly targeted at macronutrients such as N and P, also contributes to micronutrient additions. These micronutrients are generally not found in mineral fertilizers and thus the addition of organic fertilizers have the added benefit of micronutrients. After 6 years of treatment, Bedada et al. (2016) observed greater micronutrient concentrations in soils treated with compost while the combined addition of half the rate of compost and that of fertilizer tended to lower the micronutrient concentrations (Table 2.9).

In the same study, negative nutrient balances were observed with the control and the fertilizer treatments. However, although most farmers were convinced of the benefits of using farm-based organic fertilizers, they were challenged by questions such as which organic residue were good for soil fertility, how to identify the quality of the organic resource, how much to apply, when to apply it, and what ratio of organic to mineral fertilizer should be used. This calls for development of decision-support guides to support farmers' decision on resource allocation and management.

Table 2.9 Treatment effects of compost, fertilizer, compost plus fertilizer on Mehlich-3 extractable micronutrient contents in the 0–10 cm depth after 6 years of treatment application at Beseku, Ethiopia. *Similar superscripted letters in front of the values indicate non-significant difference between means.*

Treatment	Micronutrient concentration (mg kg^{-1} dry soil)				
	B	Mn	Cu	Fe	Zn
Control	0.53 b	241 b	2.31 b	1.49 ab	15.4 b
Compost	0.83 a	251 a	2.41 ab	143 b	18.1 a
Fertilizer	0.49 b	230 b	2.32 b	155 a	15.6 b
*Compost + fertilizer	0.67 ab	257 a	2.48 a	143 b	18.1 a

Means in the same column followed by different lower case letters are different at p<0.05.
*Compost + fertilizer was added at half the rate of either compared with when added alone. Means followed by the same letter within a column are not significantly different.
Source: Bedada et al. (2016).

Teklu and Hailemariam (2009) evaluated the performance of wheat and teff to the combined application of 0, 3, and 6 t ha^{-1} manure with three levels of nitrogen fertilizer from urea, 0, 30 and 60 kg N ha^{-1} on a vertisol at Debre Zeit in Ethiopia. They observed that wheat yield increased with increasing N fertilizer rates but the greatest yield of 2,026 kg ha^{-1} was observed when 6 t manure ha^{-1} was combined with 30 kg N ha^{-1}. Similarly, the greatest yield for teff was obtained when 6 t manure ha^{-1} was combined with 30 kg N ha^{-1} but was not different from 3 t manure ha^{-1} combined with 30 kg N ha^{-1} urea, suggesting that lower rates may be sufficient. These treatments also had high productivity indices over 6 years, suggesting that they may offer a sustainable option for improving and maintaining soil fertility. However, in the same study, there were no residual effects of the combined treatments on chickpeas. In a review, Haile et al. (2009) showed that ISFM resulted in greater yields than either resource applied alone. The application of *Erythrina* biomass, an indigenous legume with NPK fertilizers improved wheat yield compared to where fertilizer or biomass was applied alone in Kokate. Similarly, the application of lablab increased wheat yield compared to sole applied fertilizer in Kokate. In Chencha, Irish potato yield was greater with the combined application of FYM and NPK but half the fertilizer (55 kg N ha^{-1}, 20 kg P ha^{-1} and 50 kg K ha^{-1}) had similar yields to double the fertilizer amount. This suggests that with the combined application of organic and mineral nutrient sources, mineral nutrient additions can be reduced without compromising the yield.

4. N_2-fixing legumes and crop yield

Integration of multipurpose, N-fixing legumes into farming systems commonly improves soil fertility and agricultural productivity through symbiotic associations between leguminous crops and *Rhizobium*. However, the contribution of N fixation to soil fertility varies with the types of legumes grown, the characteristics of the soils, and the availability of key micronutrients in the soil to facilitate fixation, and the frequency of growing legumes in the cropping system. Although perennial legume are known to fix more N than annual legumes (Amede et al., 2002), the most prominent ones contributing to N enrichment of soils in Ethiopia are annual legumes, including faba beans and peas in the highlands and chickpeas in the lowlands. Some food legumes (e.g. *Phaseolus* beans) are known to fix N below their own nitrogen demand and may not contribute much to replenish the soil with additional nutrients. Perennial legumes, including those referred as legume cover crops, could produce up to 10 t ha^{-1} of dry matter and fix up to 120 kg N ha^{-1} per season (Amede et al., 2002). Studies conducted to evaluate effective rhizobial isolates and strains for different agroecologies in Ethiopia indicated that BNF could play an important role in increasing food production through increasing the yield of crops and forages. Crop yield increases of 51–158% were reported in nitisols at Holleta due to the combined application of 20 kg ha^{-1} P with strain over non-inoculated ones (Table 2.10; Hailemariam and Tsige, 2003).

Table 2.10 Grain yield and plant height of faba bean as influenced by Rhizobium inoculation at Holetta.

Treatment	Plant height (cm)	Grain yield (kg ha^{-1})
N_0P_0	42.5	680
N_0+20 kg P/ha	51.0	1,540
Strain#18+20 kg P/ha	88.6	3,980
Strain#64+20 kg P/ha	56.5	2,320
Strain#51+20 kg P/ha	57.5	2,740
23 kg N/ha+20 kg P/ha	61.7	2,050
20 kg N/ha+20 kg P/ha	66.9	2,240
$LSD_{0.05}$	10.8	2,980

Source: Hailemariam and Tsige (2003).

In an experiment conducted to determine N_2 fixation in three sites in 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 substantial mean soil N balance in the range 12–58 kg ha^{-1} N 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 a deficit (–9 to –44 kg ha^{-1} N), indicating nutrient mining and hence the need for a higher rate of fertilizer N application in a continuous wheat production system (Amanuel et al., 2000).

Apart from food legumes, other N-fixing forage legumes and cover crops that could be integrated into the Ethiopian highlands were: *Tephrosia, Mucuna, Crotalaria, Canavalia,* and vetch (Amede and Kirkby, 2004). A study conducted in western Ethiopia showed that the integrated use of improved fallow using *Mucuna* with a low dose of NP fertilizers or FYM increased maize grain yield significantly (Negassa et al., 2007). The 3-year average maize grain yield showed that *Mucuna* fallow produced double the maize yield compared to the control treatment (Table 1.8). Supplementing the improved fallow with low doses of NP fertilizers or FYM further increased grain yield, in the range 5.91–6.06 t ha^{-1}. The lowest grain yield was recorded with the control treatment, followed by recommended NP fertilizers. Thus, the integrated use of improved fallow using *Mucuna* with low dose of NP fertilizers or FYM significantly increased maize grain yield (Negassa et al., 2007). Vanlauwe et al. (2001) also reported that in addition to the direct interactions between mineral fertilizer and organic matter, improved fallow improved soil fertility by restocking nutrients lost through leaching and by modifying the pH of the rhizosphere and making unavailable nutrients available.

N fixation can be improved by improving the agronomic and nutritional management of the host plant. For instance, P nutrition increased symbiotic N fixation in legumes by stimulating host plant growth (Robson et al., 1981). Similarly, Moawad et al. (1985) reported that the application of micronutrients such as Mo, Mn, Fe, and Zn would stimulate symbiotic N fixation. The contribution of legumes could be beyond N fixation. Some legumes (e.g. chickpea) could modify the soil climate and increase the availability of major nutrient (e.g. K and P), particularly in acidic soils where P fixation is apparent.

5. Nutrient flows and balance

Soil nutrient mining, coupled with low fertilizer use, is the main cause of soil fertility decline in Ethiopia and nutrient balances in the Ethiopian farming systems are generally negative as a result (Haileslassie et al., 2005; Abegaz et al., 2007; Kraaijvanger and Veldkamp, 2015). A study in the Central Highlands of Ethiopia shows that nutrient balances were more negative in teff cropping systems (–28 kg N ha^{-1}) than in enset (–6 kg N ha^{-1}; Haileslassie et al., 2006). The differential application of organic and mineral fertilizers on a farm over many years, aggravated by erosion, commonly creates a clear soil fertility gradient from the homestead to the outfield (Tittonell et al., 2005;

Vanlauwe et al., 2007; Tscharntke et al., 2012). In southern Ethiopian farming systems, where perennial crops are grown around the homesteads, soil nutrient status commonly decreases from the homestead to the outfields, regardless of resource endowment categories (Amede and Taboge, 2007). A detailed nutrient flow analysis in southern Ethiopia revealed that nutrient distribution varied among landscapes, households, farms and farm subunits (Eyasu, 1998). In these systems, a high concentration of nutrients in the homestead is created because nutrients move from the house to the home garden in the form of household refuse, mineral fertilizers, animal manures, etc. The nutrients move from the distant fields to the homestead fields in the form of grain crop residues for feed, mulch, fuelwood and other uses. In general, the home garden fields are characterized by a positive nutrient balance while the outfields have a negative nutrient balance (Tittonell et al., 2005; Amede, 2006; Vanlauwe et al., 2006). Such a soil fertility gradient has been partly created by preferential management for food security crops (e.g. enset) and market crops (e.g. coffee). This is particularly apparent in women-led households and elderly families where shortage of labor affects the transport of manure and household waste to distant fields. A shortage of organic waste and manure also limits its application to home garden crops as the outfields are commonly exposed to heavy erosion losses and theft of high-value crops (Amede and Taboge, 2007).

Erosion causes nutrient imbalances and losses under cereals and other annuals at a country scale. Of the total nutrients removed from cereal cropping, about 70% of N, 80% of P and 63% of K were removed by erosion (Haileslassie et al., 2005). A countrywide analysis of nutrient balance indicated a depletion rate of 122 kg N ha^{-1} yr^{-1}, 13 kg P ha^{-1} yr^{-1} and 82 kg K ha^{-1} yr^{-1} (Haileslassie et al., 2005).

6. Conclusions and recommendations

The review highlighted that the average fertilizer application rate in Ethiopia in general is lower than the recommended rate, despite significant increase in fertilizer use. This is due to various reasons including: low fertilizer/nutrient use efficiency; high price of fertilizer; farmers' constrained knowledge on how to use fertilizer (improve use efficiency); acid soils in the highly-weathered soils; water logging in vertisols; nutrient imbalance in alkaline and saline soils; and old or incomplete fertilizer recommendation for varieties and some soils. We need to conduct detailed study on the best combinations of inputs that can boost crop yield in different farming systems and soil types. Many of the fertilizer recommendations have not been updated or cover mainly N and P although there are recent initiatives by EthioSIS to include micronutrients in blend formulas. Research is thus needed to further establish crop response patterns and underlying characteristics, and to define the extent of K, S and micronutrient elements limitations to crop production. The integrated use of organic and inorganic nutrient management is critical to increasing crop productivity; crucial information on the nutrient content and quality of organic inputs is lacking. The available organic resources used are usually low quality, and large quantities must be applied to meet crop nutrient demands. Hence, efforts should be made to find high quality and alternative organic materials. There are no prescriptive guidelines that relate the quality of the organic material to its fertilizer equivalency and its effect on the longer term composition of soil organic matter and crop yields. The findings of the reviewed research outputs reveal that there is potential for increasing crop productivity through improved and available soil fertility management practices. Implementation of these options in their respective agroecologies and soil types can contribute considerably to filling the yield gap. However, comprehensive information on reviewed research outputs are lacking and accessing them for various uses is difficult or impossible. Most of the results are scattered in different sources or are not published for wider public use, and it was not possible to include all of the results in this review. Therefore, mechanisms to develop a national data and agricultural information network must be developed. In addition, the studies conducted to date do not represent the diverse farming systems and soil types of the country, requiring us to continue conducting systematic research in a coordinated manner. As there are no standardized protocols for trial set up, management and data analysis we end up with unstandardized approaches and results that are not comparable.

The recent developments under the ATA which includes soil test-based fertilizer recommendations and fertilizer blending is an interesting initiative in developing site- and context-specific fertilizer recommendations. However, there is a need to bring all stakeholders together to thoroughly discuss the approaches and reach an agreement on a common protocol. There is also a need to establish demonstration trials to test the applicability of the recommendations and fine-tune the maps, approaches and/or recommendation types and rates. In addition, soil conservation based soil fertility management for crop production is needed for a sustainable land-use system in the country.

We have a unique opportunity to capitalize on the existing conducive policies and strategies on agricultural development and the government's interest in agricultural research in Ethiopia, and promote agricultural research. The presence of various research organizations and linkages can promote the necessary skills and experience needed to conduct advanced research to contribute to the country's agricultural development programs. With such capacity and capability, development organizations and donors will be willing to provide the necessary financial support.

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