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A review of soil fertility management and crop response to fertilizer application in Ethiopia

Towards development of site- and context-specific fertilizer recommendation

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Towards development of site- and context-specific fertilizer recommendation

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Summary

Lulseged Tamene and Tilahun Amede

More than 80% of the Ethiopian population is dependent on agriculture, which contributes about 50% of the country's gross domestic product (GDP) and more than 80% of its export earnings. Although the agricultural sector is the engine of economic growth and the country has designed an "Agricultural-led Industrialization", the agricultural sector is still characterized by severe soil erosion, high levels of nutrient mining, low use of external inputs, low productivity and limited capacity to respond to environmental shocks. Thus, the country is grappling with a daunting challenge: produce more food for a fast-growing population on low fertility soils on land owned by poor smallholder farmers who are unlikely to afford adequate input use. To address these challenges, several efforts are being made since the 1960s to assess the potential effects of various sources of organic and mineral fertilizers on crop yield and soil fertility status of the differing farming systems in the country.

The effectiveness of matching fertilizer applications to soil fertility problems depends on our ability to identify production constraints, target specific niches and increase economic returns for fertilizer investments. Although most smallholder farmers appreciate the benefit of fertilizers, they rarely apply them at recommended rates and at the appropriate time because of unreliable returns, high cost, lack of supportive policy to access, and limited knowledge about their efficient use. The observed limited responses of crops to fertilizer inputs and investments could also be largely explained by the blanket application of nutrients, without targeting crop types, landscape position and drought regimes. When farmers are advised to use blanket application, irrespective of their soils and landscape position, the return will be limited, prompting smallholder farmers not to adopt this practice.

Over time, progress has been made in developing recommendation for different soil types. And recently, there have been various initiatives to address the challenges of soil fertility decline and enhanced fertilizer use. The Ministry of Agriculture (MoA) and the Agricultural Transformation Agency (ATA) developed the *Soil Health and Fertility Roadmap* in 2011 and 2012 to address key soil fertility bottlenecks and transform the agriculture sector, by incorporating soil health, increasing yields and ultimately doubling smallholder farmers' incomes through a soil test-based fertilizer recommendation through the Ethiopian Soil Information System (EthioSIS) program.[1]

Various national and international research centers and researchers at higher learning institutions have also been engaged in testing crop response to fertilizer application in a quest to develop site- and context-specific fertilizer recommendations. However, preliminary reports show that results of the research

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1   Details are available at: www.ata.gov.et/highlighted-deliverables/ethiopian-soil-information-system-ethiosis/

studies are difficult to compare due to inconsistency in approaches used for sampling and analysis. In most cases, crop responses to some of the recommended combinations and rates were limited and beyond the farmers' investment capacity. The aim of this project was to review and document existing information on the response of crops to organic and inorganic fertilizer applications in Ethiopia and ultimately facilitate the design of a fertilizer recommendation tool. The study aimed to provide evidence on how changes in soil fertility status across cropping systems, land uses, landscape positions and rainfall gradients were responding to applications of various types and combinations of organic and inorganic fertilizers and to develop guidelines for innovative and targeted fertilizer recommendations for these rapidly transitioning landscapes. In collaboration with local strategic partners, the proposed work mainly focused on reviewing and collating available information on crop response to fertilizer application across the country and developed database to facilitate data sharing and further analysis. The literature review included online search, gray material from libraries, personal communication with individual authors and visiting institutions (e.g. regional research centers). When possible and available, legacy data were also extracted from research documents. As there was no centralized database available to access and conduct further analysis, the database created in this project will facilitate data sharing and enable monitoring changes over time. Using the collated data sets, meta-analysis was conducted to investigate the response of crops to fertilizers under different environmental setups. Such information can give an insight into the spatial variability of responses for various crop types, farming systems and agro-ecological zones. With crucial information available through this extensive review, it will be possible to identify gaps and opportunities and provide robust evidence for planning and targeting. In addition, research documents related to 'problematic' acid soil management and fertilizer use in Ethiopia were reviewed. The highlights of the research work conducted in the last half a century could be potentially summarized as follows:

1. The productivity of major crops has increased steadily over the last two decades. Maize yield for example has increased from about 1.7 t ha^{-1} in 1993 to the current 3.4 t ha^{-1}, although most of the increase has occurred within the last decade.

The biggest increase in yield for the other crops such as wheat, barley and sorghum has also occurred during this last decade and coincides with Ethiopia's investment in agriculture in 1995–2014 that surpasses CAADP's 10% of total expenditure target.

2. The yield increase is strongly correlated with increased use of mineral fertilizers, particularly Nitrogen and phosphorus. Traditionally, Diammonium phosphate and urea (supplying nitrogen and phosphorus) were the major fertilizers used by farmers in Ethiopia until few years back, whereby other nutrients, particularly K become limiting to produce high yielding cereals and root crops.

3. A high degree of variability exists in crop response to nutrients and amendments in major cereal growing areas in Ethiopia. This is mainly associated with variability in landscape positions, agroecologies, soil characteristics and management practices.

4. Wheat grain yield increased by 80 to 300% on vertisols and by 45 to 15% on nitosols in response to the application of higher rates of Nitrogen fertilizers. Similarly a high yield benefit was obtained when wheat was rotated with faba bean as a precursor crop, with yield increment ranging from 0.035 to 1.25 tonnes per ha.

5. In major barley growing region, the recommended fertilizer rate for barley 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. In acidic soils, up to triple yield increase was recorded by application of 3 t ha^{-1} of lime compared to no lime.

6. Maize response to fertilizer application has been consistently high regardless of locations and season. Higher grain yield and net benefits was obtained with an application of 130 kg N ha^{-1} with a split application of 50% at sowing and 50% at knee height. The N use efficiency of open-pollinated varieties was significantly lower than hybrid maize genotypes. The application of 4 t FYM ha^{-1} or more along with half doses of N and P gave reasonably high yield across locations.

7. Incorporating organic residues at a rate of about 5 t ha^{-1}, particularly by integrating predecessor green manures such as *Dolichose lablab*, *Mucuna pruriens, Crotalaria ochralueca* and *Sesbania sesban*, it is possible to enhance soil fertility, increase grain yield by at least 30–40% and offset the cost of 46 kg N ha^{-1} from urea for smallholder farmers. However, 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.

8. Despite the ongoing efforts to improve fertilizer recommendation and use through developing soil fertility maps (Ethiosis), including for micronutrients, the fertilizer recommendations have not been adequately updated or cover mainly N and P. Further 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 in various farming systems, landscape positions and soil types.

9. Although inputs organic and mineral fertilizers are the major factors affecting crop productivity in the country, integrated soil fertility management (ISFM) is becoming an important strategy to adapt. However, its implementation demands the deliberate integration of various soil fertility management interventions and the introduction of incentives for farmers to adopt and implement these strategies.

10. This paper displays a soil fertility management database whereby user interfaces were established to make easier communication between the database and users either for entering new records or retrieving information based on queries set up during the system requirement analysis phase. The developed system allows the user to enter new trial data into the database and explore and examine the response of fertilizers to different crops under different environmental setups.

11. The outcome of this synthesis was also presented in a national workshop and validated by the peers of about 70 participants from national and international research systems. The key papers extracted from the review have been processed for a special issue publication. Moreover, context-specific decision guidelines would be derived from examining meta-analysis of existing crop responses to fertilizer research data.

12. Capacity development (data collection, management and analysis) and standardized data collection (experiments, trials) set-up and data sharing (protocols, mechanisms) were some of the issues discussed and identified as gaps to be filled as soon as possible.

Section 1

Understanding crop response to fertilizer application in Ethiopia: a meta-data analysis

Job Kihara (CIAT), Degefie Tibebe (EIAR), Biyensa Gurmessa[2] and Lulseged Tamene (CIAT)

1.   Introduction

Food and nutritional requirements for the increasing human population in SSA call for sustainable intensification in the current agricultural land. Research has identified intensification options in agricultural production including integrated options such as combined use of organic and inorganic inputs, micro dosing of fertilizers, legume-cereal integration through rotations and intercropping, conservation agriculture and agroforestry options, among others (Vanlauwe et al., 2015). The use of external inputs is a nutrient management option that has attracted the most studies in SSA. Several decades of research show that deficiencies of macronutrients such as N, P, and K are major limitations to crop production (Ayalew, 2011; Aleminew and Legas, 2015; Argaw and Tsigie, 2015), and recently the limitations of secondary nutrients and micronutrient deficiencies are gaining traction (Habtegebrial and Singh, 2009; Habtegebrial, 2013).

Variable responses to fertilizer application are reported across most geographies and countries in SSA. Based on a large and consistent crop response to fertilizer

data covering five countries in SSA, four categories of response have been identified, ranging from low response to any nutrient combination to high response to N (Kihara et al., 2016). While some of the responses can be explained by management factors (e.g. timeliness of farm operations or type of fertilizer), others are due to biophysical attributes (e.g. variability in soils and climate). The resulting utilization efficiencies and profitability/benefits of fertilizer use is variable. The increasing benefits of fertilizer application requires the development of plausible fertilizer recommendation domains targeted at specific systems, landscapes and farm typologies, and management practices (Bronson et al., 2003; Zingore et al., 2007; Chikowo et al., 2014). In the complex landscapes of Ethiopia, the position of fields within soil catena will probably influence the observed responses to fertilizer application as observed in other places (Terra et al., 2006; Thelemann et al., 2010). Further, the type of cropping system influences the soil nutrient status; the availability of nutrients to succeeding crops require context-specific targeting of fertilizer application using conditions and systems that optimize fertilizer use efficiency (Kihara and Njoroge, 2013).

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2   Biyensa contributed to the project while he was CIAT staff.

The realization of site-specific management recommendations is elusive in Ethiopia as it is in other parts of SSA (Haileslassie et al., 2007). In Ethiopia, agriculture is still characterized by low productivity, a high level of nutrient mining, low use of external inputs, traditional farm management practices and limited capacity to respond to environmental shocks (Assefa et al., 2013; Amante et al., 2014; Agegnehu et al., 2016). As a first step, context-specific decision guidelines can be derived from examining meta-analysis of existing crop responses to fertilizer research data (through peer-reviewed publications and gray literature in universities and research institutes). With such guidelines, it is possible to target fertilizer applications to specific agroecologies and soil fertility problems and to increase economic returns for fertilizer investments. We hypothesize that the crop response to fertilizer is influenced by landscape positions and cropping systems (e.g. the previous crop). The objective of this study is to assemble a comprehensive database and generate a country-level distributions of crop response to fertilizers and generate guidelines for fertilizer management that result in increased nutrient use efficiency based on meta-analysis of research data. This meta-analysis of existing information over the last three decades on crop response to both application and management of fertilizers and soil protection and rehabilitation approaches across soil types, agroecologies and cropping systems will provide a baseline for development of site-specific fertilizer recommendations. In addition, it will assess the economic and yield benefits of fertilizer use on farmer fields and identify the factors that contribute to successes and failures and corresponding challenges and opportunities for fertilizer use and soil conservation. The analysis will also provide information that will help to identify entry points for best-bet fertilizer types and combinations.

2. Materials and methods

2.1. Design template and collate crop response data

A meta-analysis is essential to understand fertilizer responses as sustainable intensification depends on the sensible use of external nutrient sources (Vanlauwe et al., 2011) as most soils in Africa are becoming nutrient depleted. To conduct a meta-analysis, we needed to gather enough data sets to cover the diverse agro-ecological zones and farming systems of the country. As a meta-analysis requires that the population of studies of interest be explicitly defined (Sileshi et al., 2009), we defined selection criteria for inclusion of publications. The publications included in the meta-analysis were obtained from: (i) an online keyword search e.g. at Google Scholar; (ii) a snowballing techniques where references in relevant publications were used to obtain other publications; (iii) visits to research centers in Ethiopia; and (iv) a library search for relevant hard copy data that was not available or accessible online.

A template was developed to record data that satisfied the established criteria. Once the criteria were sent and a template developed, a large number of data points were acquired from the literature review of publications related to crop responses to nutrients. Where possible, responses to different fertilizers such as N, P, K and/or any other secondary or micronutrients such as S or Zn were collated. An attempt was made to use experimental data collected over several sites and seasons in Ethiopia to determine how crop response to both macronutrients and micronutrients was affected by management and inherent soil fertility, as defined by control yields. This was similar to a study by Kihara and Njoroge (2013) who used the similar approach to determine the crop response to P in western Kenya. Data on soil organic carbon (SOC), pH and available P was also captured. SOC is an indicator of fertility levels in a soil; pH level indicates the nutrient availability within a soil while P is a nutrient that limits plant growth due to its susceptibility to leaching and fixation. Also, P agronomic efficiency (PAE) which informs how much yield is increased for each unit of added P, is expected to drop when plant-available soil P is high (Kihara and Njoroge, 2013). Models for PAE against plant-available soil P are necessary to decide on levels where a response to fertilizer P application will be low.

Once the key data was collected, we conducted a thorough check and screening to maintain only those studies that satisfied the criteria. For a study to have met the selection criteria, it must: (i) have originated from Ethiopia, i.e. trials must have been set up within Ethiopia; (ii) have a control(s), all treated the same way apart from the nutrient being tested; (iii) have been published in a journal, a chapter in proceedings, FAO report, a thesis (master's or PhD); (iv) be randomized and well designed with replications; (v) contain data that was published twice, in which case only one of

the data was used; (vi) not have data with different names but by the same author(s). A publication was excluded if: (i) it had no control; this would have made determination of fertilizer response impossible; (ii) response data was suspected to be false; (iii) data published was entered wrongly; (iv) the reported yield was not consistent with the research design; (v) data was reported poorly. In all cases, for the publication to be considered, it should state the location (either a definite name of site or preferably the latitude/longitude).

2.2. Data retrieval and analysis

The summary of data shows that in total, 2,180 data points were captured. Out of these, 68.2%, 26.1%, 1.7%, 3.3%, and 0.6% were in response to: N, P, K, S, and Zn, respectively. We aimed to include any crop used in the determination of fertilizer responses within Ethiopia. The data points captured were on these test crops: wheat (44.8%), maize (16.1%), teff (10.2%), rice (9.3%), barley (7%), sorghum (3.4%), faba bean (2.5%), common bean (2.1%), chickpea (1.6%), rapeseed (1.1%), groundnut (0.7%), gomenzer/highland kale (0.6%), haricot bean (0.3%), Irish potato (0.3%), and field pea (0.1%). Most of these crops are important in Ethiopia's food basket and food security. For example, sorghum is an important crop in the semiarid areas of northeastern Ethiopia (Bayu et al., 2002; Bayu et al., 2006) but its productivity is low and variable due in part to the low fertility status of soils (Bayu et al., 2006) whereas teff (*Eragrostis tef*) is one of the leading cereals crops grown in Ethiopia. Maize is one of the major cereal crops in Ethiopia and is a staple food in many parts of the country (Desta, 2015). Common bean (*Phaseolus vulgaris L.*) is an important food crop in southern Ethiopia. For the purposes of our analysis, only crops with more than 100 data points were used.

Data included in the analysis originated from both on-farm and on-station trials, where the majority (98.7%) of the trials were under researcher management, and a minority (1.3%) of the trials were under farmer management. The varieties of crops captured included both local and improved varieties. Out of the data points captured, 69.7% were for improved varieties, 15.2% were for local varieties while in 15% of the data points, the crop variety was not indicated. Variety type is important as response to fertilizer depended on the variety of crop planted. For example, improved varieties were reported to be more responsive to fertilizer application than local varieties (Tamene et al., 2015). According to Vanlauwe et al. (2011), compared with local varieties, the use of hybrid maize varieties significantly increased N-AE values (17 and 26 kg [kg N]$^{-1}$, respectively).

The study captured most of the soils of Ethiopia: alfisols (8.3%), alisols (0.2%), andosols (2.2%), arenosols (1.2%), cambisols (1.6%), fluvisol (2.7%), lithosols (0.8%), luvisols (1.9%), nitosols (17.1%), phaeozems (2.2%), and vertisols (2.8%), whereas in 33.4% of cases, soil type was not indicated.

The data obtained is a good representation of the Ethiopian highlands (Figure 1.1) but accessibility was an issue in recording of some of the data. The lowlands areas also had limited crop response trials/experiments.
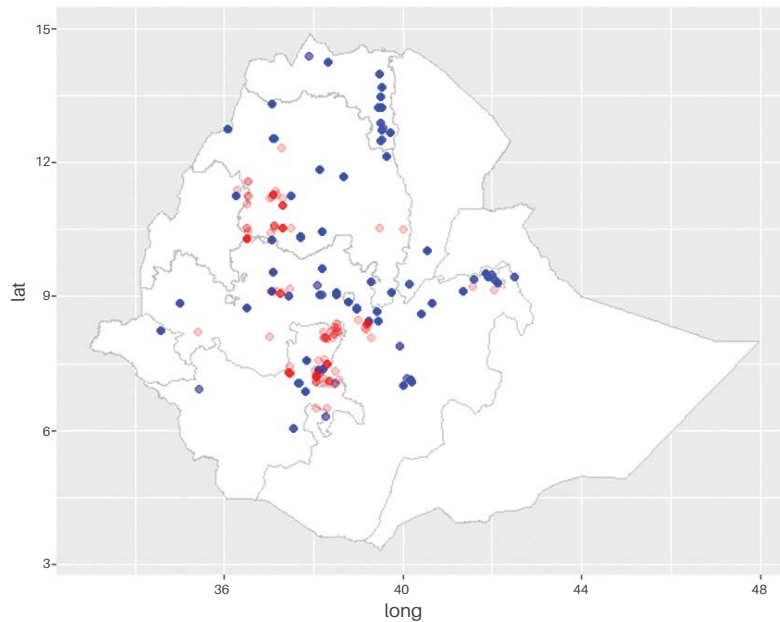
Figure 1.1 Locations with experimental data on nutrient responses to selected crops in Ethiopia (blue = non-FAO sites, red = FAO sites). Note that several points are overlaid on each other due to the scale of representation.

Before data analysis, all the trail input and response values were standardized. A random effects model was used in the meta-analysis using a restricted maximum likelihood estimator. A test of heterogeneity was also undertaken. Forest plots showing the mean effect size and confidence intervals were generated in R. Assessment of publication bias was done using funnel plots, eggers regression test (regtest) and rank correlation test (ranktest). None of the tests showed evidence of publication bias.

3. Results

3.1. Major crops response to fertilizers

The productivity of major crops has increased steadily over the last two decades (Figure 1.2). Maize yield for example has increased from about 1.7 t ha^{-1} in 1993 to the current 3.4 t ha^{-1}, although most of the increase has occurred within the last decade. The biggest increase in yield for the other crops such as wheat, barley and sorghum has also occurred during this last decade and coincides with Ethiopia's investment in

agriculture in 1995–2014 that surpasses CAADP's 10% of total expenditure target (AGRA, 2016). However, the increased productivity is still insufficient to meet the food demand in Ethiopia with a sharp rise in net imports (especially of wheat from 35 hg in 1993 to 161 hg) in 2014. Imports for maize and sorghum have not increased much during the period (at an average 2 hg and 7 hg, respectively). Of the 21 years where data is available (FAOSTAT database 2014; data not shown), Ethiopia was a net exporter for just 3 years for maize, 2 years for sorghum and zero years for wheat. Clearly, Ethiopia's crop production and imports are still inadequate to meet the nutritional needs of its population and. in 2013, out of its 90 million people, 33.2 million were still undernourished (FAO, 2014). Yet, in Ethiopia as in most SSA countries, the yield productivity gap is huge for most crops i.e. the actual yield is way below the potential yield. This demonstrates the need to intensify production including adoption of inorganic fertilizer with improved seeds coupled with good agronomic principles.
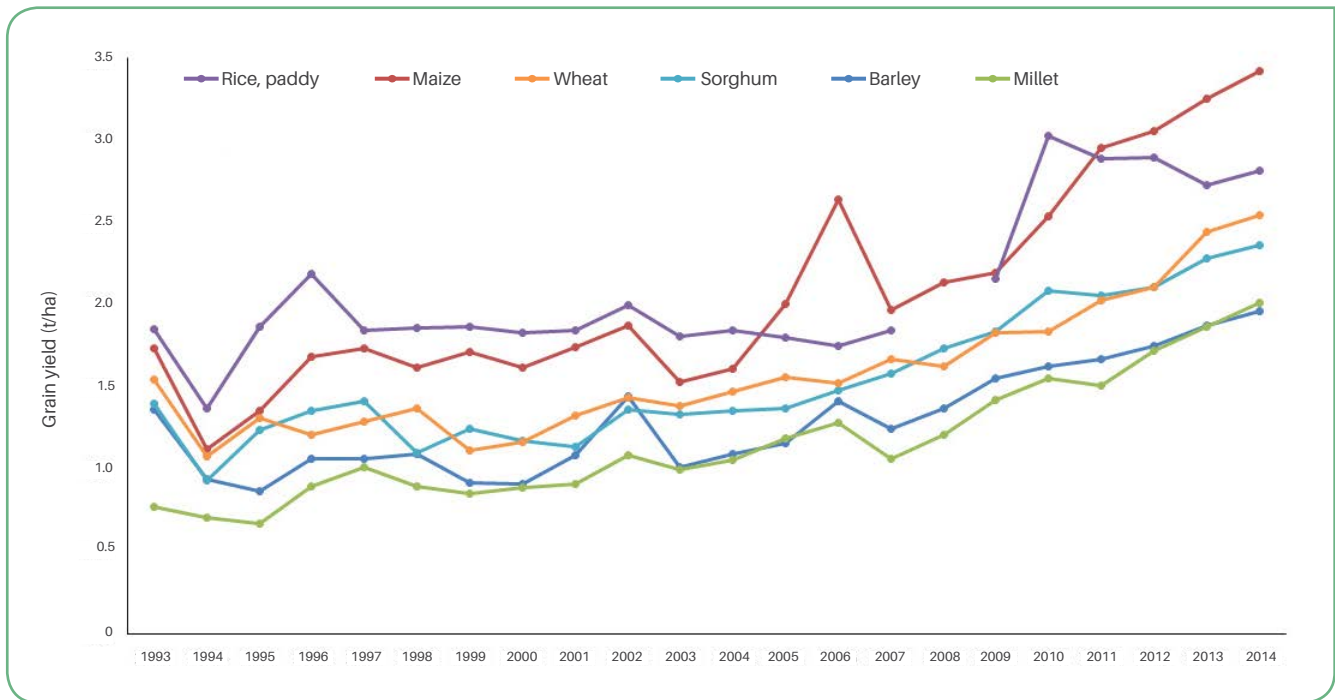
Figure 1.2 Productivity trends of major cereal crops in Ethiopia.
Source: FAOSTAT database 2014.

The results show that there is a limited response to N and P in the absence of the other while combining N and P results in large increases in yield (Figure 1.3a). Not including P in crop nutrition has a greater effect on attainable yield in areas with low than with high (>4 t ha^{-1}) unfertilized/control yield. Recommendations for fertilizer would thus likely include N and P. With fertilizer application, many observations indicate elevated yields beyond the national averages (Figure 1.3b). There was a positive response to N, P and S with the test crops (wheat, maize, teff and rice) although some of the observations show no response/ negative responses to the applied nutrient. Some crops, especially wheat, rice and teff, showed a positive response to S. There was a positive response to P although some negative observations were also made for wheat and rice.

Based on Figure 1.3b, N and P responses were observed in a majority of the cases for all the crops (except wheat) in almost all environments. The response of these nutrients related to wheat demonstrates a clear need to contextualize responses (e.g. by application levels, regions, etc.). No data shows a clear response to other important nutrients e.g. secondary and micronutrients.
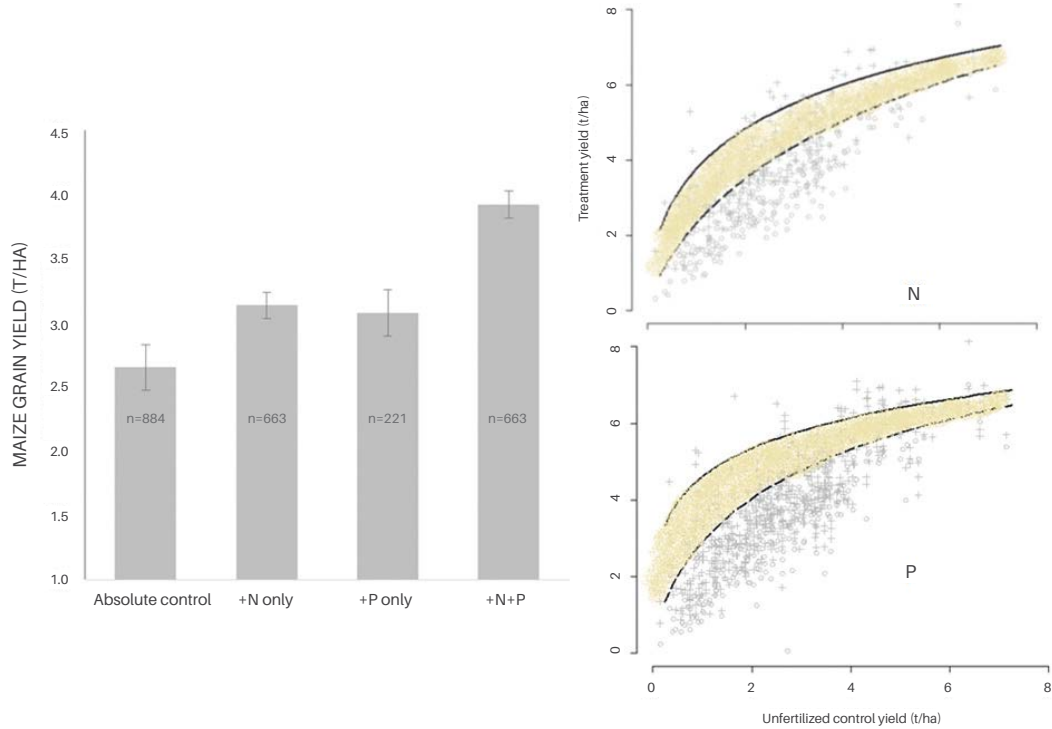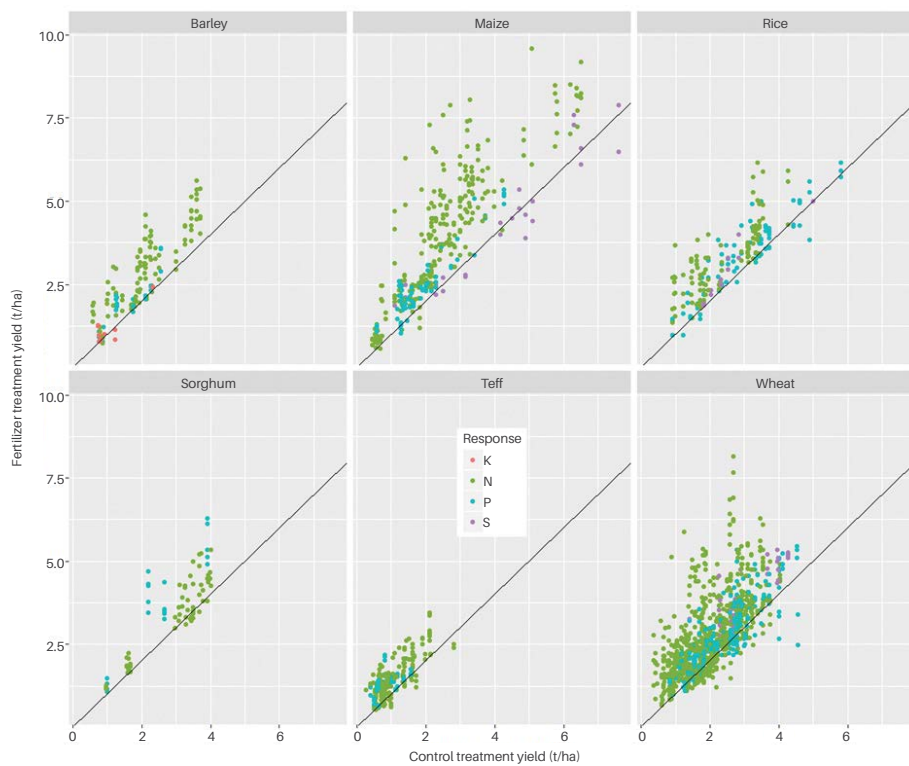
Figure 1.3 Effects of (**a**) N, P and NP and (**b**) N, P, K and S on the yield of different cereal crops across a range of controls in Ethiopia. The control did not receive any amount of the nutrients under investigation.

Like cereals, there is also a positive response to fertilizer application for major legumes (Figure 1.4) but we cannot make a firm conclusion as there are few data points. This shows that either legumes are not usually supplied with organic fertilizer or research studies on legumes' response to fertilizer are few. We need to conduct a more detailed review (including unpublished materials) to get a clear understanding of legume response to fertilizers.
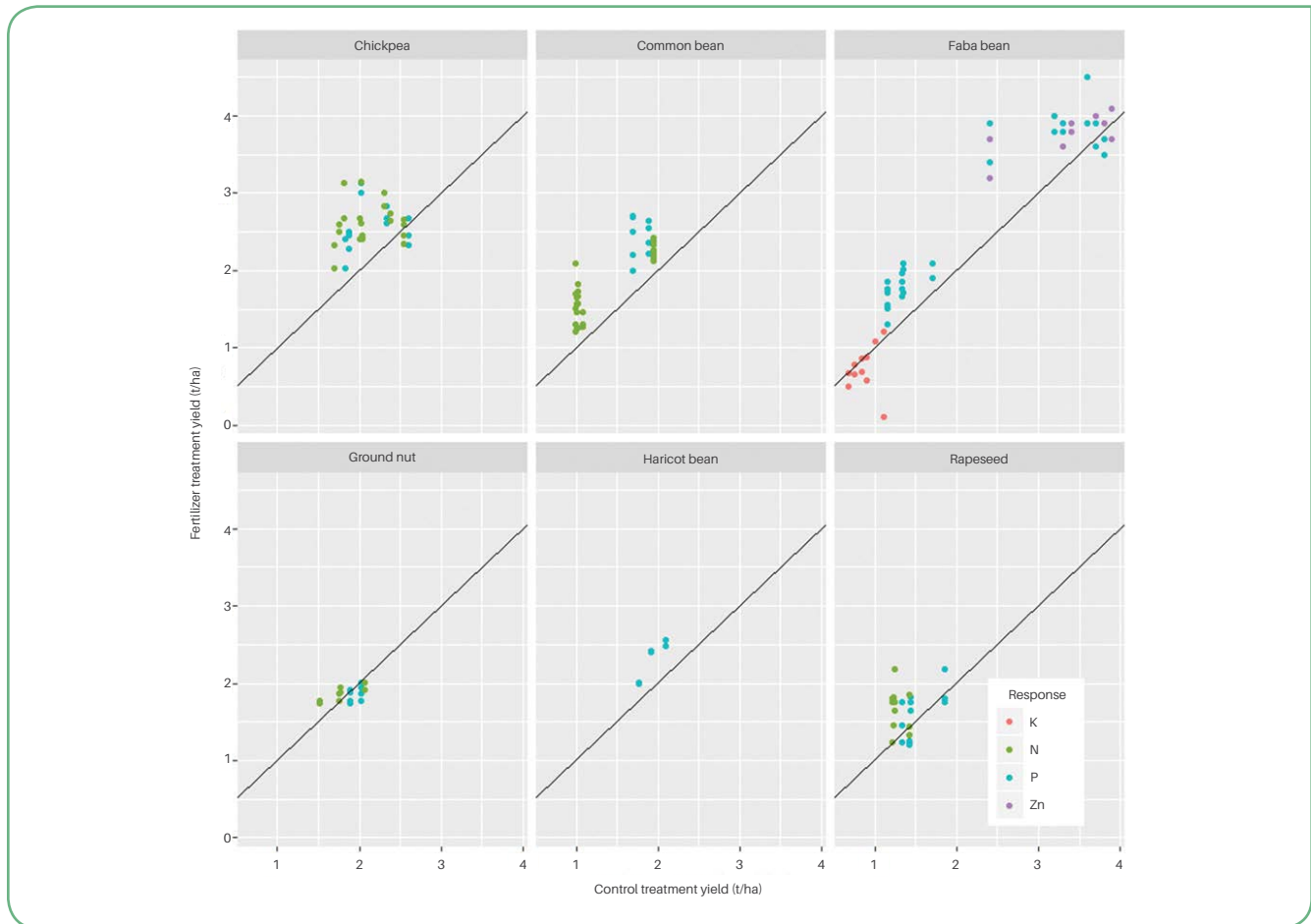
Figure 1.4 Effect of N, P, K and Zn on yield of different legume crops across a range of control yields in Ethiopia. The control did not receive any amount of the nutrient under investigation.

3.2. Response ratio

Fertilizer is an expensive commodity in SSA, and to achieve agronomic efficiency its application must be site specific. Investment in an input must make economic sense to a farmer. For example, for the technology to make economic sense and for farmers to adopt them, for every unit of fertilizer applied, the profit obtained from the yield must exceed the expenditure on inputs with good margins. A simple way to assess whether a given input use is beneficial or not is to use the response ratio (RR). RR indicates the number of times yield with fertilizer is increased over the control. It can be estimated by relating response to a given fertilizer against its control ($RR = \ln$ (yield_treatment ÷ yield_control). A RR of more than 1 shows a significant increase in grain yield due to addition of a given fertilizer/input. Figures 1.5 and 1.6 show response rations for different crops with different levels of fertilizer application. For all the crops, an increase in N application resulted in an increase in the corresponding RR. For teff there was an increase in RR with an increase in N application up to about 60 kg; any additional N after this showed a reduced RR. For rice, the RR was positive up to 75 kg of added N, and showed a decrease with more N added. Although observations showed a positive response with an increase in fertilizer application (e.g. wheat,

maize), the RR increased only up to a certain amount of fertilizer, after which any additional fertilizer resulted in a decrease in RR for some crops. Furthermore, reports showed that crop responses and economic benefits farmers got from application of these recommended fertilizer blends were limited, inconsistent (highly variable) and beyond their investment capacity (Giller et al., 2011). It is thus essential to evaluate whether a given amount of fertilizer input makes economic sense to farmers.
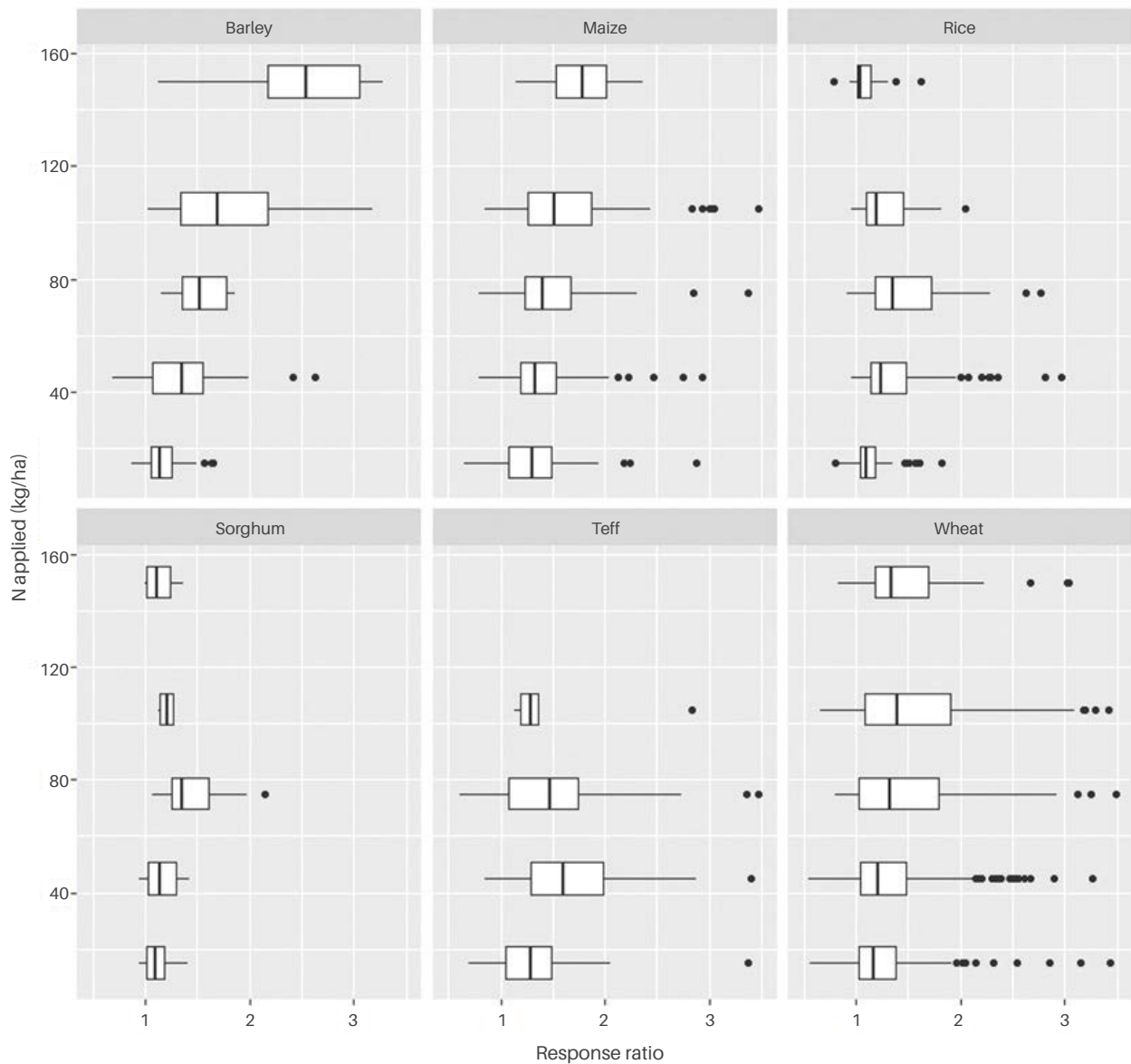
Figure 1.5   The effect of N quantity on response ratio of different cereal crops as observed in Ethiopia.

Figure 1.6a shows the RR values in relation to P application. For maize, an increase in the amount of P resulted in an increased RR. There was an increase in RR for teff up to about 60 kg of P, after which any additional P resulted in a decrease in RR. For rice, the RR increased up to 45 kg of P added after which any additional P did not result in an increase in RR. Based on Figures 4.5 and 4.6, we can see that RR to N was highest for wheat at about 1.6 followed by maize at 1.4; it was also highest to P for wheat at 1.3.
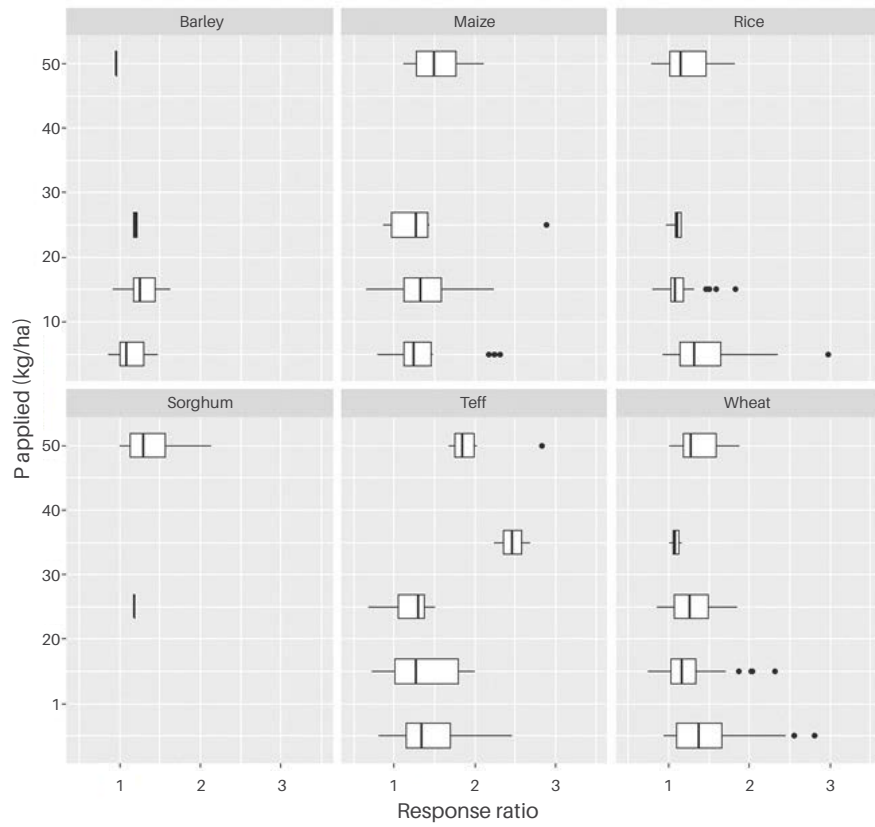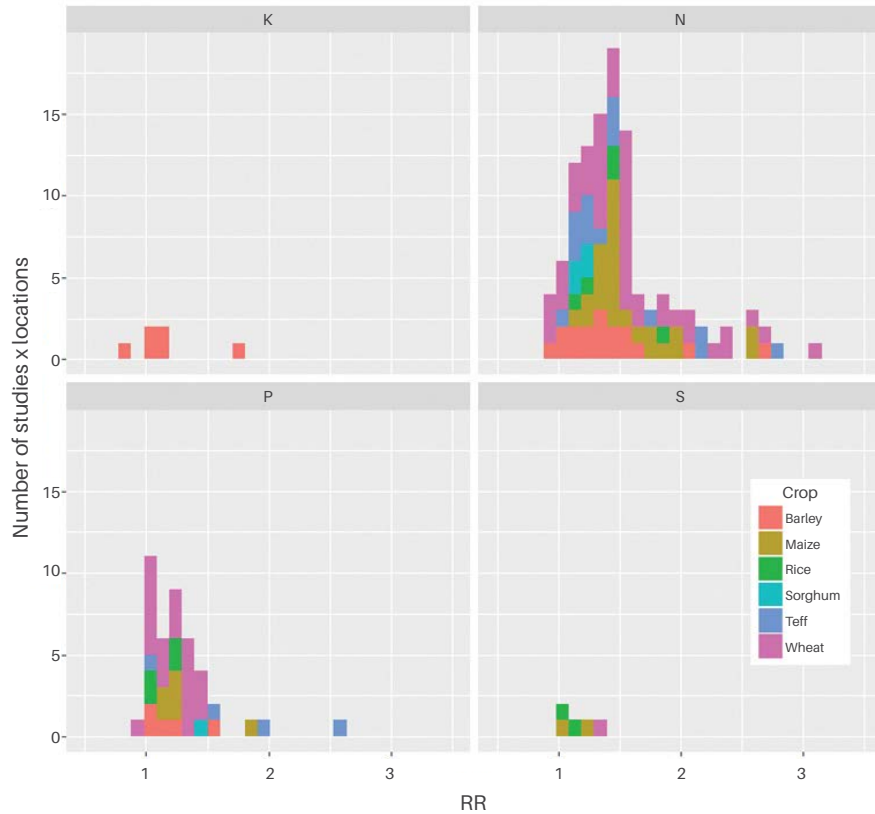
Figure 1.6 **(a)** The effect of P quantity on response ratio of different cereal crops as observed in Ethiopia and **(b)** distributions of response ratios observed with different crops at the different experimental sites for different nutrients.

Figure 1.6b shows the distribution of RR for the different crops as observed in the reviewed papers. An increase of 300% was possible in some cases though it was uncommon. The response to N of 40% was an easy target for most crops but not so for P. Generally, more information is needed for S. There are still a limited number of studies on plant response to K. This is because to date most soils in Ethiopia were considered to have no deficiency in K, though recent evidence show otherwise.

3.3. Value cost ratio

The low level of modern inputs adoption by farmers is a major impediment to food security and poverty reduction in Ethiopia. One of the reasons for low use/adoption is the risk involved in the profitability of fertilizer use mainly by smallholder farmers. To assess whether fertilizer use could be profitable, we calculated value cost ratio (VCR), or the value of increased output relative to the cost of fertilizer applied (Figure 1.7). Considering the risk averse nature of smallholders, a VCR of more than 2 was generally considered profitable i.e. given normal risks, VCR > 2 is necessary for farmers to use fertilizer. Under high-risk production environments, a VCR > 3–4 would be necessary for farmers to use fertilizer. Based on Figure 1.7, the farmers who applied N and NP were profitable while those who applied P alone were not necessarily profitable.
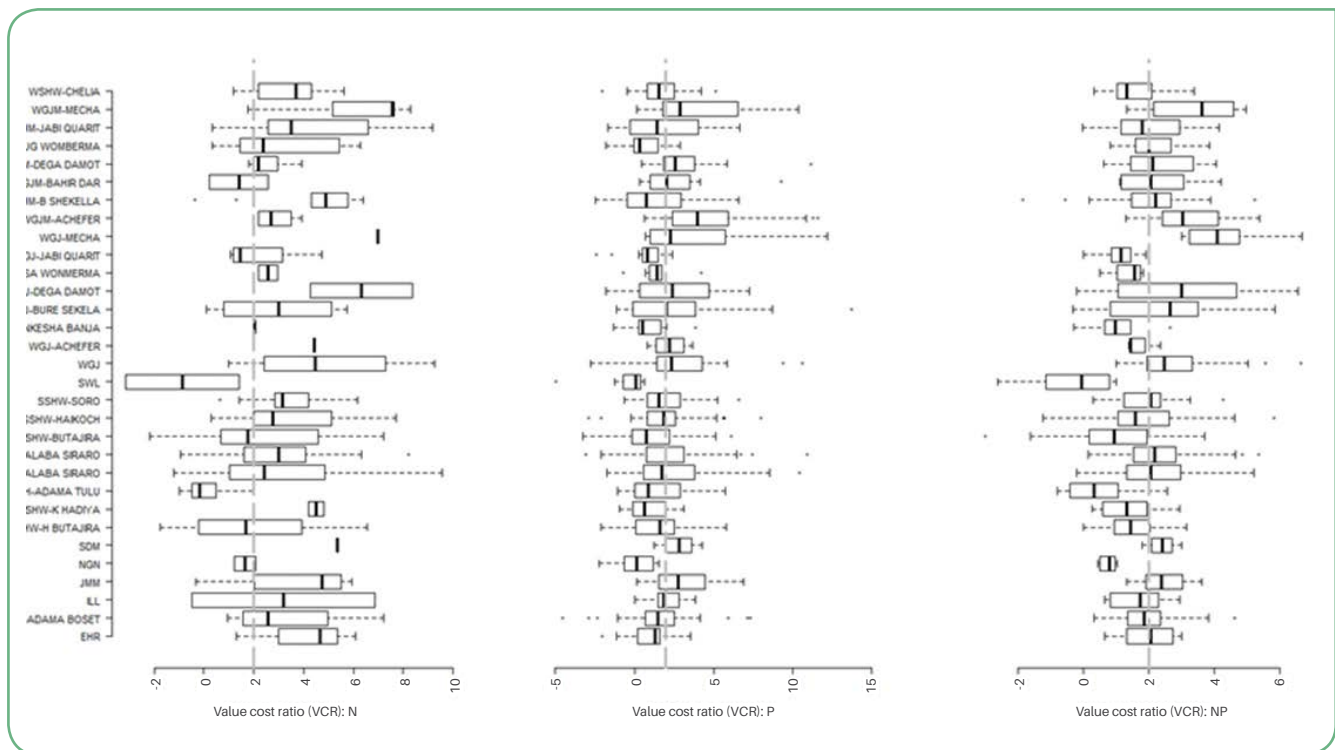
Figure 1.7   The log ratio of means computed for the various studies for wheat.

4. Discussion

Ethiopia's food insecurity renders it among the highest recipients of food aid in Africa. This is because there is huge demand for food crops in the country due to its high population of about 100 million people, but the production trends have remained low. Furthermore, in Ethiopia as in most African countries, the yield productivity gap is huge for most crops where the actual yield and the potential yield vary greatly, and this further threatens the country' food security. Therefore, demand for cereals crops i.e. wheat, rice, maize, and sorghum remains high because of their importance to Ethiopia's food basket. In addition, the yield gaps of cereal crops tend to be larger in developing countries. These gaps are closing slowly at rates surpassed by population growth rates, and this may be due to inappropriate crop management practices (Vanlauwe

et al., 2015). These deficiencies have led Ethiopia to look for supplementation through importation of food crops.

Cereal production in Ethiopia in 2011 was 2.9, 6.1, 4.0, 1.6, and 0.06 million t for wheat, maize, sorghum, barley and rice, respectively. To meet some of the demand for cereal crops within the country, 59% of wheat, 1.34% of sorghum, 3% of barley and 122% of rice equivalent of production was imported (FAO database, 2013). Clearly, from FAO-STAT data, Ethiopia's crop production and importation is still inadequate to meet the nutritional needs of its population as data shows that within the same year, out of over 90 million people living in Ethiopia, 33.2 million were still undernourished. According to World Bank (2014), household monthly food security can be up to 8.4 months, and this gets very low during droughts and extreme weather. These demonstrate the need to intensify production to meet food demands within Ethiopia.

Our results clearly show that good management of agricultural systems with the use of external inputs is necessary to achieve food security in Ethiopia. The potential yield for both subsistent and cash crops is yet to be achieved and research has shown that there is significant yield increase with both inorganic and organic fertilizer. The positive responses to fertilizer N, P and S in our study shows that these nutrients are necessary for Ethiopia to achieve food security. Furthermore, the test crops are very important for the food basket of the country (Gebrekidan and Seyoum, 2006; Ayalew, 2011; Dawit et al., 2015; Desta, 2015).

The investment in inorganic fertilizer for crop production must be profitable to a farmer to justify its continuous use. Furthermore, a blanket recommendation often leads up to some nutrients being wasted (Vanlauwe et al., 2011). In addition, the high variability between and within farms calls for site-specific recommendations that will reduce wastage and reap maximum benefits from fertilizer use. Although there are few studies on the economic benefits of fertilizer use in SSA (Kihara et al., 2015), the results shows positive returns on inorganic fertilizer investments (Dawe et al., 2003; Place et al., 2003; Sileshi et al., 2009) when either applied solely or in combination with organic amendments. The use of fertilizer not only increases yield but also improves stover yield and overall appearance of crops. Stovers

can be used as animal feeds, to prepare compost, or can be used as farm residues. Although not accounted for in our study, such benefits of stovers in addition to grain yield must be accounted for economically (Mucheru-Muna et al., 2007).

The response to fertilizers is likely to be increasingly influenced by the higher variability in weather patterns. Not only is weather forecasting information important but also agriculture should be accompanied by a suite of climate-smart technologies including conservation practices. Smallholder farmers have been seriously affected by climate variability (Reidsma et al., 2010). Consequently, adaptation strategies are critical (Rowhani et al., 2011) and this is not only because Ethiopian farmers are poor, but because of the uncertainty that variability in weather causes both in terms of magnitude and its effects. Furthermore, vulnerability differs by location (Rurinda et al., 2014), and this affects poor, smallholder farmers in Ethiopia. For example, the increasing variability in weather has interfered with planting dates (Pangapanga et al., 2012), and this is partly responsible for the crop failure that is being experienced in SSA.

Different research findings indicate that crop response to fertilizers vary across space due to different constraints such as: terrain catena, soil moisture, level of erosion and other management practices. As soil erosion is one of the major causes of soil nutrient loss and affects soil moisture availability, soil and water conservation (SWC), sustainable land management (SLM) and water harvesting (WH) practices are essential to enhance crop response to fertilizers. In countries such as Ethiopia with topographic complexity and heterogeneity, crop response can be undermined due to steep slopes (i.e. high level of soil loss and low level of soil moisture) making the soils less responsive. In such circumstances, additional interventions such as SWC and organic amendments are essential. Although not included in this study, it would be interesting to assess the impacts of the various SWC interventions in the country on crop response to input use – by asking: "how do the various soil conservation measure/interventions affect the response to nutrients?" SWC measures have become very important parts of the landscape and we need to contextualize fertilizer recommendations to those. In areas that are considered as nonresponsive to fertilizers, one could ask about the payback time after which a response to fertilizers would be expected. Answering these

questions can help planning and targeting in designing fertilizer recommendations.

Instances of droughts and prolonged dry spells that are now more frequent in SSA including Ethiopia (Cooper et al., 2008) have further aggravating the negative effects of changing weather patterns on crops as farmers rely mainly on rain-fed agriculture (Mapfumo et al., 2013). The decrease in rainfall both in amounts and frequency, coupled with biophysical and socioeconomic challenges, render farmers more vulnerable as they lack appropriate coping strategies. Preparedness techniques in combination with conventional approaches that farmers previously used to cope with small changes in rainfall patterns no longer work. This is because the effects of variability in weather now have higher magnitudes, which means we need to make interventions at higher levels. Different coping strategies have been adapted in different areas: crop diversification, crop spacing, adjusting planting dates, rotation and intercropping, agroforestry, increasing manure use, water harvesting and managing soil fertility, among others (Mapfumo and Giller, 2001; Olesen et al., 2011; Rurinda et al., 2014) and these coping strategies could also be adopted in Ethiopia to reduce the impacts of weather variability.

Technological innovations are needed to attract the growing young population to agriculture. Other transformations including farmer training would ensure that youth engage in agribusinesses. For example, the adoption of technological innovation has lowered the unit cost of crop production and has improved agricultural productivity in the densely population regions of Asia (Pingali, 2007) and this can also be adopted in Ethiopia. The population increase trend in Ethiopia calls for mechanization as land available for cultivation is on the decline. Furthermore, there are rising cases of unemployment attributable to the increase in population which has affected mainly the young population. Consequently, other avenues for income such as agriculture must be made attractive to the youth. Farming has been for decades practiced only by smallholder farmers for subsistence consumption purposes with very little inputs and poor management which often results in low yields (Vanlauwe et al., 2010). The small-scale scenarios have made agriculture seem unfruitful and unattractive to the youth. Mechanization offers an opportunity for increasing production with technology. In the past, increasing production meant simply cultivating more land, and this is no longer possible due to population pressure. Therefore, intensification through mechanization, where land is cultivated more than once a year and is characterized by multiple crop systems, can increase produce.

According to Pingali (2007), countries in SSA have continued to have very low mechanization adoption trends and even decreases have been noted in countries that were initially to the forefront in terms of mechanization e.g. Kenya and Zimbabwe. This is partly the reason for the stagnant yields as cultivated land continues to decrease as population continues to increase. Furthermore, for intensification and agribusinesses to be successful and more attractive to the young generation, access to markets must be improved (Shiferaw et al., 2009) through better roads and transport networks. Training in agribusiness and access to improved technologies and productive assets (Barrett, 2008), including proper storage of produce and value addition can further increase incomes for the youth.

Unlocking the productivity potential requires mechanisms for delivery of science-based, yield-improving technologies to farmers, and offering support to farmers when they encounter implementation challenges. Massive adoption of recommended technologies through increased access to fertilizer inputs, improved seeds and information is necessary as these factors have constraints for technology adoption (Asfaw et al., 2012). The Ethiopian government should increase subsidies on agricultural inputs as they are still too expensive for poor, rural farmers (Rashid et al., 2013), and this is partly responsible for holding back potential yield.

Grass roots support for farmers is essential in order to increase the adoption of yield-increasing technologies that have been recommended by researchers (Snapp et al., 2003; Maatman et al., 2007). Farmers often get frustrated because to be successful, new technologies must be mastered and they must be given the appropriate information and training. Therefore, extension workers should be available to farmers for support. Otherwise, new technologies are often abandoned and the trend of poor yields will continue to be the norm. According to Akinnagbe and Ajayi (2010), the linear model of technology transfer (researcher–extension worker–farmers) approach has been used for a long time to deliver technologies to farmers in Nigeria but better approaches are needed. For example,

a farmer-led extension approach, where farmers identify the technology, generate, adapt and disseminate it has resulted in better adoption of new technologies in Nigeria. Farmer participation means that they can make their own choices and decisions and even give suggestions on how particular technologies and approaches could be adopted for Ethiopia. In addition, the ratio of extension workers to farmers must be reasonable to ensure good contact. There are often just a few extension workers who have to cover farmers in vast regions (Belay and Abebaw, 2004); this means that their contact with farmers is minimal and thus ineffective.

5.   Conclusion

A high degree of variability in crop response to nutrients and amendments is observed in major cereal growing areas in Ethiopia. This is mainly associated with variability in soil characteristics within and between sites. Fertilizer trials are key for yield gap assessment and provide data and information relevant to developing strategies and identifying possible solutions to improve crop productivity. The analyses of response patterns of crops to the various treatments in different fields can enable grouping of fields into response classes. The management of soil fertility through balanced crop nutrition that takes account of site-specific deficiencies in macronutrients and micronutrients and considers the use of manure and other organic soil amendments is needed to achieve optimum crop yields in the country. Through meta-analysis conducted in this study, we examined the variabilities in crop responses to input use and devised mechanisms to improve it. With some additional data sets including soil types and landscape position, it can be possible to develop fertilizer formulations that address site-specific limiting nutrients. In addition, there is a need to evaluate the impacts of integrated uses of organic and inorganic fertilizers, crop sequences and different moisture enhancing mechanisms. It is thus essential to collate all available crop response data (including associated biophysical and socio-economic attributes), establish a sound database and conduct detailed analysis. Further research is also needed to establish crop response patterns and underlying characteristics, and to define the extent of micronutrient element limitation to crops in Ethiopia.

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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.

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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.
    Note: [1]ILRI, [2]EIAR, [3]ICRISAT.

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$_2$O$_5$ 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$_2$O$_5$ ha^{-1}, representing a yield increase of 2,336 kg ha^{-1} over the control, but 138–46 kg N–P$_2$O$_5$ 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$_2$O$_5$ ha^{-1} at Farta and 123–46 kg N–P$_2$O$_5$ 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$_2$O$_5$ 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$_2$O$_5$ 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$_2$O$_5$ 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$_2$O$_5$ 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$_2$O$_5$ 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$_2$O$_5$ in the 4th year, wheat with 48–15 kg ha^{-1} N-P$_2$O$_5$ in the 5th year and rape seed with 23–10 kg ha^{-1} N-P$_2$O$_5$ 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$_2$O$_5$ 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$_2$O$_5$ 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$_2$O$_5$ 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$_2$O$_5$ 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$_2$O 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$_2$O 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$_2$O$_5$ 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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Photo: Lulseged Tamene/CIAT

Section 3

Towards building a crop response to fertilizer database

Degefie Tibebe (EIAR) and Lulseged Tamene (CIAT)

1. Introduction

Nutrient deficiency has been reported for a long time in Ethiopian soils. Low availability of N and P has been commonly recorded in different areas (Tekalign et al., 1988; Asnakew et al., 1991; Amsal et al., 1997) and the effect has been reflected in the production and productivity of the major crops grown in the country. This is mainly associated with the practice of multiple and continuous cropping systems using low fertilizer rate and use. In Ethiopia, fertilizer is applied in less than 50% of the total crop area. As a result, the application of chemical fertilizers to soils is one of the solutions to nutrient deficiency and decline in soil quality. The determination of fertilizer rate is the most important step in the fertilizer recommendation processes as inadequate and/or over supply of fertilizer greatly reduces yields and profit.

Against this background, various research institutes and centers in Ethiopia have been conducting fertilizer related research. The Ethiopian Institute of Agricultural Research (EIAR) in collaboration with its partners has been conducting soils and agronomic research for more than 50 years. A large volume of experimental, survey and weather related data have been and are being produced from government and donor-based projects across farming systems and crop types. Such data are essential to develop 'crop response curves' based on appropriate fertilizer recommendations.

However, the data are not well organized and stored in a way that can be easily extracted and used. Evidence shows that studies done to date on 'crop response' trials are scattered and there is no comprehensive database in a centralized location. In most cases, once a project is concluded, the research data set is usually kept by individual researchers or project coordinators. The absence of an integrated system to organize, store and manage the huge data set collected to date means that researchers will repeat the same kind of experiments to get similar data, resulting in unnecessary duplication of effort and resources. In a quest to contribute towards developing a fertilizer recommendation tool, we reviewed all the available literature and collated the data to conduct a meta-analysis. The aim of this project was to extract yield response information from published articles and research reports across different agro-ecological zones and farming systems to contribute to developing a fertilizer optimization tool for major crops across diverse soils, agroecologies and land-use systems.

2. Approach to the collection of data and creation of a database

2.1. Data inventory and collation

Before collating the data, we developed and defined appropriate criteria on the kinds of data sets, types and parameters that should be used. To determine and select the parameters, similar systems developed elsewhere were reviewed and discussions with senior professionals in the area were held. In addition to information about the rates and types of fertilizer applications and corresponding yield responses, the locations of and the varieties used in the experiment were considered crucial (Figure 3.1). A total of 42 parameters were selected as a basis for collating the necessary information. Once the parameters were determined, and appropriate descriptions and

definitions were agreed, an Excel sheet was prepared to facilitate data entry, organization and screening. The template was discussed with the team who were responsible for collecting and analyzing the data and building the database. A literature review was conducted to search for documents which contained the required information. The main source of data was found in online and hard copy published journal articles, proceedings and annual research reports from research centers located across the country. In addition, personal contacts and institutional visits were carried out to access data that was not available online or in other publications.

Figure 3.1   Collected data in Excel sheet for different parameters.

2.2. Database development

Along with system requirements for determining the relevant and important parameters, a database was developed with an entity-relationship model using Microsoft Access. The entity relationship model was created using independent tables that store values for the independent parameters prepared in system requirement analysis. A relationship was established to enforce data integrity among the tables.
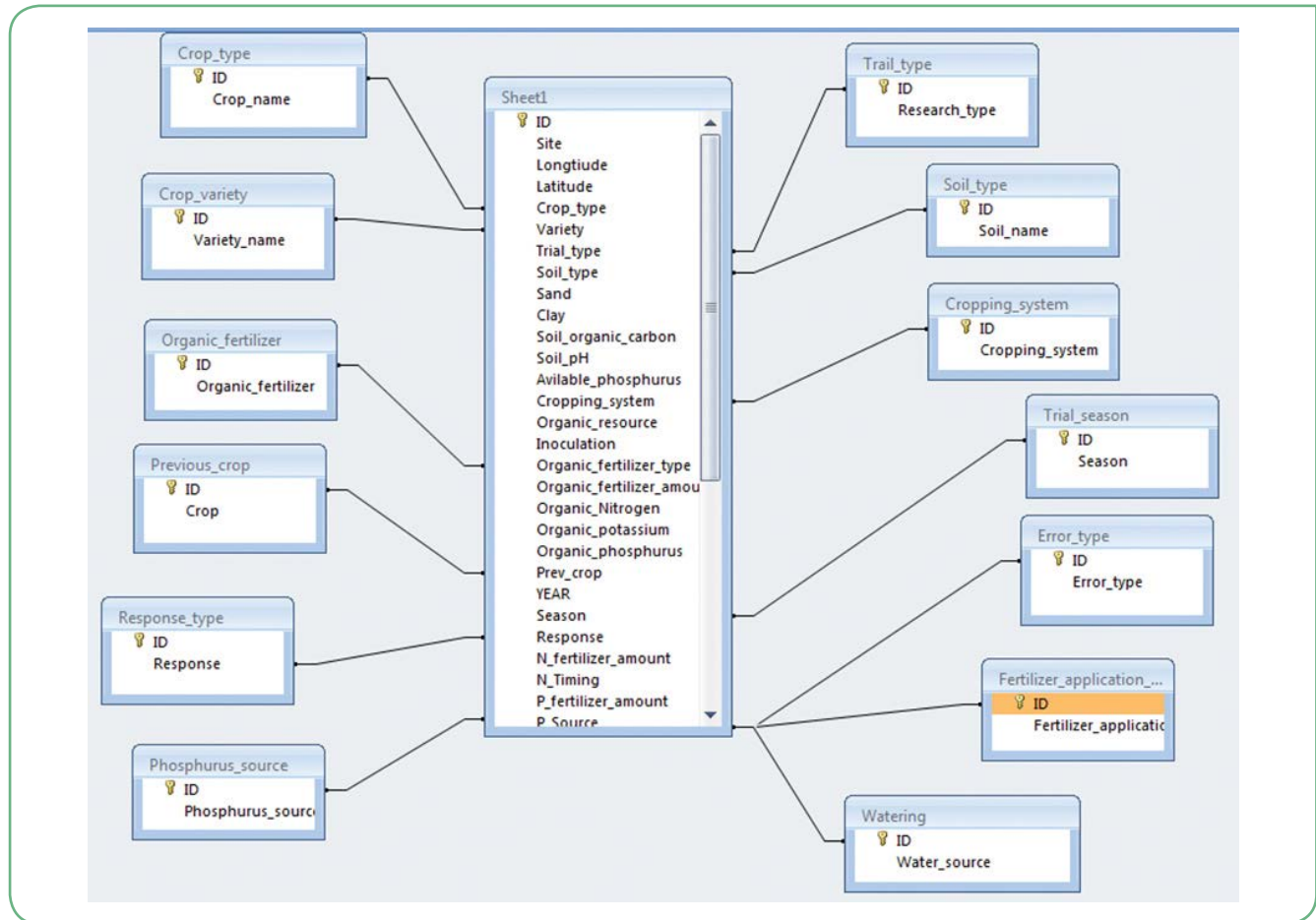
Figure 3.2   Entity-relationship model for the preliminary database developed in this project.

The template for the data recording was organized to input key parameters that were available in the literature and necessary for meta-analysis and other purposes. However, in most instances it was not possible to get useful information related to the trials and sites. In order to fill this gap, we overlaid the data set with other layers in a GIS and 'extracted' correspond values for each location. Accordingly, the database included information related to terrain, soils, agro-ecological zones etc. corresponding to each entry. In addition, we 'linked' the template (database) with other geodatabases so that users could extract the necessary co-variates for further analysis.

2.3. User interface development

User interfaces were established to make easier communication between the database and users either for entering new records or retrieving information based on queries set up during the system requirement analysis phase. The developed system allowed the user to enter new trial data into the database and explore and examine the response of fertilizers to different crops under different environmental setups. Users could also query the database to check on the availability of data and to conduct preliminary analysis. For instance, it was possible to query for possible yield of a certain crop in a specific agroecology and soil type at a different fertilizer rate application (Figure 3.3).
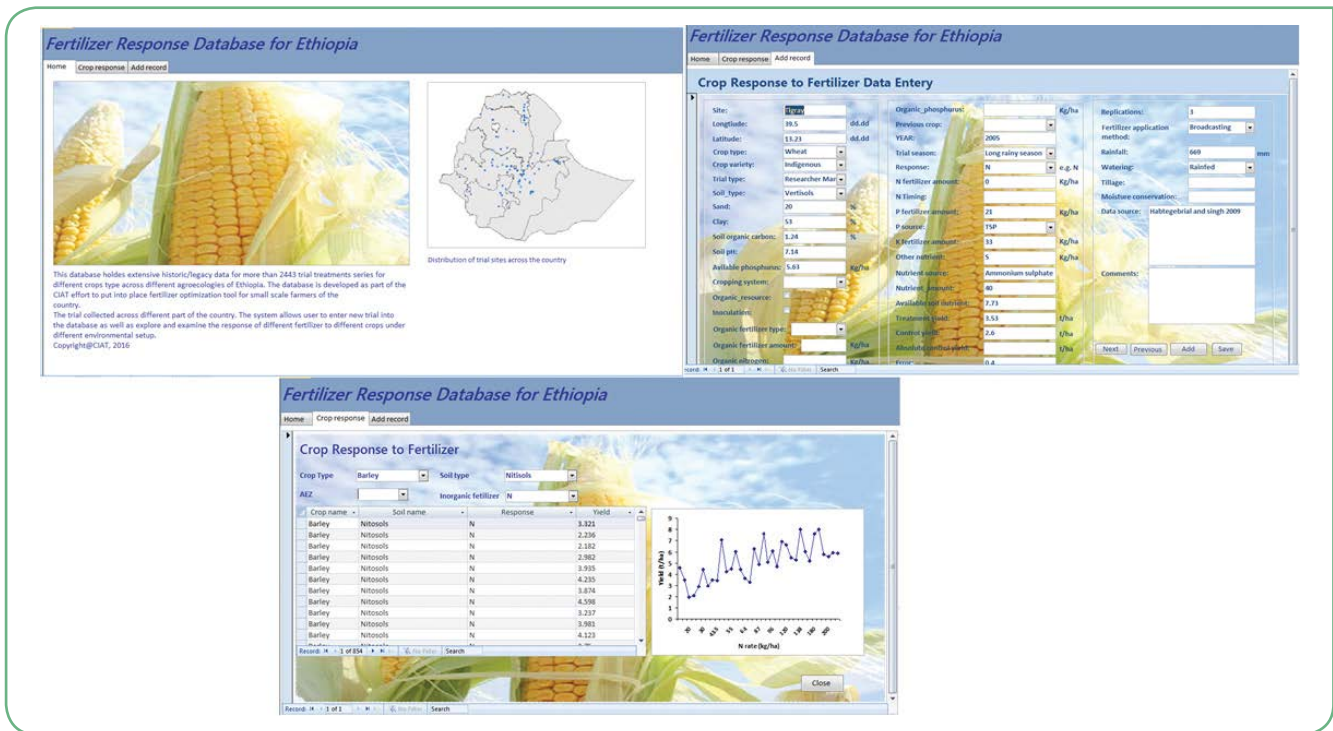
Figure 3.3   User interfaces of the fertilizer response database.

2.4. Description of the data set

From the literature review that included online and library searches, a total of 2,443 trial treatments series for more than 15 crops type conducted across different agroecologies and soil types were collated and entered into the database (Figure 3.4). Most the entries were related to: wheat, maize, teff, barely and rice (Figure 3.5).
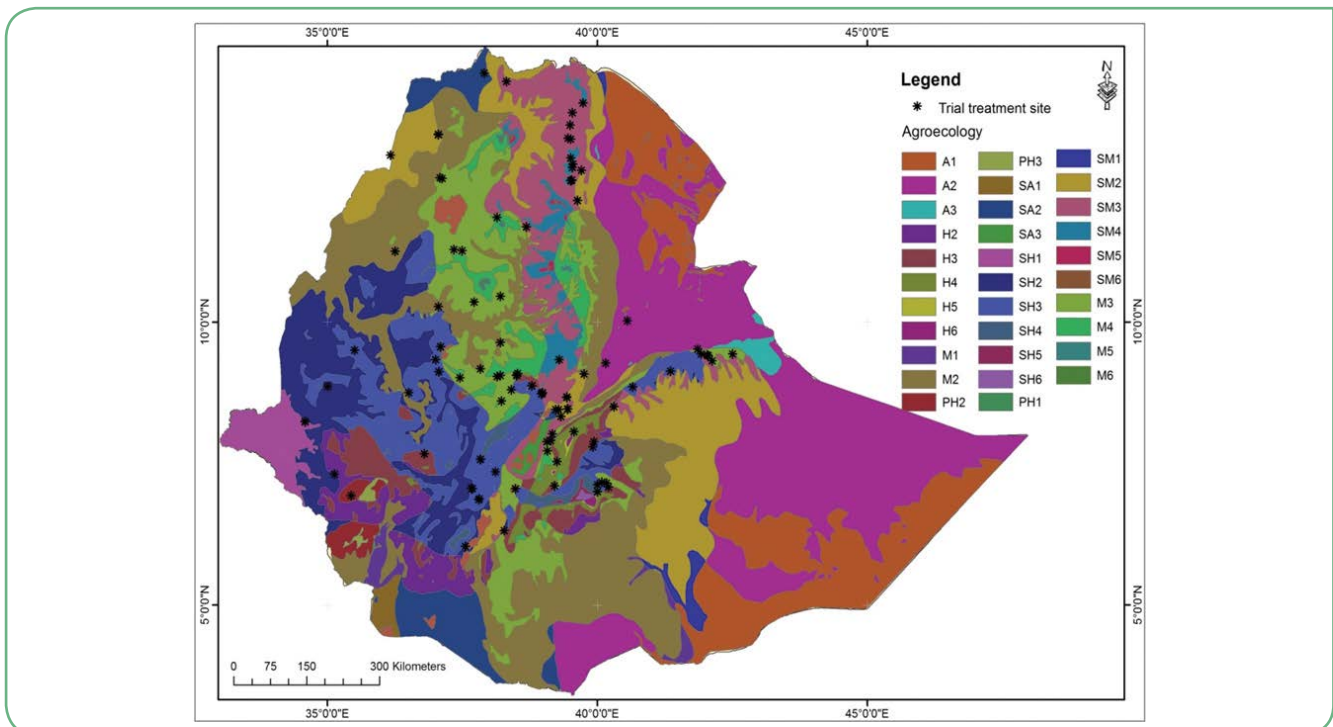
Figure 3.4   Trial treatment sites across different agroecologies.

Preliminary analysis showed that the trial treatments were conducted on 11 different soil types with vertisols and nitosols being the dominant ones. When overlaid with the recent agro-ecological zone of Ethiopia, we observed that the trials were conducted in 15 different agroecologies (Figure 3.4, 3.5). The majority of the trial treatments were undertaken in tepid moist mid-highland (M3) and tepid subhumid mid-highland (SH3) agroecologies.

M4	Cool moist mid highlands
SH4	Cool sub-humid mid highlands
SM4	Cool sub-moist mid highlands
SH1	Hot sub-humid lowlands
SM3	Tepid sub-moist mid highlands
H3	Tepid humid mid highlands
M3	Tepid moist mid highlands
SH3	Tepid sub-humid mid highlands
A2	Warm arid lowland plains
M2	Warm moist lowlands
H2	Warm per-humid lowlands
SA2	Warm semi-arid lowlands
SH2	Warm sub-humid lowlands
SM2	Warm sub-moist lowlands

Legend: Sulphur · Phosphorus, Zinc · Phosphorus · Nitrogen, Sulphur · Nitrogen, Phosphorus · Nitrogen · Potassium, Nitrogen · Potassium

Figure 3.5 Trial treatments by fertilizer and agroecology zone.

In terms of fertilizer, nitrogen (N), phosphorus (P), potassium (K), sulfur (S) and zinc (Zn) were the dominant types used in the trial treatments recorded in the system (Figure 3.6). N and P were the most commonly used fertilizers.
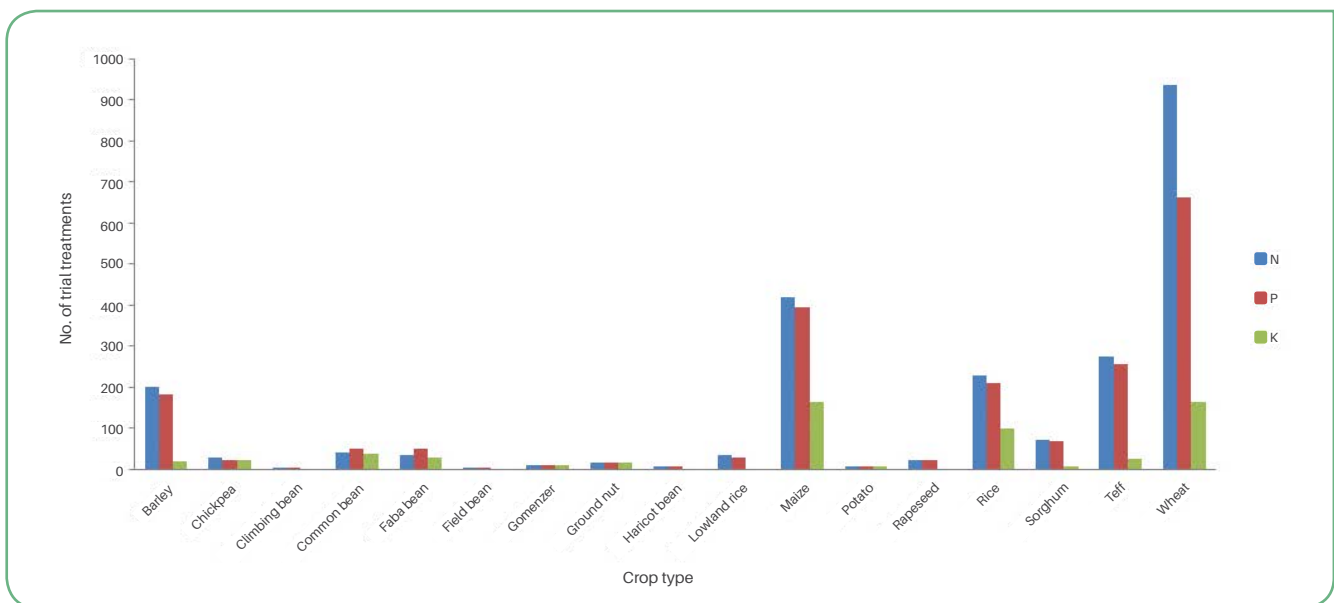
Figure 3.6 Trial treatments by fertilizer and crop types.

In terms of soil types, most of the trails were conducted on vertisols, followed by nitosols and alfisols. These soil types cover many of the area in the country and/or are the most dominant crops (that are heavily studied)

which are grown on these soils. As indicated above, N and P are the main types of fertilizers tested on these major soil type.
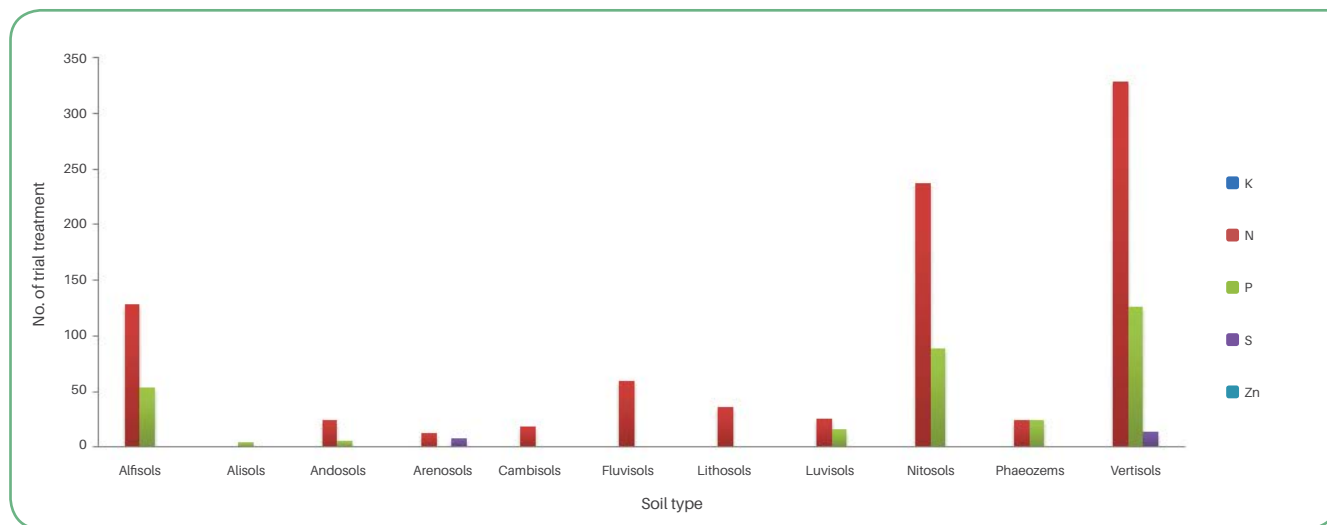
Figure 3.7 Trial treatments by fertilizer and soil types.

More detailed analysis of the data set is presented in Section 1. We aim to collate the remaining data set and improve the response curves.

3. Conclusion

One of the main purposes of the database organized in this study is to collate all available information related to crop response to fertilizer application based on which fertilizer recommendation tool will be developed. This will be achieved through first developing crop response curves which will be used to optimize fertilizer application and produce fertilizer recommendations. Key results related to crop response curves are presented in the next chapter.

Following the reviews conducted in this study and the various stakeholder engagements and workshops, it was noted that there was no centralized database related to the various crop response trials conducted in the country. This is unfortunate as this could result

in duplication of efforts, wastage of resources and may undermine our ability to develop appropriate fertilizer recommendations. There is thus an urgent need to develop a strong database and devise mechanisms of data sharing (information exchange) system. Making the data and recently released maps by the EthioSIS available for research and develop practitioners will be crucial so that validations, verifications and improvements can be made at different scales (levels).

The database created in this study is based on published documents and does not include unpublished data or reports or proceedings. In addition, many data set were not entered into the database because they did not satisfy some of the basic criteria. This means what we have presented only a tiny fraction of the data. We need to collate the remaining data and enter it in the database. We also need to ensure that the quality of data is assured, and a policy is put in place on the accessibility of the data for different users.

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Section 4

Trends and challenges of fertilizer use in Ethiopia

Degefie Tibebe (EIAR) and Lulseged Tamene (CIAT)

1. Introduction

Ethiopia recognized the indispensable role of chemical fertilizer use in its effort to transform its agriculture as early as the 1960s. The third 5-year development plan of the Government of Ethiopia that was launched in 1968 made agriculture a top priority for the country's economic transformation. The success in expanding industrial output during the second 5-year development plan of the government with an annual growth of 16% in manufacturing production created demand for agricultural output both in the form of food and input to the manufacturing sector. While smallholder subsistent agriculture was left to grow at 1.8% per annum, the monetized part of the agricultural sector was expected to grow at an annual rate of 5.7% over the period of the third 5-year development plan.

A major challenge that needed to be tackled to effectively implement the plan in agricultural development was that the land in the northern and eastern parts of the country was already depleted, overgrazed, eroded and was thus labelled as exhausted and inadequate to support the population. Elsewhere in the country, land productivity was not more than 12 quintals per hectare of land. In parallel with natural resource rehabilitation programs, the use of modern chemical fertilizers was one of the ways in which crop

yield was boosted (Imperial Ethiopian Government, 1968).

Key potential areas were selected under major package programs. The major areas of intervention for agricultural development in the country were: the Chilalo Agricultural Development Unit (CADU), the Wolayita Agricultural Development Unit (WADU), the Southern Livestock Development, the Setit Hummera, and Awash Valley Development. At the heart of such interventions that focused on increasing yield in crop production was the use of fertilizer. While such intervention helped to build agricultural capabilities in some intervention programs such as CADU, replicating the efforts in other parts of the country was expensive. The evaluation of the performance of ongoing projects led to an application of the interventions to the wider parts of the country under a minimum agricultural package program.

The first agricultural minimum package project which was launched in 1970 under the third 5-year development plan "had its origins in a countrywide FAO fertilizer trial program" and earlier experiences of an increase in crop yield due to the use of fertilizers, seeds, and extension services. The second agricultural

minimum package project that was implemented under the socialist regime between 1980 and 1984 served as the core of the government's development program for smallholder agriculture. One of the major objectives of the program was increasing agricultural productivity and rural income through increased use of fertilizer, improved seeds, and other agricultural inputs (World Bank, 1980).

Such interventions in the agricultural sector in the 1960s and early 1970s helped to increase crop yield and average rural income. Crop yield in quintal per hectare almost doubled from 6.6 in 1961 to 13.5 in 1974/75. The labor productivity in crop production during the late 1960s and early 1970s was 8 quintals per hectare. This contrasts to 9.5 quintal per hectare registered in 2015/16. The worst case in the performance of crop agriculture in Ethiopia occurred between 1984/85 and 2003/04 when yield as low as

6 quintals per hectare failed to keep pace with the growing rural population. Crop production per hectare fell to 3 to 4 quintals between 1984/85 and 2004/05.

2. Recent trends and impacts

The incumbent Ethiopian government (EPEDF) introduced the strategy of agriculture development-led industrialization (ADLI) in 1995. Agricultural development was the third beneficiary of the government budget after education, and road infrastructure. A major component of the government program on extension services was to provide fertilizer to smallholder farmers. As a result, application of chemical fertilizer has been increasing over the years. For instance, fertilizer use per hectare of arable land increased from 10.3 kg in 2004 to 23.7 kg in 2012 (Figure 4.1).
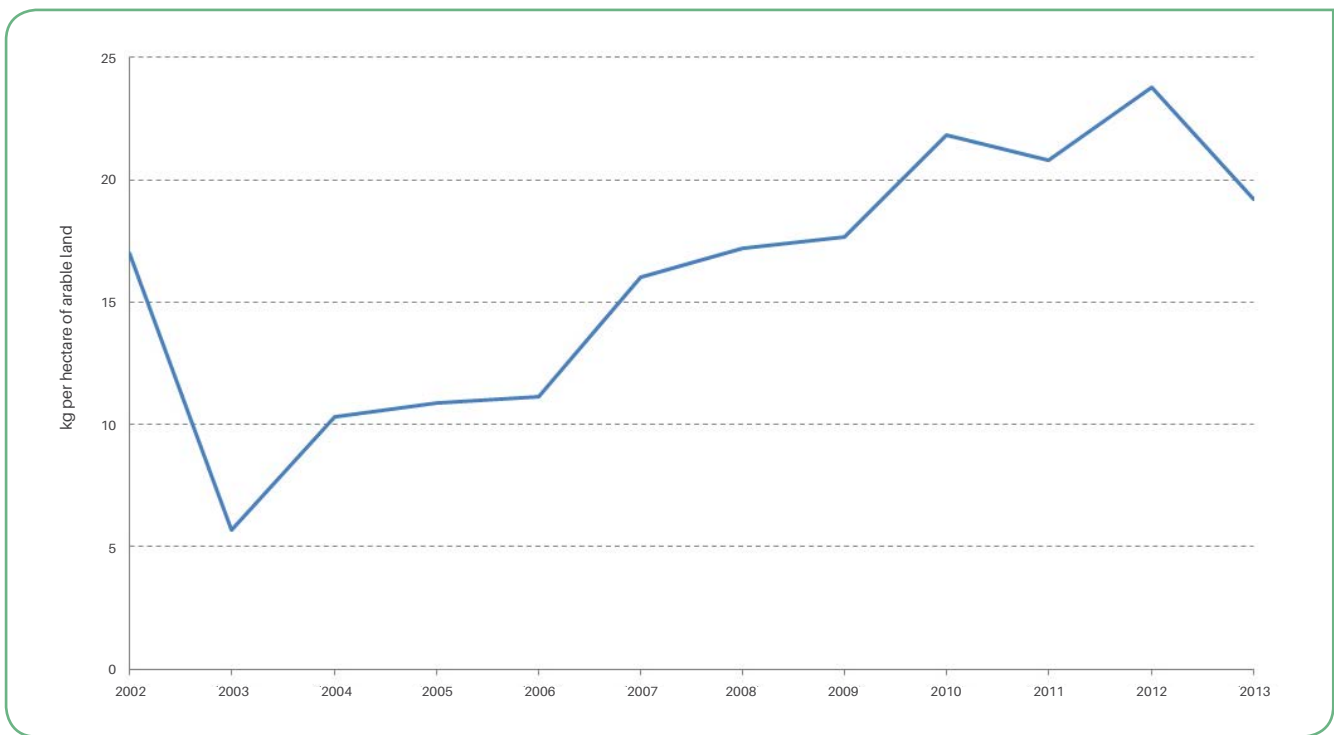

Figure 4.1   Trends in the application of chemical fertilizer (kg per ha of arable land).
Source: World Bank 2016.

Ethiopian agriculture was hailed for its good performance in the period 2005/06 to 2013/14. Average yield increased from 13.2 quintals to 20.3 quintals per hectare. The value added in crop production increased at an average rate of 8.8%. About 2.8 percentage points of the 10.2% overall growth in GDP or 26.4% of the growth in GDP was accounted for by crop agriculture. During the same period, the area of land under crop production that used chemical fertilizer increased by 69.7%, and the total volume of chemical fertilizer applied on farms increased by 85.3% (CSA, 2006, 2014; National Planning Commission, 2016).

One of the major research challenges is attribution of the recent growth episode in agricultural productivity to various inputs including fertilizer. A study by the International Food Policy Research Institute (IFPRI) attributed 8% of the growth in crop output observed during the period 2004/05 to 2013/14 to the growth in fertilizer use. Use of improved seeds and total factor productivity accounted for 12%, and 22% of the growth, respectively (IFPRI, 2016).

Under the second phase of the growth and transformation plan (GTP II) of the country, the supply of fertilizer was targeted to increase from the baseline of 1.223 million t in 2014/15 to 2.062 million t in 2019/20. It was also targeted to base fertilizer application on soil laboratory results that ensured compatibility of soil types with certain fertilizers in all parts of the country. The fertilizer adoption scheme was linked to other important packages, particularly access to credit. The voucher credit system which "has been pilot tested in 81 woredas to increase agricultural input utilization will be scaled up to all regions and woredas" [National Planning Commission, 2016]. There is also an effort within the country to produce fertilizer. For instance, Ethiopia has agreed with Morocco's Office Cherifien des Phosphates (OCP), the world's largest phosphate exporter, to build a $3.7 billion plant which is expected to produce 2.5 million tonnes of fertiliser in its first phase by 2022, and a second phase would see a further $1.3 billion invested to increase production to 3.8 million tonnes three years later (www.reuters.com/article/morocco-fertilizers-ethiopia-idUSL8N1DK0BR).

3. Factors affecting fertilizer adoption by smallholder farmers

Food production has been a major problem for Ethiopia and malnutrition is severe and hardly improving (Jayne

et al., 2003; Endale, 2010). Among others, the low level of use of fertilizer and its limited adoption for crop production is one of the main reason for low crop yield in the country (Endale, 2010). The average use of DAP and urea application in Ethiopia ranged from 3 kg/ha for sorghum to 40 kg/ha for teff (CSA, 2011). There are many complex and interrelated issues that contribute to the current low adoption of chemical fertilizer by smallholder farmers in Ethiopia (Kassie et al., 2009; Yu et al., 2011). The main factors are location and household specific (Deressa et al., 2008; Kassie et al., 2009; Spielman at al., 2011). Generally, these factors can be classified into three major categories: lack of incentive from fertilizer; lack of capacity to invest in fertilizer; and external factors. Below we discuss some of the major factors that determine fertilizer adoption by smallholder farmers in Ethiopia.

3.1. Absence of site- and context-specific recommendations

Despite the high level of trust farmers have in chemical fertilizers in increasing agricultural productivity in Ethiopia, there are still gaps in reaping the maximum benefit of fertilizer adoption. One of the major gaps in fertilizer adoption in Ethiopia is the blanket application of fertilizer with little attention to the type of soils, climatic conditions, and crop types. Such challenges were recognized even during the implementation of the first agricultural minimum package project in early 1970s. The evaluation of the program revealed that varying soil type, climate, and inaccessibility of rural areas meant that fertilizer adoption had less impact on crop yield. The consideration of other packages such as the use of modern seeds, pesticides, soil preparation and plantation procedures, and conserving soil and water were sought along with use of fertilizer (World Bank, 1980). DAP and urea have dominated Ethiopian fertilizer application over the last six decades.

In some cases, inherent and/or human-induced soil fertility problems undermine fertilizer use because those soils do not response to input use. For instance, acid soils do not adequately respond to organic fertilizers and/or will require large amounts. This makes the intervention expensive for stallholder farmers. In such circumstances, the application of lime or other soil fertility amendment practices are needed so that fertilizer application can work.

Recent soil mapping exercises in the country are expected to change the status quo and will promote targeted fertilizer application in the coming years. The development involving soil test-based fertilizer application and other improved agronomic practices can increase the likelihood of success of input use and thus enhance its adoption. For this to succeed however, there is a need for a comprehensive study to critically evaluate the combinations of fertilizers, and the location and rate that would provide the highest return. It is important to consider not only biophysical suitability but also socioeconomic issues as expensive options are unlikely to be picked up by farmers.

3.2. Risk aversion due to climatic conditions

Although the application of chemical fertilizer and other inputs such as modern seeds, and water is important during the evaluation of the performances of early interventions such as the minimum package project, the lag in harnessing water resources as a way of achieving high productivity with robust resilience to climatic shocks, is still a major gap. The severe drought that occurred in 2014/15 and which is still lingering into 2016/17 tested the overall capability of the agricultural sector in resisting a one-time adverse shock. While episodes of high growth in crop production can be achieved through applications of chemical fertilizer, better capabilities that ensure agricultural transformation requires harnessing water resources as part of the overall technological packages. This is crucial in countries such as Ethiopia where rainfall variability and episodes of drought have significant effect on crop yields and farmers' livelihoods, which also ultimately affect fertilizer use due to the increased risk of failure in times of drought. In such circumstances it is also essential to introduce 'crop insurance' packages for smallhodeer farmers. Based on exeriences elsewhere, Ethiopia has now launched crop insurance scheme wherby the insurance company will pay insured famers when rainfall amounts fall below a certain level and is a measure farmers can take to "insulate" themselves from the effects of drought (www.jica.go.jp/english/news/field/2014/150213_01.html).

3.3. Lack of economic incentives from fertilizer investment

Subsistence and smallholder farmers should get economic incentives from the fertilizers they apply. Economic incentives from fertilizer specific to the households depend on net returns/profitability/ of investments; relative returns; riskiness; the household-specific discount rate and the biophysical environment (Deressa et al., 2008; Kassie et al., 2009). Below we present some of the economic related incentives that determine fertilizer adoption by smallholder farmers in Ethiopia.

Net return/profitability is one of the most important factors governing the use of fertilizer by smallholder farmers in Ethiopia (Beshir et al., 2012). If the costs of fertilizer exceed the short-term and the long-term economic benefits, farmers have no incentive to adopt fertilizer (Lamb, 2003). The net returns of use of a given fertilizer depend on the yields and inputs (e.g. fertilizer, seed) requirement per unit of output and the prices of inputs and outputs. Leaving aside the question of capacity of farmers to purchase fertilizers, the better the net return of investment in fertilizer, the greater the probability of farmers to adopt it. In general, smallholder farmers in Ethiopia are sensitive to net returns and implicitly compare the expected costs and benefits and then invest in options that offer highest net returns, either in terms of income or reduced risk (Shiferaw et al., 2007). Their decision to invest in fertilizer is affected by the (perceived) profitability of fertilizer (Getinet, 2008; Beshir et al., 2012).

A given investment may be profitable but not sufficiently *attractive* relative to alternative farm and nonfarm investments to motivate farmers to invest (Reardon et al., 1995). Some studies have reported that the availability of off-farm income has a negative impact on farmers' investments in fertilizer (Shiferaw et al., 2007; Kassie et al., 2009). This is mainly because household workers face higher opportunity costs and prefer to allocate financial resources into off-farm activities where it fetches higher returns than on-farm activities.

Another important factor affecting farmers' incentives to invest in fertilizers is risk. Smallholder farmers in Ethiopia are generally producing under an environment full of risks and uncertainty. Investments become riskier, and incentives decline if farmers are not sure that they will be able to recover the full benefits of their investments in fertilizer. Studies showed that investment in fertilizer can significantly be affected by productivity risks caused by rainfall variability in Ethiopia (Kassie et al., 2008).

The *market* for agricultural inputs and outputs has been poorly developed in Ethiopia and this contributes

to an unfavorable relationship between input and output prices (Aune and Bationo, 2008; Yusuf and Köhlin, 2008). The prices of agriculture products are unknown at the time of planning and there are uncertainties related to the price of inputs and their availability. Uncertainty in output market outlets has also plagued several promising technologies in Ethiopia (Yusuf and Köhlin, 2008; Beshir et al., 2012).

Crop *yields* in Ethiopia are generally low, and *highly variable* (Alem et al., 2008). Studies have clearly demonstrated that rainfall is the predominant factor influencing yield variability in the country (Edwards et al., 2007). The increase in extreme weather events such as spells of high temperature and droughts has also increased yield variability and reduced average yield (Sinebo, 2005; Tittonell et al., 2008). Yield variability also affects farmers' investments in fertilizer and other inputs due to risk aversion (Graves et al., 2004). Because of this uncertainty, farmers in Ethiopia are logically reluctant to invest in potentially more productive and economically rewarding practices when the outcomes and returns seem so uncertain from year to year (Edwards et al., 2007).

3.4. Biophysical environment

The biophysical environment, such as the natural fertility of the soil, rainfall, topography, temperature, diseases and pests, determine the feasibility of investments in fertilizer through their effect on profitability and riskiness. Rainfall variability is the most important cause of year-to-year variability in crop production, and farmers living in such areas are highly insecure (Shiferaw et al., 2007). Studies in Ethiopia showed that farmers with degraded and steeps plots don't invest in fertilizer (Bekele and Drake, 2003; Asrat et al., 2004). This has been explained by the positive relationship between slope and level of severity of soil erosion. Plots with greater perceived erosion are not responding to fertilizer as fertilizers are washed away through erosion. The soil fertility status of plots is also an important factor in fertilizer use. Farmers invest more in fertile plots than in infertile ones (Bekele and Drake, 2003). This is because the marginal productivity of fertilizers from plots with fertile soils will be higher than those with less fertile topsoil and are expected to give a higher return in the short term. Generally, areas with good soil fertility and relatively abundant rainfall will have a good agricultural profit and farmers will invest in fertilizers (Alem et al., 2008).

3.5. Lack of capacity to invest in fertilizer

Farmers' capacity to invest in fertilizer depends on the household's landholdings, physical and financial capitals (Demeke et al., 1998). Some of the major factors associated with household overall capacity (and thus fertilizer use) is presented below.

Landholding is one of the critical factors that can represent farmers' livelihood status because land is a major source of wealth and livelihood in Ethiopia. The size and quality of land affect the types and intensity of investments, which are technically feasible and profitable. Farmers with larger plots and farm sizes are more capable of undertaking investments in fertilizer (Just and Zilberman, 1983; Asrat et al., 2004). This is because farmers with more land can take more risks, including relatively high investment, if required, and survive crop failure due to pests, hailstones, and low/excess rainfall (Admassie and Ayele, 2004).

Education level, knowledge and farming experience are important assets for households because the quality of labor which includes the worker's education, technical knowledge and age are important in determining the farmer's ability to make appropriate investment decisions on fertilizer (Admassie and Ayele, 2004). The level of education has been included in many studies as a proxy for the capacity of the head of household to understand technical aspects of fertilizer use (Asfaw and Admassie, 2004). In most of the studies, higher education levels were associated with more access to information on fertilizers and their benefits (Tadesse, 2014). Longer schooling of the household head increased their ability to access information, gave them a better understanding of new technologies and strengthened his/her analytical capabilities with new technologies (Swinton and Quiroz, 2003). Many authors report that education had a positive impact on investments in improved agricultural technologies such as fertilizer and improved seed (Fufa and Hassan, 2006; Tamene et al., 2015; Mponela et al., 2016).

Physical capital to invest in fertilizer include the ecological factors, infrastructures and physical characteristics of plots. Steeper plots were more susceptible to erosion and decreased the incentive to invest in fertilizer (Yusuf and Köhlin, 2008). The greater the land degradation in a village, the less likely the resident farmers would be to invest in fertilizer (Matsumoto and Yamano, 2010). Empirical studies revealed that distance from homesteads to farmers'

fields affected the intensity of fertilizer use in Ethiopia (Pender and Gebremedhin, 2007). Studies have showed that farmers are more likely to invest in fertilizer on plots closer to their residence as they have better access to supervise and manage their nearby plots compared to distant plots (Fufa and Hassan, 2006).

Financial capital consists of cash and liquefiable assets, such as livestock and crop sales that are used to finance an investment in fertilizer. Livestock and crop sales, off-farm activities and credit are the main sources of cash for Ethiopian farmers (Pender and Gebremedhin, 2007; Tadesse, 2014). Livestock husbandry is a boon to farm investments as it provides cash income (Hayes, 1997). However, the effect of livestock on investment in fertilizer is mixed. The effect of large livestock size discouraged investment in fertilizer (Fufa and Hassan, 2006; Matsumoto and Yamano, 2010). This was because households focused more on livestock than on crop production due to its relative profitability. Ownership of livestock was associated with greater use of fertilizer, probably because income generated from livestock products helped farmers to afford to buy inputs (Pender and Gebremedhin, 2007).

The availability of credit also determined the level of the level of adoption of fertilizer in Ethiopia (Yirga, 2007; Tadesse, 2014). Farmers who had good access and information to credit were more likely to invest in inputs and other technological uses; 'cash' was the major constraint of smallholder farmers in Africa.

3.6. External factors/conditioners of incentive and capacity variables

External factors include those which are beyond the control of farmers and which are relevant to policy makers. These factors affect investments in fertilizer through their effect in influencing farmers' incentives and capacities to invest in fertilizer. The external factors common to all households in a particular agro-climatic/policy context includes: a lack of appropriate fertilizer, limited extension services, poor agricultural policies, weak institutional collaboration, and poor infrastructure (Getinet, 2008). Below we present some of the external factors that influence farmers' use of fertilizers.

Lack of (appropriate) technology/fertilizer limits farmers' investment in the use of fertilizer by reducing the profitability and increasing riskiness of their investments (Vallaeys et al., 1987). Some authors reported that technologies in SSA are lacking and that the available technologies are not appropriate because they often fail to consider biophysical, socioeconomic and policy factors (Crane and Traore, 2005). A lack of access to appropriate fertilizer are also major constraints to farmers in the country (Carlsson et al., 2005; Yusuf and Köhlin, 2008).

Extension services promote adoption and cut the cost of using new agricultural technologies (Dercon and Christiaensen, 2007). Most of the studies in Ethiopia revealed that farmers who have close contact with extension workers adopt fertilizers (Aune and Bationo, 2008; Wale, 2008). The number of visits of farmers by extension agents significantly affected farmers' investment in fertilizers (Benin and Pender, 2001; Wale, 2008).

The effectiveness of fertilizer use depended on how *institutions* work together to provide technical support to farmers (Dercon and Christiaensen, 2007). However, lack of transparency, accountability, capacity, access to information and networking were main features of many institutions in Ethiopia (Getinet, 2008). Imperfect institutional arrangements also affected agricultural technology adoption by smallholder farmers (Yu et al., 2011).

Agricultural growth in Ethiopia has been constrained by many deficiencies in agricultural output marketing and input supply systems due to inadequate *physical infrastructure* (Spencer, 1996). Most farmers in Ethiopia have insufficient access to markets because they are producing in remote areas and roads are in poor condition or are nonexistent (Spencer, 1996). The quality and quantity of roads affect transaction costs, risk and price fluctuations, and nonfarm activities. Transport and communication infrastructure determines the availability of information, access to markets, and costs and returns of investments. Better access to roads and markets promotes higher income per capita by providing greater economic opportunities to rural households and in turn, investment in fertilizer (Carlsson et al., 2005). Poor infrastructure increases the prices of fertilizer and reduces the agricultural output, which further diminishes the profitability of fertilizer (Shiferaw et al., 2007). An increase in the price of agricultural products may make fertilizer investment profitable or attractive to farmers. Accordingly, some studies found a positive relationship between an increase in the price of agricultural produce and adoption of fertilizer in Ethiopia (Shiferaw and Holden, 2000).

Policy plays a pivotal role in the use of fertilizer by creating enabling conditions for investment in land. Macro and micro policies directly and indirectly affect output and input prices, and hence net and relative returns to investments (Shiferaw and Holden, 2000). Generally, price and credit policies are changing dramatically and frequently in Ethiopia and farmers do not know how to plan and tend to avoid making on-farm investments such as fertilizer and improved seed (Carlsson et al., 2005; Tadesse, 2014).

3.7. Additional challenges

Another challenge in the adoption of chemical fertilizer is the apparent shift of farmers from natural fertilizers to chemical fertilizers, arguably due to the high intensity of promotion of chemical fertilizers by various stakeholders. Between 2005/6 and 2013/14, land treated by natural fertilizers in Ethiopia decreased by 12.4% (CSA, 2006, 2014). This requires attention as continuous application of chemical fertilizer alone could not bring about the intended impacts without associated trade-offs such as pollution. A second challenge is that the campaign of distribution of chemical fertilizer to farmers may make it difficult to assess the impact of applications of chemical fertilizer on crop yields. Application of fertilizer should be purposeful, and farmers need to trust in its positive effects. This calls for identification of potential areas and informed farmers on the role of chemical fertilizers. Awareness creation can make the interventions useful and sustainable. Lastly, agricultural transformation cannot be achieved without overall structural transformation that presupposes industrialization. Agriculture can benefit from a mutual interaction between the agricultural sector and the nonagricultural sector. High demand for agricultural outputs guaranties purposeful demand for fertilizer. Outmigration of labor from the agricultural sector in search of better wages in the nonagricultural sector help to accompany the increase in yield due to the use of chemical fertilizer with labor productivity – a sign of durable rural livelihood. Industrialization ensures the provision of the agricultural sector with agricultural inputs at lower prices, thereby increasing overall agricultural capabilities.

4. Conclusion

Despite increasing trends over time, fertilizer use in Ethiopia is still at a relatively low level and rate.

Biophysical, socioeconomic, policy and institutional factors contribute to the limited fertilizer use and adoption in the country. Decisions on fertilizer adoption by small farmers are rational decisions about technological choice and their reason for not using fertilizers should be heard. Farmers' indigenous knowledge for instance shows that they prefer to avoid applying natural fertilizer such as manure during periods of low precipitation. The applications of chemical fertilizers depends on access to water, and use of improved seeds, soil management, planting techniques, and pesticides. The use of chemical fertilizer has financial costs. If the terms of trade turns against farmers in the market during a bumper harvest, profitability would decline, threatening future use of fertilizer. Thus, plans that target an increase in agricultural yield due to application of chemical fertilizer also must target markets that maintain a stable price. Both researchers, policy makers, NGOs, development organizations, and the government should work closely to make sure that the right type and amount of fertilizer is applied to the appropriate soil type and at the right time, so that is become profitable and sustainable.

The move from no fertilizer use to blanket application is a step forward and recent interventions in soil mapping will change the long tradition of relying on the same types of chemical fertilizers, with little or no focus on soil type. The use of fertilizer at a national level is a huge investment. Most of the annual supply of fertilizer needed by the country is imported; this means that fertilizer adoption is an expensive investment for the national economy. A careful cost-benefit analysis must be carried out on the different agro-ecological zones, and crops chemical fertilizers should be used. The recent shift towards establishing fertilizer blending companies is commendable. However, concerted effort should be made to make sure that the right combinations (and rates) of fertilizer are 'blended' as generally factories tend to desire for more profit for optimum combinations with less attentions paid to return for farmers. Research institutions in the country should be consulted (and brought together) to make sure that what is proposed and being promoted brings socioeconomic rewards without compromising the integrity of the environment. It will also be hugely important to create forum and database to share experiences and data sets related to fertilizer application rates to facilitate decision making related to site- and context-specific fertilizer recommendations.

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Section 5

Efforts and challenges related to acid soil management in Ethiopia

Biyensa Gurmessa (CIAT) and Degefie Tibebe (EIAR)

1. Introduction

About 40% of the total land area of Ethiopia is acidic (Abdenna et al., 2007; Taye, 2007). Of this, about 27% is moderately to weakly acidic with a pH of 5.5–6.7, while the remaining 13% is strongly to moderately acidic with a pH of <5.5 (Schlede, 1989 *in* Mesfin, 2007). A total of 28% of all agricultural land is estimated to be acidic, with a significant impact on crop productivity. Most of the areas affected by soil acidity in Ethiopia occupy the highlands where wheat, maize, and teff are grown. These areas are characterized as those with the highest annual rainfall. The southwestern and northwestern parts of the country, where nitosols and alfisols dominate, are reported to be acidic to a level that could limit productivity.

Soil acidity is a natural phenomenon that can be managed for better agricultural productivity or worsened by poor management practices. It can be caused by several factors, from the nature of the soil and climatic conditions (mainly rainfall) to anthropogenic factors such as poor soil and crop management practices. Acidity in most tropical soils is caused when the parent material is acidic or has low basic cations naturally. Intensive cultivation, continuous tillage, and/or excessive application of urea or other fertilizers that are sources of nitrate, crop residue removal, land-use change and monocropping of legumes, all exacerbate soil acidity exchangeable Al^{3+} on arable and abandoned lands (Rengel, 2003; Negassa and Hiluf, 2006).

Soil acidity limits or reduces crop production primarily by impairing root growth and reducing nutrient and water uptake (Marschner, 1995). Acid soils also create toxicity in soil solution that hinders growth of plants and results in poor crop yield. The toxicity hinders the growth of roots, microorganism activity, and results in soil compaction and water erosion (Fageria and Baligar, 2008). Moreover, low pH converts the available soil nutrients into unavailable forms and acidic soils are poor in basic cations such as Ca, K, Mg, and some micronutrients that are essential to crop growth and development (Tisdale et al., 1985; Wang et. al., 2006). Crops grown on acidic soils can be stunted and are not very responsive to fertilizers, which causes their productivity to be low. Farmers in these areas tend to apply higher rates of fertilizers than the blanket recommendation (100 kg DAP and 100 kg urea) as the soils are not responsive to low rates of fertilizer applications.

The impact of soil acidity on wheat production is estimated to cost Ethiopia over ETB 9 billion per year (MoA/EIAR, 2014). To tackle this problem, the national agricultural research system (NARS) in partnership with the Ministry of Agriculture (MoA) and regional bureaus of agriculture in the acid affected regions of Ethiopia have been testing, developing and promoting ISFM practices suitable for the high rainfall, acid-prone farming systems of the highlands (Abebe, 2007; Haile, and Boke, 2011a, 2011b). Consequently, Ethiopia has established an acid soil reclamation system to ensure that lime is produced and distributed to farmers and has developed acid soil management packages and launched demonstrations to increase awareness and adoption of liming practices. Despite these initiatives, the lime application rate has fallen far short of GTP I goals, with only 6% of planned agricultural lands receiving liming treatment, and only 7% of farmers who were targeted to carry out liming doing so (MoA/EIAR, 2014). In addition, the number of farmers who adopted liming has been minimum and the challenge is still serious. Liming experiments conducted in different parts of southern Ethiopia also revealed that the application of lime alone did not improve the yield of crops (Wassie et al., 2009; Haile and Boke, 2011a, 2011). The aim of this study is to review the attempts made to reclaim acid soils and the associated challenges in Ethiopia.

2. Methods

We used a literature review of published materials (including online resources) to collected the literature and review the research work on the soil acidity problem and its management in Ethiopia. We used Google Scholar and key words and phrases such as 'lime application in Ethiopia', 'soil acidity in Ethiopia' and 'soil management practices in Ethiopia'. In addition, we contacted scientists and project leaders who have worked/contributed to soil acidity related issues in the country. Once the key publications were

acquired, we presented the findings of studies that aimed to enhance pH, reduce exchangeable acidity, reduce Al toxicity and increase crop yield. We also analyzed and presented the effects of liming on crop yield based on a summary of the research results, taking the control (no lime applied) as a reference. Moreover, the research results of the effects of integrated application of liming and other organic and inorganic fertilizers was also presented. Key reviews of the challenges of acid soil management and the necessary policy and institutional set-ups for successful management of acid soils in the country were also presented. However, due to time constraints, we were unable to review and discuss the results of all the studies and research outcomes related to acid soil management in Ethiopia.

3. Areas prone to soil acidity in Ethiopia

3.1. Soil pH distribution in Ethiopia

Soil pH is a useful indicator of the relative acidity or alkalinity of a soil. The pH scale ranges from 0 to 14, and the soil is assigned a value from the pH scale to describe its acidity or alkalinity. A pH values of 7 which falls midway along the scale is considered neutral, while pH values that fall below 7 are acidic and those above 7 are alkaline. The southwestern part of Ethiopia is the most productive and the most prone to acidity in the country (Figure 5.1). The area covers parts of Wollega, Jimma and Ilubabor from Oromia region, and Gojjam, Southern Amhara region. The region is a mixed cereal-based farming system. The most widely grown crops in the area are maize, wheat and teff. The pH ranges from < 5 to 6, with most of the areas having a pH value of 5.5–6.0, which is conducive to most of the crops grown in these areas (Stevens et al., 2010). These soils are fragile and could gradually become acidic if they are not managed properly.
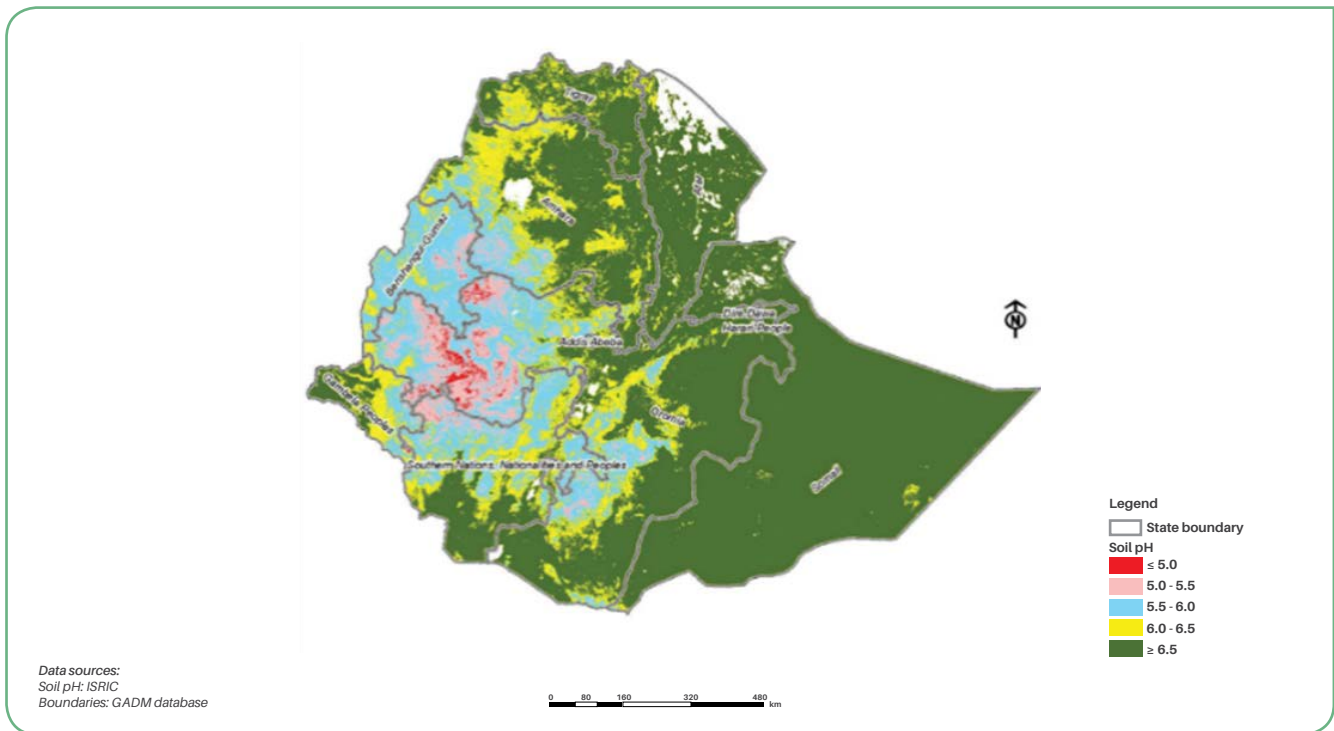
Figure 5.1   pH of soils in Ethiopia, mapped from the ISRIC model.
Source: Hengl et al. (2015).

Soil acidification occurs because the concentration of hydrogen ions in the soil increases. Some of the major causes of acidity include: frequent tillage, removal of crop residues and monocropping, which speed up the decomposition of soil organic matter, which has a strong affinity for H^+ that would help reduce H^+ from the soil solution. Frequent application of inorganic N would enhance soil acidity in the long term, especially when residue or organic incorporation is low (Cai et al., 2015). Nitrogen containing fertilizers such as urea releases H+ by the nitrification process, decreasing soil pH (Fageria and Baligar 2008; Cai et al., 2015). In Ethiopia, most farmers apply urea as a source of N, and a significant amount of H^+ is released into the soil solution. The rate of urea application is increasing over time as soils have become less responsive to the business-as-usual application.

Frequent tillage enhances microbial activities in soils; this is turn accelerates the decomposition of soil organic matter which is a buffer zone for soil health. The absence of organic matter that has affinity to H^+ because of its rich negative charge sites, could leave high concentration of H^+ in soil solution. High H^+ means low pH. This low pH condition creates Al^{3+} toxicity that reduces the availability of nutrients to crops even if fertilizers are applied.

3.2. Aluminum concentration distribution in Ethiopian soils

Aluminium is generally present in soils in a variety of forms and is bound to the soil constituents, particularly clay particles and organic matter. When soil pH drops, Al becomes soluble and the amount of Al in the soil solution increases. Aluminum concentration is one of the indicators of soil acidity (Rengel, 2003). Soil aluminium concentration of 2–5 parts per million (ppm) is toxic to the roots of sensitive plant species and above 5 ppm is toxic to tolerant species. A high concentration of Al in acidic soils means the soil is toxic to plant growth. Most areas (except Somali, northern Borena and most areas of southern and northern Tigray regions) are saturated with Al (Figure 5.2). However, Al concentration is not a direct indictor for Al toxicity, but Al toxicity occurs in acidic soils. Such overlaps occur in Eastern Benishangul, Western Oromia and Southern Gojjam (Figures 6.1 and 6.2). If the current land mismanagement practices are not altered, the areas under acidic soil conditions could expand, creating conditions for the occurrence of wider Al toxicity.
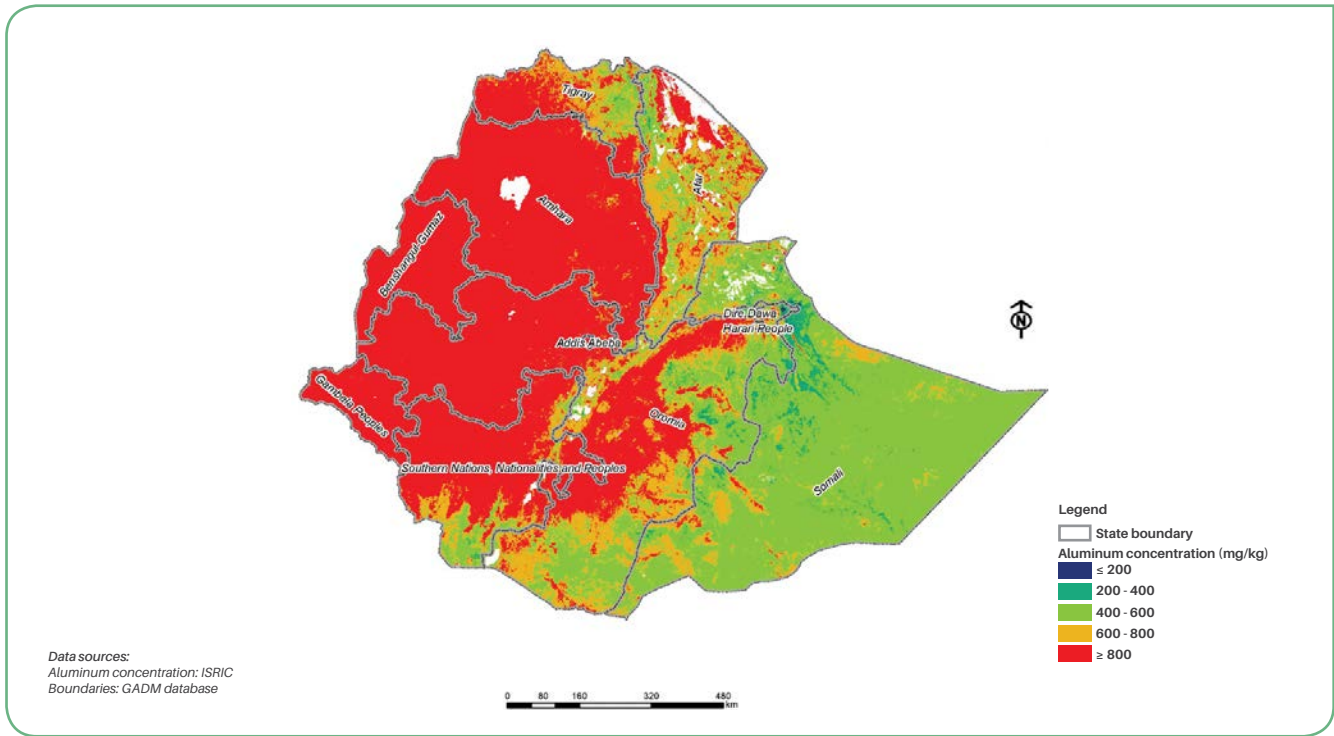
Figure 5.2 Al concentration (mg kg^{-1}) of soils in Ethiopia based on ISRIC (Hengl et al., 2015).

4. Strategies to tackle acidic soil challenges

4.1. Liming to improve soil properties

The rehabilitation of acid soils requires us to: reduce soil acidity; address poor soil fertility conditions; and managing soil organic matter (Myers and De Pauw, 1995; Lopes et al., 2004). One of the primary interventions needed to rehabilitate acid soils is the application of lime. Lime can shift soil acidity towards neutral levels and render nutrients more available to crops as well as reduce or eliminate Al toxicity (Figure 5.3a). Lime amounts of 2–5 t ha^{-1} are typically needed to neutralize acid soils sufficiently for crop production, depending on the soil types and levels of acidity (Peterson, 1971; Anderson et al., 2013). However, the amount of lime required to raise soil pH depends on the type of lime, the previous land use and the pH status before lime application. Moreover, the subsurface soil condition should be known before determining the amount of lime that needs to be applied. Low pH subsurface soils (below 10 cm depth) are the most detrimental to plant root growth that could significantly reduce the crop productivity. Thus, in areas with low pH soils in the subsurface layer, a low-dose application of lime may not neutralize Al toxicity and would not support the plant growth (Calegari et al., 2013). To see the effect of surface liming, it may be important to treat the subsurface soils with a higher dose of repeated lime application until the required pH level is achieved. When subsurface soils are not properly treated, continuous surface application of lime even in high doses may not bring about the intended result as Ca^{2+} and Mg^{2+} could go below the root zone by leaching or diffusion, and P would remain adsorbed and may not be available to plants.
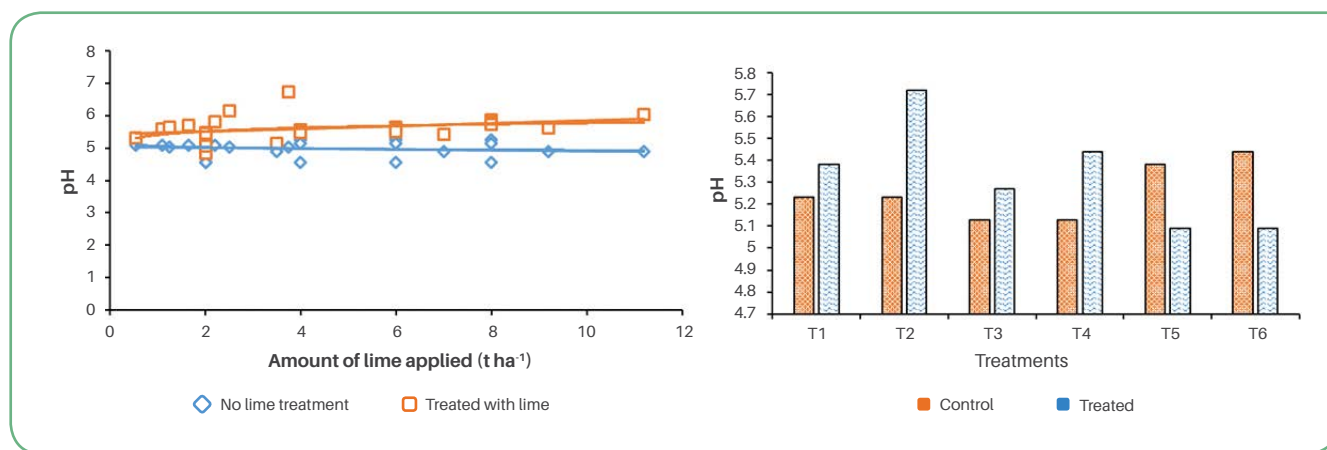
Figure 5.3   Effect of (a) liming and (b) biochar on the pH level of acid soils in Ethiopia. T1= zero chromium + 5 t ha^{-1} biochar, T2 = zero chromium + 10 t ha^{-1} biochar, T3= 10 chromium + 5 t ha^{-1} biochar, T3 = 10 chromium +10 t ha^{-1} biochar, T4 = 20 chromium + 5 t ha^{-1} biochar, T5 = 20 chromium + 10 t ha^{-1} biochar (based on review data).

As an alternative to lime, the application of biochar was also found to improve soil pH (Figure 5.3b). A study by Abewa et al. (2014) showed that the application of biochar and lime as a soil amendment significantly increased yield, even in the absence of fertilizer. For instance, application of 12 t ha^{-1} biochar and 2 t ha^{-1} lime without fertilizer exceeds the full fertilizer rate without amendment in grain yield (Table 5.1). However, increasing soil pH by the same magnitude would require application of more biochar than lime

(Abewa et al., 2014). The effects of liming will not be as long-lasting as that of biochar, especially when the subsurface soil layer acidity was not previously adequately treated (Wang et al., 2013). As a result, integrating lime application with biochar can be beneficial. For instance, a study in Hawaii showed that a combination of moderate application rates of biochar (e.g. 2 to 4%) with lime (an equivalent of exchangeable acidity or about 2 t ha^{-1}) could significantly improve soil quality and increase crop growth (Berek et al., 2011).

Table 5.1   Effect of biochar combined with chemical fertilizer on the yield of teff.

Amendments	Fertilizer rate N/P$_2$O$_5$ (kg ha^{-1})	Grain yield (t ha^{-1}) +	Dry biomass yield (t ha^{-1})
No Amend	0	0.817[h]	9.22[f]
	20/30	1.623[gf]	11.54[def]
	40/60	1.870[ef]	13.89[cde]
4 t ha^{-1} biochar	0	0.959[h]	9.37[f]
	20/30	1.860[f]	14.33[cd]
	40/60	2.354[cde]	15.76[bc]
8 t ha^{-1} biochar	0	1.266[gh]	10.40[ef]
	20/30	1.999[def]	13.59[cde]
	40/60	2.676[abc]	17.03[bc]
12 t ha^{-1} biochar	0	2.413[bcd]	16.15[bc]
	20/30	2.462[bcd]	16.14[bc]
	40/60	3.129[a]	21.04[a]
2 t ha^{-1} Lime	0	2.182[cde]	13.36[cde]
	20/30	2.296[cde]	13.59[cde]
	40/60	2.877[ab]	18.16[ab]
Probability (0.05)		**	**
CV		12.87	12.35

+= Means with the same letter are not significantly different.
Source: Abewa et al. (2014).

Although the effect of acidity can vary by crop type, liming can improve soil productivity by decreasing Al^{3+} and Mn^{2+}, reducing the deficiency of Ca and/or Mg which are otherwise slightly available to crops in the soil solution of acidic soils (Abate et al., 2013; Desalegn et al., 2014; Kassa et al., 2014). Liming also improves desorption of phosphorus from the soil solution and enhances crop response to P fertilizers.

4.2. Liming to enhance crop yield

Soils with a pH less than 5.5 require liming to give better yield (Chimdi et al., 2012; Desalegn et al., 2014;

Desalegn et al., 2016). The effects of liming on crop yield have been studied for several crops (e.g. legumes) (Bekere, 2013; Kifle, 2014) and cereals (Abewa et al., 2014; Dejene, 2015; Balla, 2016) in Ethiopia. Generally, the amount of lime required to raise optimum soil pH depends on the initial properties of the soils. Our synthesis shows that there is an increase in crop yield with application of lime from 0.5 t ha^{-1} despite the unknown level of acidity the respective crops can tolerate (Figure 5.4).
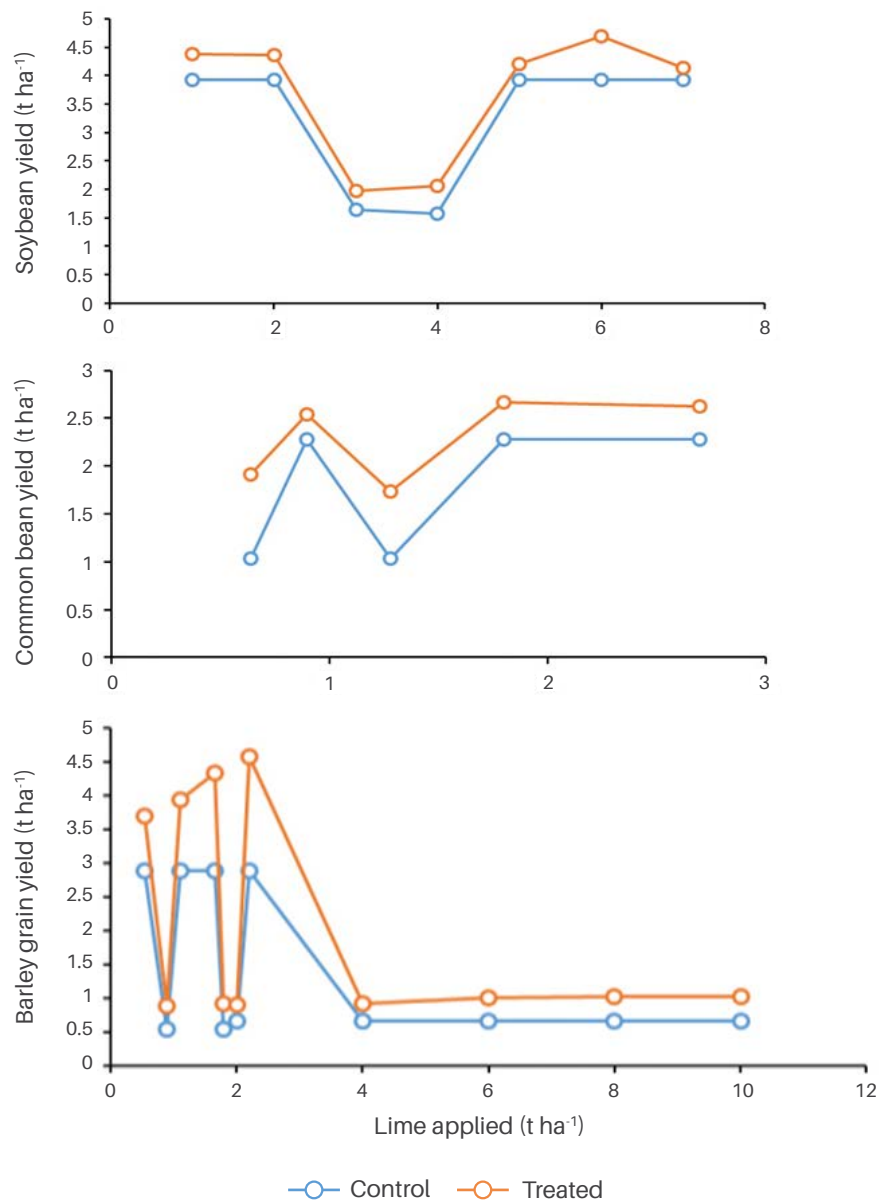

Figure 5.4 Response of crops to lime application.

Table 5.2 shows the relative yield advantage when soils are treated with lime. The yield increase by applying lime over the control (no liming) at the different sites and on the different crops is in the range of 0.24–1.7, 0.2–0.8 and 0.3–0.9 t ha^{-1} for barley, soybean and common bean, respectively (Table 5.2). The response of a given crop to lime application varies from site to site mainly due to differences in soil pH across sites.

Table 5.2   Yield advantage of lime application on acidic soils.

Control	Treated	Difference	Crop	Reference
3.9	4.1	0.2	Soybean	Kifle (2014)
3.9	4.2	0.3	Soybean	Kifle (2014)
1.6	2.0	0.3	Soybean	Kifle (2014)
3.9	4.4	0.4	Soybean	Bekere (2013)
3.9	4.4	0.5	Soybean	Bekere (2013)
1.6	2.1	0.5	Soybean	Kifle (2014)
3.9	4.7	0.8	Soybean	Kifle (2014)
0.7	0.9	0.2	Barley	Chimdi et al. (2012)
0.7	0.9	0.3	Barley	Chimdi et al. (2012)
0.6	0.9	0.3	Barley	Bekele et al. (2015)
0.7	1.0	0.3	Barley	Chimdi et al. (2012)
0.7	1.0	0.4	Barley	Chimdi et al. (2012)
0.7	1.0	0.4	Barley	Chimdi et al. (2012)
0.6	0.9	0.4	Barley	Bekele et al. (2015)
2.9	3.7	0.8	Barley	Desalegn et al. (2016)
2.9	3.9	1.0	Barley	Desalegn et al. (2016)
2.9	4.3	1.4	Barley	Desalegn et al. (2016)
2.9	4.6	1.7	Barley	Desalegn et al. (2016)
2.3	2.5	0.3	Common bean	Balla (2016)
2.3	2.6	0.4	Common bean	Dejene (2015)
2.3	2.7	0.4	Common bean	Dejene (2015)
1.0	1.7	0.7	Common bean	Dejene (2015)
1.0	1.9	0.9	Common bean	Balla (2016)

4.3. Organic amendment practices to improve crop response to acidic soils

In addition to the use of lime, there needs to be a substantial effort put into rebuilding depleted soil fertility. As an alternative option to liming, ISFM practices that combine the application of manure with residue and inorganic fertilizers can improve crop yield on acid soils (Fageria and Baligar, 2008; Xiao et al., 2013; Cai et al., 2015). Acid soils, in addition to being poor in many plant nutrients, bind important ones such as P, and render them unavailable to crops. The fertilizer application regime for acid soils differs from that in more neutral soils in that high amounts of P must be applied to counteract the fixation/binding of this nutrient. This also needs to be accompanied by the introduction of high amounts of organic matter into the production system. This can be accomplished through the use of leguminous cover crops (Von Uexkull and Muttert, 1995) that will enhance biological activity in the soil as well as increasing soil nutrients. Al becomes soluble under acidic conditions and can become toxic to crops when present in the soil. Levels of calcium

(Ca) are also often low in these soils. Because lime is incorporated into the topsoil, it does not have much impact on subsoil Al toxicity. This is usually addressed through the application of gypsum, which has sufficient solubility to reach the subsoil; and it also provides Ca and S throughout the soil profile, thus providing nutrients required by crops in addition to addressing Al toxicity. Toma et al. (1999) have demonstrated the long-term benefits of gypsum on crop yields in areas with subsoil acidity.

As indicated above, lime alone may not significantly enhance yield as most soils in the country are depleted of major soil nutrients (Haile and Boke, 2009; Haile et al., 2009). For example, a study by Wassie and Shiferaw (2011) on Irish potato showed that NPK treatment increased the tuber yield by 216 and 183% over the control and lime treatments, respectively. Similarly, NPK + lime treated plots increased the tuber yield of potato by 200 and 168% over the control and lime treated plots, respectively (Wassie and Shiferaw, 2011). It is also shown that improving the soil pH with the application of lime, nitrogen and phosphorous has increased yield three-fold (Beyene, 1987). Another study by Kidanemariam et al. (2013) showed that the applications of combined NP fertilizers and with Wukro and Sheba limes (NP + Wukro lime and NP + Sheba lime) gave significant augmentation over the control by about 239 and 233% in grain yield and by 174 and 172% in total biomass yield, respectively (Table 5.3). Because of the application of NP + Wukro lime and NP + Sheba lime, the grain yield obtained with the application of NP rose by 86 and 90%. Similarly, the grain yield obtained with the application of Wukro and Sheba limes alone increased by 88 and 73% when it was applied in combination with NP. The significant increment in wheat grain yield with the combined application of NP fertilizers and lime, and to some extent, only N and P together with lime showed

that liming not only enhanced soil organic N and P mineralization in acid soils but also facilitated uptake of the applied inorganic N and P fertilizers by the crop. Significant maize yield increment with combined application of lime along with NP fertilizers was also reported in Araka, south Ethiopia (Ayalew, 2011). This shows that lime alone may not result in increased yield, indicating the need for a soil test-based application. If the soils are acidic and depleted of essential nutrients, lime should be applied along with organic or inorganic fertilizers, or both.

In addition to organic and inorganic fertilizers, sustainable land management such as conservation agriculture (CA) such as no till (NT) that could lower frequency of tilling and loss of nutrients and soil organic matter could be essential to tackle soil acidity and enhance crop response to liming in some soils (Caires et al., 2008; Calegari et al., 2013). These practices reduce subsurface and surface soil disturbances and minimize leaching of cations which in turn reduces the acidity and Al toxicity in the soil solution. According to Caires et al. (2008) and Calegari et al. (2013), unlike in tilled acidic soils that require prior subsurface liming to get a response of surface liming, NT practices could respond to surface liming. Crop residues enhance soil organic matter and the organic anions formed during decomposition of the organic matter forms a 'neutralizing house' for H^+ (Wang et al., 2013, Xiao et al., 2013; Aye et al., 2016). Removing the residues for different uses would harm the soil and could create soil health instability (Chowdhury et al., 2015). Integrated application of lime with ISFM and best agronomic practices are essential to tackle both soil nutrient depletion and acidity problems and sustainably enhance crop yield (e.g. Haile and Boke, 2009; Haile et al., 2009; Haile and Boke, 2011a, 2011b, 2012).

Table 5.3 Effect of fertilizers and liming materials on grain yield (mean ± SE) of wheat crop.

Recommended N and P (kg ha⁻¹)	Without lime	Liming material (kg ha⁻¹) Wukro lime (5771)	Sheba lime (8607)	Mean
Grain yield (g pot⁻¹)				
N/P (0/0)	2.09±0.36d	3.69±0.36bc	4.11±0.36bc	3.30
N (46)	2.56±0.36d	3.53±0.36bc	3.43±0.36bc	3.18
P (20)	3.15±0.36c	4.29±0.36bc	4.11±0.36bc	3.85
N/P (46/20)	3.73±0.36bc	6.95±0.36a	7.09±0.36a	5.92
Mean	2.88	4.62	4.69	
Total biomass yield (g pot⁻¹)				
N/P (0/0)	6.65±0.74f	10.80±0.74cd	10.94±0.74cbd	9.46
N (46)	7.62±0.74ef	9.77±0.74d	9.74±0.74ed	9.04
P (20)	9.45±0.74ed	12.39±0.74cb	13.03±0.74b	11.62
N/P (46/20)	10.63±0.74cd	18.11±0.74a	18.19±0.74a	15.64
Mean	8.59	12.77	12.98	

+= Means across rows and columns followed by the same letter(s) are not significantly different at P ☐ 0.05; LSD (0.05) = 1.0176 (grain yield); LSD (0.05) =2.1343 (total biomass yield).
Source: Kidanemariam et al. (2013).

4.4. Breeding strategies for acid soil tolerant crops

The presence of diverse vegetation growing even in acidic soils tells us that there are genetic tolerances in plants. Thus, breeding could be an effective solution to the challenge of soil acidity/Al toxicity although it may take some time to obtain the best breed. Therefore, genetic improvement strategies to enhance plant tolerance to Al toxicity and efficiency in utilizing applied P fertilizers should be put into practice (Zheng, 2010).

In Ethiopia, there is little research work to date on breeding plants for acidic tolerance. However, different suggestions have been put forward. The short-term plan could be to collect germplasm, characterize and evaluate it for Al tolerance. The long-term option is genetic recombination and progeny evaluation using the available genetic resources (Abate et al., 2013). A study was conducted to select potential barley cultivars that could tolerate acidic soils in Jimma, in the western part of the country. Out of 11 cultivars, more than half (8) were acid-tolerant (Sisay and Balemi, 2014). But not all acid-tolerant cultivars were responsive to lime. From the experiment conducted by Sisay and Balemi (2014), out of the eight cultivars that were found to be acid tolerant, only half (4) were responsive to lime. Some

forage varieties were tolerant to soil acidity. But the economic benefits of plants that can adapt to acidity should be investigated as they may not be preferred by or relevant to smallholder farmers.

4.5. Trade-offs between lime application and global climate change

Despite the critical importance of liming to enhance agricultural productivity by improving the toxicity of Al^{3+} and Mn^{2+} oxides and by increasing the Ca^{2+} or Mg^{2+}, it may contribute to greenhouse gas emissions, particularly CO_2 (Aye et al., 2016). This is because liming improves biological activity, which enhances soil respiration by microorganisms, and thereby enhancing CO_2 emission. Moreover, liming enhances the amount of labile C in soils that can be utilized by microorganisms and this would enhance N and C turnover (Aye et al., 2016). Liming could increase microbial SOC content (Aye et al., 2016) and moderate soil structure supporting the formation of caly-organic matter bonds (clay-Ca^{2+}-SOM/SOC) that would be difficult for microbes to break. Liming could also improve biomass yield either in arable land or grasslands and contribute to C sequestration.

4.6. Policies and strategies to liming in Ethiopia

Studies in Ethiopia and elsewhere in Africa indicate that technological interventions and technical advice alone, in the absence of a favorable policy environment, do not bring the desired widespread adoption of agricultural technologies (Sanginga et al., 2004; Yirga et al., 2014). We need to put in place infrastructural and policy support at different levels for technical interventions to address the problem of acid soils (Ayarza et al., 2007). For example, the substantial amount of lime required to treat acid soils (2–5 t ha^{-1}) requires a robust and well-functioning infrastructure to excavate, crush, transport, and distribute it across the areas affected by soil acidity. Moreover, farmers would need to include lime as an additional required input , as well as last-mile transport, application, and incorporation into their fields. There is thus a need for institutional best practices to complement the technical ones. From the perspective of the production and transport of lime, for example, we need to establish an appropriate incentive mechanism for the participation of the private sector and for setting up public-private partnerships that can deliver lime. In addition, from the farm-level perspective, a strong credit scheme that facilitates the purchase and application of lime should be put in place (Warner et al., 2016). Based on experiences from other countries, some of the preconditions to be satisfied for acid soil management include: technical support (research institutions as well as specific institutes to coordinate and contribute to rehabilitating acid soils), infrastructure (transport, machinery), other macronutrients and micronutrients, financial credit, and monitoring and evaluation (Warner et al., 2016).

Ethiopia has taken some deliberate policy decisions to address the country's soil acidity problem. Some of these actions, such as providing lime at subsidized prices, are essential interventions. However, it is important to examine whether these decisions are leading to the most efficient pathways of achieving the policy goal – i.e. treating the country's acidic soils in a cost-effective and welfare maximizing way. The country has planned to rehabilitate 226,000 ha of agricultural land by the end of the GTP II period. Three broad aspects of cost-effectiveness analysis should be considered (Warner et al., 2016): (a) the benefits of treating acid soils with lime, (b) the value chain efficiency (i.e. the effectiveness of delivering lime to farmers), and (c) the behavioral responses of farmers (i.e. willingness to pay/adopt the lime technology).

5. Conclusion

Agricultural research and development efforts in Ethiopia that have shown breakthroughs in acid soil management were achieved using ISFM practices involving agricultural lime. Liming is a soil management practice essential for correcting low pH and aluminum toxicity and increasing the availability of P, Mo and N nutrients, with a dramatic effect on crop productivity (Yamada, 2005; Abebe, 2008; Ayalew, 2011). Lime used in conjunction with other complementary agricultural practices/inputs, offers substantial yield improvements. Analysis of net farm returns to lime application based on experimental results suggest that the application of lime is generally profitable, particularly when it is used in moderate amounts in conjunction with other improved agricultural practices (i.e. use of inorganic fertilizers, high yielding varieties and associated better agronomic practices). These studies create a range of estimated annual gross and net returns to be between ETB 7,524–8,000 per ha and ETB 1,900–2,324 per ha, respectively (Warner et al., 2016).

However, the level of current lime use for reducing soil acidity is very low in Ethiopia. According to the MoANR, as of 2015 production year, lime use is restricted to about 5,100 ha. In GTP II, the Ethiopian government plans to rehabilitate about 226,000 ha of agricultural land by expanding the production, distribution, and promotion of lime by smallholder farmers. Achieving widespread adoption of lime, especially where soil acidity is severe, will depend on addressing the challenges along the lime value chain. The key aspects of the lime value chain that should be considered include: improvements in extraction and processing of raw lime, transportation and distribution of processed lime, research for development, and improvements in support services (e.g. information provision and credit). Based on a detailed study of sites with predominantly acid soils, Warner et al. (2016) suggested the following approaches to achieve overall success of the lime program.

- Exploring, locating, and developing the raw materials required to produce lime should be done systematically involving a wide array of stakeholders including the private sector.

- Because lime processing facilities are often situated in distant locations, we need to coordinate the transportation and distribution of lime to smallholder farmers, who often live in scattered locations.

- Research and extension activities should be conducted in a coordinated fashion to demonstrate the benefits (i.e. desirability and profitability) of lime to farmers and other stakeholders (e.g. fertilizer dealers, mainly cooperatives).

- Credit and insurance services are critical in helping often cash-constrained farmers to purchase the required quantities of lime as well as complementary inputs.

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Photo: Georgina Smith/CIAT

Section 6

Notes on the national workshop on evidence generation for integrated soil fertility management practices in Ethiopia

Addisu Asfaw (ILRI)[4] and Lulseged Tamene (CIAT)

1.   Background

Soil nutrient depletion due to soil erosion, nutrient mining, and limited input use in Ethiopia is a major bottleneck to land productivity. Integrated soil fertility management (ISFM) at farm/plot level is required to improve overall system productivity, enhance yield, and improve food security. Soil fertility amendment practices have been implemented in Ethiopia since the 1970s. As a result, the application of fertilizer in the country has evolved from 'blanket' application to soil type-based recommendations. However, there is still a need to develop soil test-based, site-specific fertilizer recommendations. For this, it will be essential to critically assess results of crop response to fertilizer application conducted across the country. Against this background, the GIZ Ethiopia Soil Health Program supported CIAT and ICRISAT to collate and document existing information related to crop response to input use and evaluate its profitability. Accordingly, CIAT, ICRISAT, and EIAR were engaged in collating all available crop response data and present the results at a national workshop. This section summarizes the

presentations made and discussions held during the 2-day workshop conducted in the period 1–2 December 2016 in Addis Ababa. This report only focuses on key results and discussion points. Details are published in a special issue of the Ethiopian Journal of Natural Resources (EJNR), Vol. 16, Number 1 & 2, 2017.

2.   Welcome address

The welcome address was delivered by Mr Gebreyes Gurmu from EIAR. After recognizing and welcoming participants, Mr Gebreyes highlighted the major challenges of soil fertility in the country's agricultural productivity and the various efforts conducted to remedy the challenges. Among the various efforts and stakeholder engagements made, he focused on recapping on the December 2015 workshop outputs organized at the ILRI campus and its linkages with the current workshop. He highlighted the establishment of a task force that aims to develop sustainable soil management interventions and decision strategies to standardize and finetune fertilizer recommendations in Ethiopia. CIAT was tasked to lead reviewing and documenting crop response to organic and inorganic inputs in different agro-ecological zones and farming systems in the country. While CIAT was engaged to

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4   Addisu is part of the Africa RISING team coordinating Bale project implementation. He participated during the workshop and took the workshop minutes and compiled notes.

review and collate existing information in the literature and to conduct a meta-analysis, EIAR was assigned to review the response to fertilizer of major crop commodities. After thanking CIAT for engaging EIAR in this important endeavor and appreciating the effort of the various scientists, Mr Gebreyes called upon Dr Fantahun Mengistu, the DG of EIAR, to make his opening speech.

3.   Opening remarks

Dr Fantahun started his opening speech by extending a warm welcome to all the participants of the workshop. In his speech, Dr Fantahun highlighted the role played by agriculture in GTP-I and the challenges facing the sector. The main points raised included the declining of existing ecosystems of Ethiopia over time due to human and livestock population pressure; expansion of farmlands and unsustainable land management practices; competing use of crop residues with other services resulting in nutrient deficiency in the soil; and land degradation in the form of soil fertility, erosion, acidity, etc., becoming serious obstacles in agricultural productivity. Dr Fantahun also indicated the need to transform the agricultural system through technological progress and innovations such as improved seeds, fertilizers, and best agronomic practices, etc. He highlighted the need to perceive a carbon neutral economic development in line with a climate-resilient green economy strategy of the country. He stressed that unless investment was made in the improvement of agricultural productivity, it would not be possible to achieve the objectives set out by the country to transform from an agricultural-led to an industrial-led economy. He also mentioned the soil nutrient mitigation strategy that the country has been implementing over the last 50 years. Dr Fantahun stated that about 56% of the cultivated land was targeted by organic fertilizer while the remainder was targeted by inorganic fertilizer. The country has been using inorganic fertilizers (DAP and urea alone) until recently and now there is a need for site-specific application. The Ministry of Agriculture and Natural Resources (MoANR) in collaboration with ATA came up with this required fertilizers and promising results have been observed so far. Along with these successes, there is a need for best agricultural and soil nutrient management practices to supplement the achieved results. In line with this, he stressed that a considerable output was expected from the National Workshop and called upon all the participants to actively participate and come up with concrete policy and extension recommendations at the end of the workshop.

4.   Objective of the workshop

The objective of the workshop was briefly presented by Dr Lulseged Tamene from CIAT. He started by acknowledging the contribution of key partners such as GIZ; ILRI through Africa RISING; CIAT, ICRISAT and EIAR who were instrumental in making the workshop a reality. He also reminded everyone that during the discussions held during the last workshop it was recognized that there were numerous research results carried out by different national and international researchers, higher institutions, and students, among others. However, there was a limitation in accessing and referring those research results that were available in different libraries across the country. It was agreed to review all these research results available and contextualize the situation and develop a benchmark for site- and context-specific fertilizer recommendations. For this work, three institutes (EIAR, CIAT and ICRISAT) were engaged to collate existing data, establish a task force, and organize workshops that could lead to data sharing, database development and standardization of agronomic trial establishment and data analysis protocols. EIAR was mainly tasked with assigning its key researchers to conduct a review of existing 'crop response to fertilizer' and present their findings in such a forum. Dr Lulseged mentioned that the overall aim of the workshop was to discuss the results to contribute towards developing site- and context-specific fertilizer recommendations.

5.   PowerPoint presentations

Over the 2 days, a total of 12 research results and reviewed papers were presented. Details are available in the PowerPoint presentations and a separate workshop report. In this section, major issues raised and deliberations made are presented.

6.   What we have achieved and where we go from here

Dr Teklu Hirkosa who facilitated the session started by explaining the major objectives: assess what we have seen during these 2 days and combine with our experiences and try to suggest recommendations for research, extension and policy. He stated that a lot of very good presentations were made and plenty of

exchanges made during the workshop and in between the breaks. He highlighted that it will be very critical that the experts who attended the workshop come up with relevant recommendations that can promote the agricultural system in the country. He said that it is our responsibility to suggest useful, feasible and relevant recommendations based on our research. He also pointed out that the organizers and EIAR should follow-up implementation of suggestions.

After these brief remarks, the following observations have been highlighted to guide the discussion:

- Landscape approach – we may have different options of landscape models (hillside-mid-slope-foot-slope/ plateau-mid-slope-foot-slope) – with a need to make sure that relevant co-variates are considered

- Sensor-based studies, especially for N

- Initiatives to develop DSST for extension

- Soil test-based, context-specific recommendations

- Initiatives to manage acid soils including liming and soil fertility

- Initiatives on micronutrients

- Crop response to fertilizer is not always guaranteed- 4 scenarios: low yield – no response, low yield – response, high yield – no response, high yield – response

- Crop response N>P>K/S

- Huge information and data in the country – not well digested

- Idea and effort to develop database is commendable

In addition, the following major gaps have been identified:

- Soil fertility research tends to be more on agronomy than on soil science

- Some major crops such as teff are not addressed in the review – but justified

- Only yield impact is reported without looking into soil processes and other confounding factors

- Soil health and environmental implications are not captured

- Site characteristics are less consumed in interpretation of results

- Little attempt to relate soil fertility with nutrition and health

- Limited systems approach – looking at soil fertility in the context of the whole farming system, considering livestock as a source and sink of nutrients

- Soil fertility research under irrigated system is limited

- Interaction between soil moisture and soil fertility by crops/soils not considered adequately

- Limited research on industrial and domestic organic sources of fertilizers

- Lack of a centralized database and documentation system

- Little information on fertilizer use on the environment (soil, water, etc.)

- Recommendations related to soil and water conservation are controversial

- Research related to soil microbiology is limited

- Soil salinity is not considered in soil fertility research

- Limited attention to nutrient recycling with a system and across systems

- Insufficient attention is given to the role of legumes

Based on the positive highlights and gaps observed, detailed deliberations were made and arrived at key recommendations for further research, policy, and extension.

- There is a lack of integration between extension and research, which confuses the farmer. Research is done under EIAR while extension is under MoA. This has resulted in poor linkages between research systems and extension in demonstrating research outputs. A researcher may provide advice, which the extension worker may not know about and may not understand well. The challenge is also related to structural issues – there may be a need to restructure extension and research.

- We mostly have scientific papers or long report outputs that do not appeal to policy makers. It is thus necessary to prepare briefs that policy makers could read and understand.

- Research and extension must be complementary (i.e. the researcher has to analyze and synthesis results and handover to extension and extinction to apply on the ground). For this to happen, researchers should

produce acceptable and easy-to-use manuals and leaflets with suitable guidelines and provide training to the extensions and DAs who will implement the practices/suggestions.

- It is essential to develop technology manual/package for scaling out. This is critical for extension and DAs to properly utilize the technologies.

- There were many cases where farmers did not take on readily available technologies. Maybe the options were not suitable, had trade-offs, or were expensive. We should try to be flexible and offer alternatives when possible. We need to expand our research on this.

- There is a need to reconcile research studies and government policy (matching the research work with the government policy).

- Standardizing methods and techniques of research is essential. It will be crucial to develop a standardize agronomic trial protocol so that data sharing and analysis can be easier.

- Analyzing residual effect of nutrients/fertilizer on precursor crops is needed. In most cases the 'economics' of interventions are not determined well. Thus we don't have clear information to find out if they are feasible. And this affects farmers' adoption. This is key to recognize that economics matters a lot.

- There is no technology releasing mechanism for research outputs related to natural resources. Natural resource management recommendations are not linked to extension. A package developed under SWC/SLM can't be easily sold as the institutional framework doesn't allow it. This affects researchers (less incentive) and extension will miss using good technologies (not officially released and communicated to them). There is thus a need to 'empower' watershed and SWC research.

- Failure to update the recommendations; they can be outdated over time unless there is continuous assessment and updating.

- Developing DSS must be coordinated similar to research to avoid unnecessary repetition and unwise duplication of efforts. There are some projects already engaged in 'developing' DSS related to fertilizer application. Optimizing available models

and contextualizing it to Ethiopian conditions will be necessary. There are many tools out there and it would be good to customize the better ones to our context.

- Extend the research on nutrient water use efficiency.

- Establish a permanent/fixed plot (long-term experiment) considering the gradient ecology

- Partnership issues (NRS, RRS, universities, CGIAR and others) are not well coordinated.

- Transforming the soil analysis system from a manual to an infrared (IR) system. Maybe there is a need to work more in a mobile laboratory and a basic laboratory (coordinate). Develop policies and mechanisms to produce field soil-testing kits on a small scale.

- Need for capacity building (e.g. gap in soil science, lab technicians, DAs, extension). This can include data analysis (biometry, statistical tools, modelling).

- There is also an analytical capacity gap in implementing a full package (of technologies). We need to strengthen the capacity of research institutes (i.e. create an attractive working environment)

- Need to create linkages between research and factories (e.g. blending).

- Need to evaluate the compatibility of agriculture policy with other policies. If there are no complementarities and synergies, there will be an issue of sustainability.

- Developing a standardized database system is essential. This has been observed and discussed many times but so far there has not been much progress. With recent developments in computation power, getting all the data at one central point could hugely enhance the analysis and communication of results. It is necessary to develop policy and build capacity in managing and distributing data.

- Establishing a multi-disciplinary national task force with clear ToR is essential. It may be necessary to establish a task force from different stakeholders to filter the research outputs and make them ready for use by extension workers. But this should be inclusive and not just consist of people who know each other well.

Photo: Georgina Smith/CIAT

Section 7

Conclusions and recommendations

Job Kihara, Lulseged Tamene, and Tilahun Amede

In Ethiopia, grain yield is generally low compared to global and regional standards. This is primarily due to depletion of soil fertility caused by continuous nutrient uptake of crops, low fertilizer use and insufficient organic matter application. Continuous cropping and inadequate replacement of nutrients removed in crop harvest or loss through erosion and leaching are the major causes of soil fertility decline. This is particularly evident in the intensively cultivated, high-potential areas that are mainly concentrated in the highlands of Ethiopia. To rectify this problem, experimentation and research studies have been conducted for a long time.

Since the 1960s when fertilizer was introduced to Ethiopia by the African Highlands Initiative (AHI), research has demonstrated the positive effects of NP fertilizer use on yields. For example, the Freedom from Hunger campaign, assisted by the FAO Fertilizer program (1967–1969), conducted over 940 simple fertilizer demonstration trials on major cereal crops. The Extension and Project Implementation Department (1971–74) implemented more than 1,500 un-replicated NxP factorial fertilizer trials on selected and fenced sites. The Institute of Agriculture Research and the Agricultural Development Department (ADD) implemented a program on newly released crop varieties in a range of agro-ecological zones in Ethiopia with and without mineral fertilizer. The National Field Trials program launched by ADD with the assistance of National Fertilizer Input Unit (NFIU) in 1986 replicated trial designs at field trial sites based on prioritized agro-ecological zones and soil units. It also used to further initiate dispersed simple fertilizer trials in 1988 under smallholder farmers' conditions.

Although the results of the various trails showed significant responses to fertilizer application, the productivity index of N and P was variable, ranging from negligible to considerably positive on different soils for different crops. The yield increase due to fertilizer for the improved varieties was found to be far higher than for the local varieties. Accordingly, different recommendations were made including the blanket recommendation irrespective of crops and soil types (64/20 kg N/P ha^{-1} i.e. urea/DAP 100/100 kg ha^{-1}) and blanket but at soil orders/colors and crop type. With this development, additional efforts were made based on ADD/NFIU (1988–1991) fertilizer demonstration and crop response trials, application of chemical fertilizers remained among the main yield-augmenting technology being aggressively promoted by the government. Furthermore, substantial soil fertility research efforts have been made for major cereal crops since the 1990s by the NARS that include: the Ethiopian Institute of

Agricultural Research, Regional Agricultural Research Institutes, international research centers, and higher learning institutions.

After the 1990s, nationwide major research efforts by MoA and IAR was initiated. This included the fertilizer experiments by EIAR on different Phosphate source fertilizers and P calibration trials. The recent EIAR-ATA joint soil test-based trials are specifically of great development as recommendation will be made on the response, optimum rates, time & method of application for different crops to increase productivity on different soils. These include location specific fertilizer recommendations on different soil types for different crops and varieties and develop 'demand-based' fertilizer blending factors. Major findings thus far showed that progressive but variable increase of grain yield to increased level of NP applications particularly for cereal crops on different soils was found. The effects were particularly pronounced with the first increment of nitrogen and phosphorus than with subsequent increments. Meta-analysis based on data collected across different farming systems and soil types also clearly reflected the responses of crops to NP application (Figure 7.1). With the increasing number of germplasms of different yield potential and response to fertilizer application, researchers have identified better recommendations specific to the germplasms and soils and their agro-ecologies.
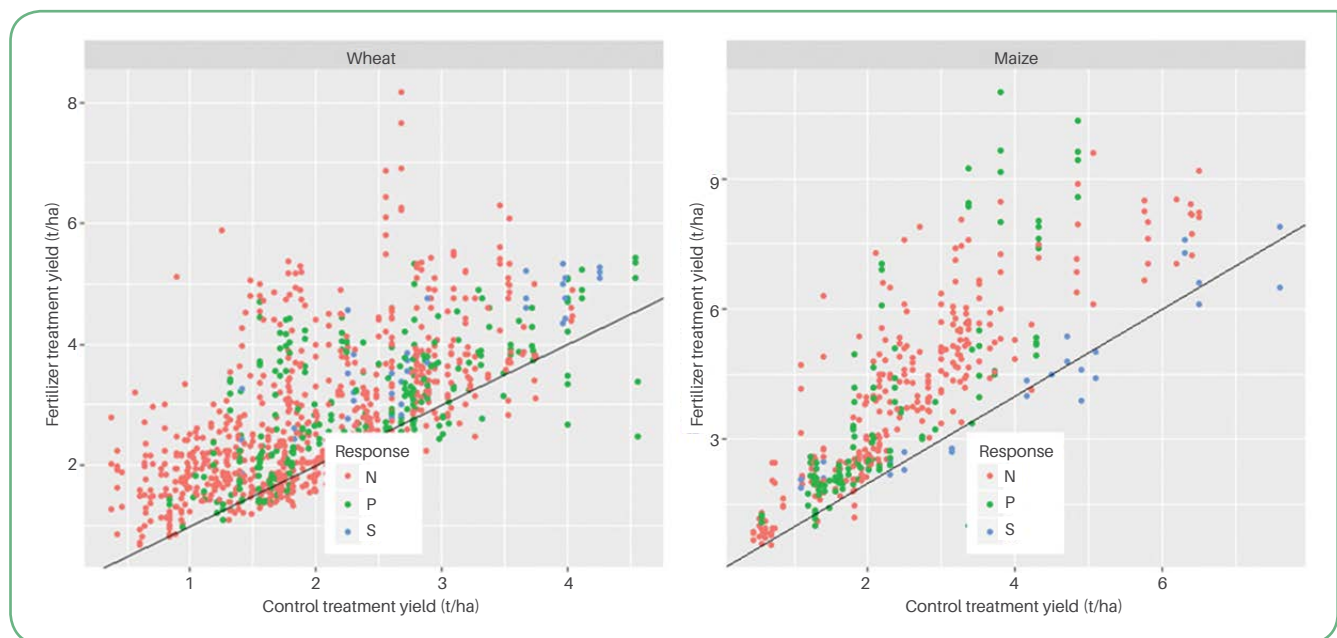

Figure 7.1 N and P response observed in a clear majority of cases i.e. for maize and wheat based on experimental data in different environments.

Note: The responses of these nutrients demonstrate a clear need to contextualize responses (e.g. by application levels, regions, etc.). Clear and interesting wheat response to sulfur is also observed while no clear response is observed for maize.

Despite the tremendous effort to develop fertilizer trials and establish blending factories, evidence show that fertilizer adoption is still limited; this is due to: price, accessibility, risks and absence of detailed site-specific information on the types and rates of applications for different crops under different environmental conditions. Ethiopia has very diversified and complex farming systems and agro-ecological zones and this makes the possibility of developing an applicable fertilizer recommendation tool difficult.

There is also an absence of standardized approaches and no comprehensive database to facilitate data storage, sharing and analysis. Because of this, efforts are duplicated when researchers and institutions try to develop fertilizer recommendations. We need to standardize methods to develop framework that can provide evidence on how changes in soil fertility status across cropping systems, land uses, landscape positions, and rainfall gradients are responding to application of various types and combinations

of organic and inorganic fertilizers and to develop guidelines for innovative and targeted fertilizer recommendations for these rapidly transitioning landscapes.

Until appropriate tools are developed to help tailor the application of fertilizer types and amounts to specific crops, soils types and landscape conditions under different agro-ecological zones, it will be important to continue research to:

- Identify sustainable, profitable fertilizer technology packages, with site-specific nutrient management with the help of decision support tools.

- Verify, demonstrate and pre-scale up of improved inorganic soil fertility management technology and options.

- Enhance the capacity for assessment/interpretation of soil data through improvement of laboratories, human capability and management systems.

- Identify strategic research themes that demand basic study to be conducted by students.

- Update the optimum/economic fertilizer recommendation rates with the dynamic prices of fertilizers and products as well as soil fertility status.

- Major agents of nutrient movement, mainly soil erosion, are minimized through improved management of upper-watersheds. In this case, there could be a need for integrated application of soil and water conservation, afforestation, establishing waterways and other practices through enhancing collective action and farmer innovation.

- Assess the impacts of the various SWC interventions in the country with regard to crop response to input use. The Ethiopian government is investing in SLM/SWC and water harvesting practices. For example, one would ask "how do the various soil conservation measure/interventions affect response to nutrients." SWC measures have become (and continue to be) important parts of the landscapes and we need to contextualize fertilizer recommendations to those. In those areas of the slopes currently considered as unresponsive to fertilizers, one could ask about the length of payback time, after which a response

to fertilizers would be expected. Answering these questions can help us to design better fertilizer recommendations.

- Produce sufficient organic matter within the cropping systems that would satisfy the competing demands of animal feed, household energy and soil fertility management. While increasing biomass through application of mineral fertilizers to crop and forage fields is possible, this may require solutions that could be beyond soil management practices. For instance, introducing fuel-efficient stoves and introducing alternatives energy sources would minimize competition and avail more organic matter for soil fertility improvement.

- Develop effective policy strategies to enable communities to recycle organic resources to valuable nutrients in homesteads and farm niches at household and community levels. This may also demand collective action to collect, processing and market organic resources, particularly in peri-urban settings.

- Need soil ameliorating materials to sustain crop yields, particularly on highly weathered, acidic soils. The integrated use of selected mineral fertilizers and locally available soil amendments is the best approach to achieving higher crop yields, higher fertilizer use efficiency and economic feasibility.

- Establish crop to fertilizer responses that would consider economic returns and socioeconomic requirements. Accordingly, sound soil-test crop response calibration is essential for successful fertilizer promotion for increased crop production. In this regard, the government has already taken initiatives to promote balanced and integrated use of fertilizers. Balanced use of fertilizers based on soil test fertilization would also strengthen soil testing facilities and human resources in the country. This will also help the extension system to advice farmers on the use of correct and balanced use of fertilizers for maximum efficiency and profitability.

- Despite the fact that multi-nutrient fertilizers are available, there is a need to improve on clear recommendations on the crop and location specific rates for different sites.

- Create a national task force that involves all relevant stakeholders and actors in order to facilitate standardized trial establishments and collect relevant management and agronomic practices, develop systematic database for easy storage, sharing and analysis and build capacity of the national research system in data gathering, analysis and intrepretatiom, including introducing digital agronomy and use of Big Data approaches. In order to avoid rudendency and duplication of effort, creating national soil health and agronomic database should be given priority.

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