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The Role of Potassium in Cropping Systems of sub-Saharan Africa: Current Status and Potential for Increasing Productivity

Edited by:
Prof. Tekalign Mamo, Ethiopia

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Atsbaha Gebre-Selassie and Tessema Bakela: A Review of Ethiopian Agriculture:Roles, Policy and Small-scale Farming Systems
http://global-growing.org/sites/default/files/GGC_Ethiopia.pdf

Foreword

In many regions of the world, increasing rates of mineral fertilizer application over the past 50 years have been accompanied by growing crop yields. Consequently, production is usually more than adequate to supply food for both domestic purposes and exports. By marked contrast, however, in most parts of Africa fertilizer application rates have increased at a much lower rate, resulting in relatively poor yields that nowhere near satisfy the demands of a rapidly rising population. On a global scale, demand for agricultural produce is currently at unprecedented levels as a result of increasing populations and consumption *per capita***.** In sub-Saharan Africa (SSA), the world's poorest region, the already high population is set to more than double by 2050 to 2.2 billion. Feeding this huge population increase presents a major challenge to mankind; today, over 200 million Africans are chronically undernourished and 5 million die of hunger every year. To add to these difficulties, are the challenges presented by the impacts of global climate change and the effects of human conflict.

Ethiopia is a mountainous landlocked country in northeastern Africa. It is surrounded by Eritrea to the north and northeast, Djibouti and Somalia to the east, Kenya to the south and Sudan to the west, which all include land situated within SSA. Agriculture is the backbone of the Ethiopian economy. A remarkable feature of this economy is the dominance of small-scale farmers, who cultivate about 95% of the land under agricultural use and are responsible for 90% of total agricultural output. On average, crop production makes up about 60% of agricultural output and provides employment for around 85% of the country's population. Coffee is Ethiopia's leading export, followed by oil seeds, pulses, vegetables and fruits.

The climate in Ethiopia results in a wide range of biodiverse ecosystems, which allows a broad variety of crops to be grown, with about 65% of land potentially fertile for agricultural use. Crops used for home consumption include *eragrostis tef* (teff), sorghum, wheat, lentils, chickpeas and maize. All these crops are rain-fed, but there is great potential for improvements in production with the introduction of irrigation. Ethiopia has been referred to as 'the water tower of East Africa' with ten rivers that are all capable of being used for irrigation, as well as for providing a clean source of electricity. The population is now over 100 million, with a high proportion of young people and a large potential workforce living mainly in the countryside. The human capital and fertile environment in Ethiopia are conducive to improving soil fertility – through measures such as mineral nutrient application – which could greatly improve crop production and food security in the country to meet the future needs of the growing population.

Fertilizers often account for more than 50% of yields produced and, in soils with low nutrient reserves (as in SSA) fertilizer attributable yields can be much higher. An important approach to enhancing food production and security in SSA is therefore related to improving crop fertilization. In Ethiopia, only two types of mineral fertilizers that supply plant nutrients are currently in common use. These are urea, as a source of nitrogen (N), and diammonium phosphate (DAP), which is a source of N and phosphate (P). The application of farmyard manure (FYM) provides a source of potassium (K) for crops, in addition to whatever K may be taken up from the soil. There has been a long-standing perception among agronomists, researchers, extension officers, and advisors.that Ethiopian soils are rich in K. However, in recent years evidence has suggested a possible depletion of K in these soils, which has limited crop growth.

In cooperation with various Ethiopian agronomists, for the last 10 years, the International Potash Institute (IPI) has organized field experiments involving a variety of crops grown on different soils in various regions of Ethiopia. Reports on the findings of these experiments, together with other complementary and relevant review papers, were key to discussions at the 1st IPI-Ministry of Agriculture-Ethiopian ATA joint symposium on "The Role of Potassium in Cropping Systems of sub-Saharan Africa: Current Status and Potential for Increasing Productivity," which was held in Addis Ababa, Ethiopia, 4-5 September 2014.

The eleven chapters produced as a result of these proceedings provide a valuable addition to our knowledge of the role of K in cropping systems in subaqueous soil and its potential for increasing productivity. The experimental findings presented at the symposium provided a clear message about the highly beneficial influence of K fertilization in Ethiopian soils. For example, research findings from field experiments in southern Ethiopia highland (chapter 6) soils, which compared P and N fertilization, both with and without K, showed the dramatic influence of introducing K. Potato tuber yields and wheat grain yields also increased with the addition of K. Interestingly, the experiment found that relatively high applications of potash (150 kg/ha) were required to meet the economic optimum yields for both potato and wheat.

Chemical analysis of Ethiopian soils has determined low values of available K, which also highlights the necessity for K supplements through fertilization. Even in vertisols, which are often high in K, the benefits of small applications of K and P were found for growing wheat (chapter 7) due to the soil's characteristically high fixing capacity for both nutrients. Chapter 9, which specifically deals with soils in Burundi, Mozambique, Rwanda, Uganda and western Kenya, also highlights positive crop responses to K, although in some highly extreme sites, excess soil acidity and a deficiency of other nutrients, including micronutrients, limited the crop response.

Providing balanced crop nutrition is key to increasing yields. Crop nutrient requirements may differ, but numerous observations of many different agricultural crops indicate that they often remove very similar amounts of N and K from the soil. It is only in fruit and vegetable crops that K uptake exceeds N. The role of K in soil-crop relationships can never be overstated, it is an essential plant nutrient involved in physiology, metabolism, growth, development, and thus, in the yield and quality of all crops. K plays a vital role in carbon dioxide fixation by plants, functioning directly or indirectly at various stages during photosynthesis, including light interception and chlorophyll synthesis. K is also closely and essentially linked to nitrate assimilation in plants, as well as protein metabolism. In the vacuole, K plays a key role in the maintenance of turgor and control of stomatal movement. As the predominant cation in plants, K also transports nitrate from roots to shoots and loads assimilates (sucrose and amino acids) into the phloem, which it subsequently transports to the plant's fruits and storage organs. Furthermore, crops well supplied with K are more resistant to biotic (e.g. pest attack) and abiotic (e.g. drought, cold and salt) stresses.

In the processes described above, field observations have found that relatively similar amounts of N and K are always present. In order to optimize yields, soil fertilization involving these two nutrients must therefore ensure they are provided in similar quantities, with the level of supply depending largely on the crop species and K status of the soil. It should be remembered that, while over fertilization of soil with K is undesirable and a waste of nutrient resources, the K ion itself is harmless to the environment. On the other hand, excess application of mineral and organic N fertilizer is highly detrimental to the environment. Nitrifying bacteria in the soil release excess nitrate, which may be leached into deeper aquifers or acted upon by many species of bacteria capable of reducing nitrates into nitrogenous gases (NO N_2O N_2) that may then be released into the atmosphere.

Editing of the symposium proceedings was carried out with great dedication by Professor Takalign Mamo of the Ministry of Agriculture, Addis Abba, Ethiopia and the final draft of the manuscript was ready for publication in late August of this year. Very sadly, and most unexpectedly, however, Professor Mamo passed away on September 4th. This volume is therefore dedicated to his memory as a token of respect.

Ernest A Kirkby
Faculty of Biology, University of Leeds, UK

In Memory of Tekalign Mamo

These proceedings are dedicated to late Professor Tekalign Mamo.

Professor Tekalign Mamo started working with IPI in 2011, at which time, he was also State Minister, Advisor to Ethiopia's Minister of Agriculture and Program Leader for two national projects that he had proposed; the National Soil Fertility Mapping Project and the Fertilizer Blending Project.

Prof. Mamo completed his BSc in plant sciences at the Haramaya University College of Agriculture in Ethiopia, and his MSc and PhD in soil chemistry and fertility at the University of Aberdeen in Scotland. On returning to Ethiopia, his research helped to arrest land degradation, resolve waterlogging problems, tackle soil acidity, transform the fertilizer advisory service, add value to nitrogen use efficiency, and tackle the lack of information about Ethiopia's potassium fertilizer needs.

Prof. Mamo spent his life improving Ethiopian agriculture and received many awards for his contribution to improving soil health. These included the 2016 IFA Normal Borlaug Award, and an award from IPI in 2014 in recognition of his contribution to the advancement of knowledge in potash research in Ethiopia.

The Professor guided and supervised numerous MSc and PhD students in the study of soil fertility. He loved practical science and appreciated those who wanted to apply their scientific knowledge to help farmers grow more and better crops. He often visited rural areas and listened to the farmers in order to address the problems they experienced. As a result of his various work, his name is known among politicians, consultants, agronomists, students and leading farmers in Ethiopia, where he was called 'Prof' by everyone.

We will miss Prof. Mamo for his great energy, endless dedication, and his vast knowledge and experience, as well as for being a dear friend, teacher and colleague. Prof. Mamo leaves behind a beloved wife and two daughters of whom he always spoke proudly. To his family, we extend our heart-felt condolences.

International Potash Institute, Switzerland

Chapter 1

The Role of Potassium in Cropping Systems of sub-Saharan Africa: Current Status and Potential for Increasing Productivity*

*Hillel Magen[1]**, and Ernest A. Kirkby[2]*

The history of mineral fertilization of crops: a brief outline

From ancient times it was recognized that applications of animal manure, bird faeces and plant ash were beneficial to crop growth and soil fertility, although the reason was not understood. It was not until the early part of the 19th century that the fundamental significance of chemical elements on plant growth became clear. In 1807, the English chemist Humphry Davy (1778-1827) demonstrated the isolation of metallic potassium (K) using electrolysis in the Bakerian lecture at the Royal Society in London. In 1828, the German agricultural chemist Carl Sprengel (1787-1859) working on soil humus extracts reported a list of 20 chemical elements including nitrogen (N), phosphorus (P), K, sulfur (S), magnesium (Mg) and calcium (Ca) occurring as various salts in the rooting zone of a large number of soils. These he showed to be the 'real nutrients' that induced crop growth and not humus as had been previously believed. In this investigation, Sprengel also formulated the "Law of the Minimum" which states that if any one growth factor including one of these essential plant nutrients is limiting, improving any other growth factor is without effect. The same law was also proposed independently in two books written in 1840 and 1855 by another agricultural chemist, Justus von Liebig (1803-1873) working in Giessen, Germany, this work becoming better known to agronomists than that of Sprengel. Van der Ploeg *et al.* (1999) and others, however, have rightly rectified Sprengel's role as co-founder of agricultural chemistry with Liebig, and the Law of the Minimum is now referred to as the Sprengel-Liebig Law of the Minimum.

A significant development in the history of plant nutrition was the 57 year long, fruitful collaboration of two Englishmen, John Bennet Lawes (1814-1900) and

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Joseph Henry Gilbert (1817-1901) working on mineral crop nutrition at Rothamsted in Harpenden, England, as described in detail by Holden (1972). An innovative practical farmer full of ideas, Lawes took an interest in applying chemistry to agriculture. One of his greatest achievements was to take out a patent in 1842 for the manufacture of so called 'superphosphate' obtained by the treatment of calcium phosphate with sulphuric acid, a fertilizer still in use as one of the most important sources of P for crop plants. The appointment of the dedicated, trained chemist Gilbert in 1843 to support the experimental work marks the foundation of Rothamsted Experimental Station and the setting up of long-term field experiments to test the effects of different fertilizer combinations and omissions. Valuable results are still being obtained from these field trials which are the oldest in the world.

Throughout the 19th century, farmers were restricted in their choice of N fertilizer largely to Guano (sea bird excrement) imported from islands off the coast of Peru and saltpetre (potassium nitrate) from Chile. Deep concern was expressed that these finite resources would be unable to sustain long-term agriculture and the future needs of the world population. However, in 1909, two German chemists, Fritz Haber (1868-1934) and Carl Bosch (1874-1940) succeeded in synthesizing ammonia from N and hydrogen (H), first in the laboratory then later industrially. The process required a high temperature 450°C, a high atmospheric pressure of 200 atmospheres (200 times greater than atmospheric pressure) and an iron-based catalyst. This successful development meant that a key constraint to crop nutrition had been removed by allowing for the sustainable production of ammonium fertilizers. Both scientists received the Nobel Prize in Chemistry, Haber in 1918 and Bosch in 1931. It has been estimated that without the Haber-Bosch invention world food production would have been reduced by half (Smil, 2011). Nevertheless, as will be discussed later, the use of these N fertilizers requires careful agronomic management to obtain optimal crop yields and quality, as well as to avoid environmental pollution.

A major development in the 20th century of enormous significance to crop nutrition and fertilization was work of the American agronomist Norman Borlaug (1914-2009), Father of the Green Revolution (GR) of the 1960s and recipient of the Nobel Peace Prize in 1970. Working in Mexico from the mid-1940s, Borlaug used innovative techniques in breeding new wheat varieties. These included: the use of so called 'shuttle breeding' utilizing two very different photoperiods available in Mexico; selecting from multi-line varieties each with disease resistant genes; and finally incorporating the Japanese semi-dwarf strongly tillering Norin variety into the programme. In this way, he produced high yielding varieties that could be grown worldwide - varieties which were insensitive to daylight length, resistant to disease and with an abundance of short thick stems capable of supporting high grain yields in response to fertilizers. Using these semi-dwarf wheat varieties produced in Mexico, the GR moved into the Indian sub-continent in the mid-1960s where, in India and Pakistan, wheat yields almost doubled between 1965 and 1970. Other countries in Central America, Asia and Africa also benefitted greatly. The remarkable life of Borlaug and his outstanding scientific contribution has been well written up in three volumes, Vietmeyer (2008), Vietmeyer (2009) and Vietmeyer (2010).

The importance of potassium as a crop nutrient

Potassium is a major plant nutrient involved in the metabolism, growth, development, yield and quality of crops. Deficiency gives rise to problems in numerous physiological functions resulting in poor growth, reduced yield and decreased resistance to various stresses. Potassium activates about 60 enzymes in the cytoplasmic pool including those which control carbohydrate and protein metabolism; the fixation of carbon dioxide (CO_2) in photosynthesis; and the assimilation of nitrate by plants. Potassium in the vacuole plays a key role in water relations in the maintenance of turgor and control of stomatal movement. It is also essential in the regulation of cell growth. In the process of photosynthesis, K functions directly or indirectly at various stages including light interception, CO_2 availability and chlorophyll synthesis. Potassium is the predominant cation in plants and, in this form, functions in the transport of nitrate from root to shoot, as well as the loading of assimilates (sucrose and amino acids) into the phloem and their transport to fruits and storage organs. Crops well supplied with K are more resistant to stresses both biotic (e.g. pest attack) and abiotic (e.g. drought stress, cold stress and salt stress). For details see Cakmak (2005), Oosterhuis *et al.* (2014), Mengel and Kirkby (2001), and Marschner (2012). Potassium and N interact in the processes described above and both nutrients are required in relatively similar amounts. In crop fertilization these two nutrients must therefore be provided in a balanced supply in order to obtain high yields, as well as ensuring the most economic fertilizer use and restricting wastage of N fertilizer to reduce environmental pollution.

The importance of K fertilization for crops was recognized with the founding of the International Potash Institute (IPI) in 1952 in Switzerland. As described by Magen (2012), in a publication commemorating 60 years of its scientific work, the Institute's headquarters were originally located in Berne and research was undertaken with the support and guidance of a scientific board with scientists from 16 European countries. The aim of its agronomists and soil scientists was, and still is, to carry the message of 'Balanced Fertilization' and to demonstrate and disseminate the role of potash in yield performance in bringing more profit to the farmer. Over the years IPI has developed enormously worldwide; currently more than 50 ongoing field experiments and demonstration plots are executed each year and regular seminars, workshops and farmer field days take place. Contact with farmers, and their suppliers and advisors, is seen as a major role of the Institute. International symposia are held regularly demonstrating the essential role of K in optimized crop nutrition. The Institute also publishes quarterly its own online journal, International Fertilizer Correspondent (*e-ifc*). IPI's website also provides an enormous library giving information on many aspects of K in crop nutrition, published in several languages.

The paper presented here discusses the potential role of K supplied together with N and P fertilizers to enhance productivity of cropping systems, with particular reference to sub-Saharan Africa (SSA) and the principles involved in achieving this aim. It also considers, more generally, the global use of fertilizers in food production and the benefits of using fertilizers with greatest efficiency.

Fertilizer consumption

An enormous increase in global consumption of the three mineral fertilizers (N, P_2O_5 and K_2O) has taken place over the past 50 years. From the early 1960s, annual world usage increased steadily through the 1970s and 1980s, declined during 1988-1992 following the breakup of the USSR, but continued to increase rapidly from then on. From a total annual usage of 40 million metric tonnes (Mt) in 1961, consumption increased to as much as 182 Mt per annum by 2013 (Fig. 1A) (IFA). This very high value represents an eightfold increase of N usage (to 110 Mt) with corresponding threefold increases for both P_2O_5 and K_2O to 42 Mt and 30 Mt, respectively. However, in terms of fertilizer usage in various regions of the world, it is very clear that marked differences occur (Fig. 1B) (IFA). It is of immediate interest to observe that only 3% of global fertilizer usage is applied across the entire the continent of Africa - a value that has stagnated over the past 50 years. By contrast, the figure illustrates that the greatest rate in increases of fertilizer usage corresponds to the huge demands of East Asia (mainly China) and, to a lesser extent, to requirements in South Asia and Latin America, including the Caribbean. In West and Central Europe and North America, consumption has more or less stabilized since the early 1990s.

The similar worldwide trends for the consumption of potash (Fig. 1C) (IFA), again shows the high and steadily increasing usage of K_2O in East Asia, and to a lesser extent in South Asia and Latin America, including the Caribbean. The relative decrease in K usage in West and Central Europe and North America from the early 1990s is also obvious. The very low value of only 1.7% of K_2O global usage in Africa is in keeping with the low fertilizer use in general. This value is even lower in SSA because Africa includes countries with reasonable average potash usage per unit area i.e. the Republic of South Africa (8.5 kg ha^{-1}), Egypt

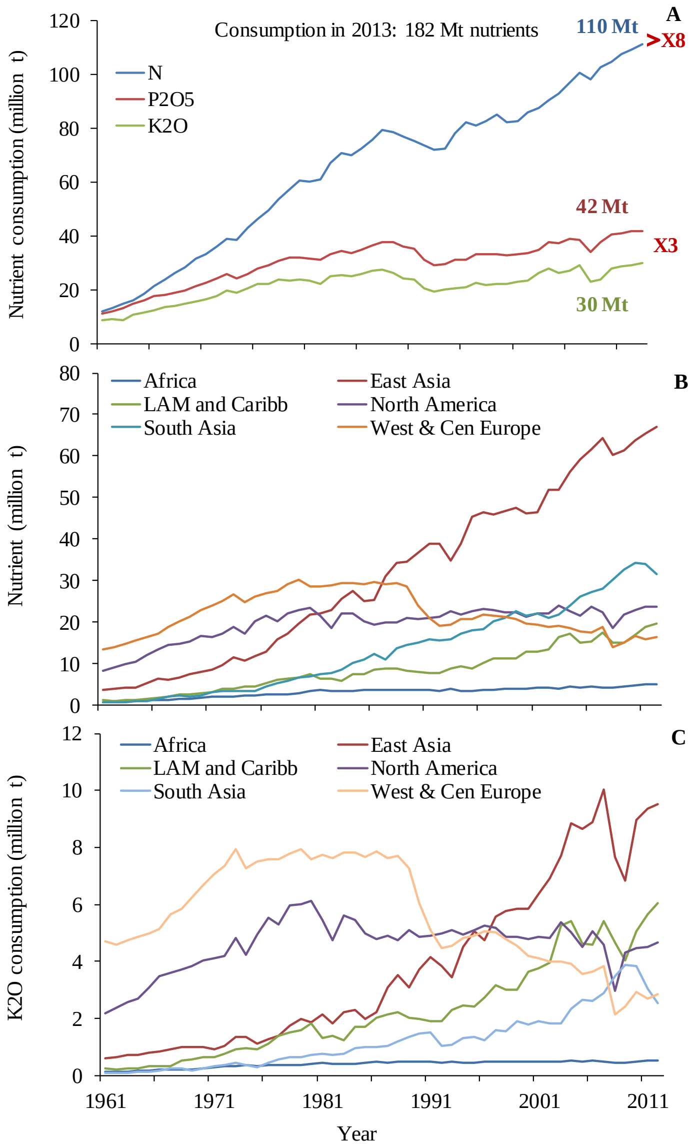

Fig. 1. A: Global N, P_2O_5 and K_2O consumption 1961-2013 (growth is interrupted only by global crisis). B: Growth in nutrient consumption (almost all regions). C: Potash consumption in regions 1960-2012.

(14 kg ha^{-1}), as well Morocco and Nigeria (FAOSTAT 7-2011). Currently, some13% of the world's cultivated area is in SSA, yet the region accounts for less than1% of global fertilizer use (Wendt, 2012); the figure for K_2O is likewise low. The very varied K fertilizer use within Africa is evident from Fig 2.

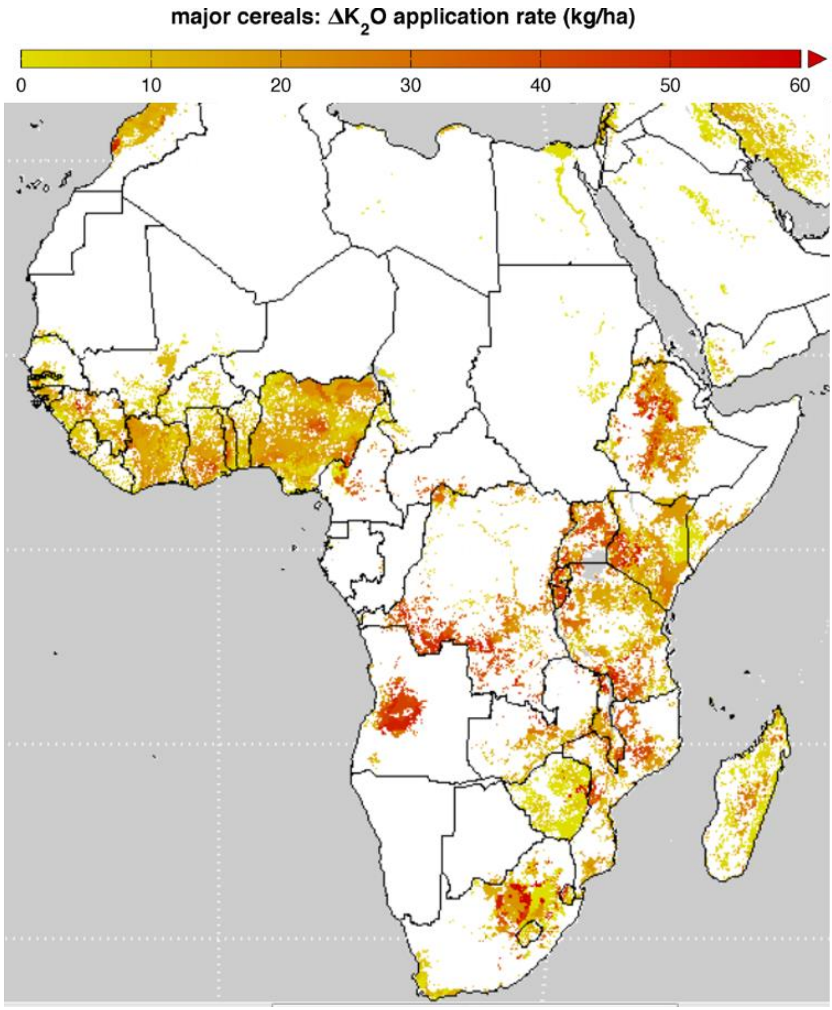

Fig. 2. Rate of potash application to major cereals from 0 to 60 K_2O kg ha^{-1} throughout Africa. *Source:* Mueller *et al.*, 2012.

Wendt (2012) suggests that there is a need for rapid acceleration in fertilizer use in SSA to feed its growing population and to reverse environmental degradation and increase yields through agricultural intensification. Sustainable intensification has been discussed by Mueller *et al.* (2012) as a way of increasing yields on underperforming landscapes, while simultaneously diminishing the environmental impacts of agricultural systems. These authors point out that global yield variability is heavily controlled by fertilizer use, irrigation and climate and that large production increases (45-70% for most crops) are possible from closing yield gaps (i.e. differences between observed yields and those attainable in a given region) to 100% of attainable yields. We suggest that by closing yield gaps to 75% of attainable yields, while also eliminating input overuse, would require smaller net changes in nutrient inputs. This could be achieved by increasing N application by 9%, P_2O_5 application by 2.2%, and K_2O by 34% to reach these yields for maize, wheat and rice. The much greater need for K_2O than the other nutrients reflects the steady decline in K_2O:N ratio of fertilization from about 0.8 to 0.2, which has gradually taken place over the past 50 years (Magen, 2012) even though, as previously mentioned, most crops require and take up K and N in relatively similar amounts to achieve full yield potential.

Fertilizer contribution to food production

The marked increase in crop production that has accompanied higher nutrient consumption over the past 50 years is evident from Table 1 (Magen, 2012). Particularly high increases are shown in oil crops, vegetables, melons, sugarcane and fruit. As with fertilizer consumption, however, very large differences in

Table 1. Production increase (metric tonnes) of seven crops over the past 50 years.

Crop	1961	2014	Increase
	--------------*Million mt*--------------		%
Oil crops	25.8	197.8	660
Vegetables and melons	222.6	965.7*	334
Sugarcane	448.0	1,900.0	324
Fruit (excl. melons)	175.0	609.2*	248
Cereals	876.9	2,800.7	219
Pulses	40.8	77.7	90
Roots and tubers	455.3	838.5	84

Note: *2010 data. *Source*: FAOSTAT.

production matching those of consumption are present in various regions of the world. There are many examples worldwide showing that increase in crop yield closely follows increasing fertilizer application. In cereals for example, North America and Western Europe starting from a baseline of just over 2 mt ha^{-1} 50 years ago, grain yields are now between 7-8 mt ha^{-1}. By comparison grain yields in Asia and South America, with an original baseline of about 1 mt ha^{-1} are now more than threefold greater at between 3-4 mt ha^{-1}. In Africa, however, average grain yields have stagnated at about 1 mt ha^{-1} (FAOSTAT).

A useful means of expressing fertilizer usage is the relationship between nutrient consumption per capita per year and kilograms of grain produced (Fig. 3). Interestingly the very marked differences in kg nutrient use per capita between China, India and Africa (37, 23, and 4.5 respectively) relate to relatively similar current total population numbers (China 1.36 billion, India 1.25 billion and Africa 1.11 billion). Per capita grain production in China, however, has doubled since 1949 (and is above the world average), a success story, with only 7% of the world's arable land and 5% of its water resources but the need to feed 20% of its population (Zhang, 2011). By contrast the much lower grain production in SSA, more or less stagnating between 100-150 kg per capita, demonstrates the requirement of increased fertilizer use to feed its growing population and to reverse environmental degradation. To improve the present position Wendt (2012) suggests that SSA may draw upon the experience and achievements of other countries over the past four decades including China and Latin American countries with similar soils, agro-ecologies and cropping systems.

The extent to which crop yield is dependent on nutrient inputs and specifically on commercial fertilizers has been assessed by Stewart *et al.* (2005). Several long-term studies in the USA, England and the tropics were evaluated, along with the results from an agricultural chemical use study and nutrient budget information of several crop species. This data represents 362 seasons of crop production. Significant variation in crop response to fertilizer inputs depends on crop species, soil conditions, climate, geographical location and other factors. All of these factors, however, are integrated into long-term harvested yields. The average percentage of yield attributable to fertilizer was generally found to range from 40 to 60% in the USA and England. The continuous maize yield attributable to N, P, and K fertilizer and lime over 46 years in the University of Illinois Morrow plots shows a mean value of 57% (Fig. 4). Stewart and his collaborators (2005) reported a very much higher attributable yield of crop to fertilizers in tropical soils because these soils are usually extremely weathered with low nutrient reserves. The same high response to well managed fertilization is to be expected from SSA nutrient deficient soils.

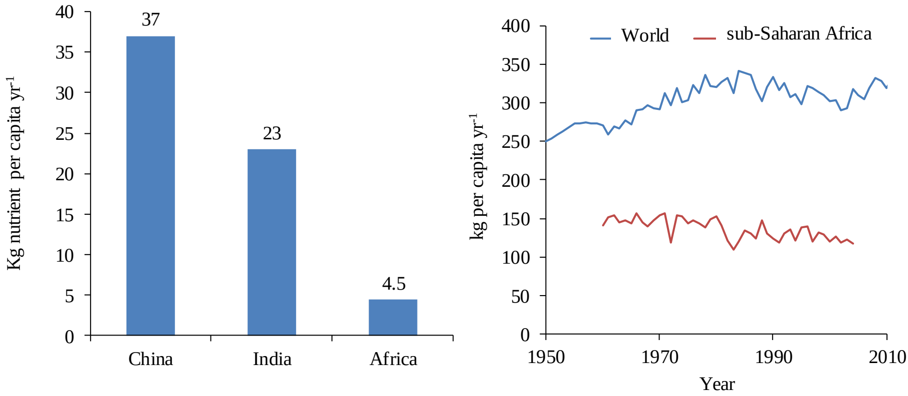

Fig. 3. Nutrient consumption per capita per year and kg of grain produced per capita. *Source:* Nutrient consumption per capita calculated from FAOSTAT and IFA; nutrient consumption per kg of grain produced per capita grain from Worldwatch, USDA and UNPOP.

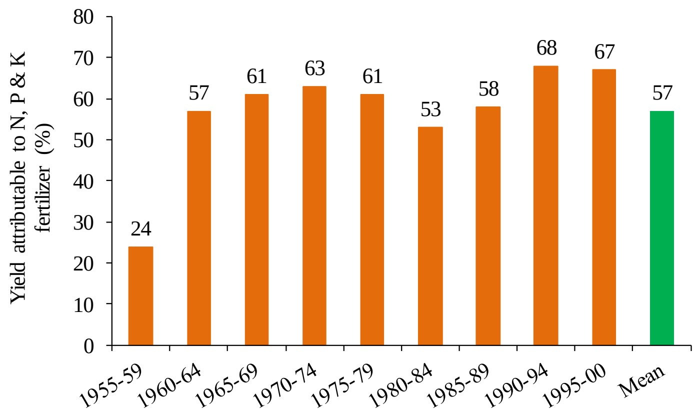

Fig. 4. Continuous maize yield attributable to N, P and K fertilizer and lime over 46 years in the University of Illinois Morrow plots. *Source:* Stewart *et al.*, 2015.

ETablevidence of K as the most limiting macronutrient was revealed in a study examining nutrient balances in common cropping systems on degraded soils of the Red River Valley in Vietnam (Mussgnug *et al.* 2006). Various cropping systems were investigated in these long-term experiments with mean yields over five years reported. Mean harvested grain yields for the cropping systems for rice (spring season), rice (summer season) and maize (autumn-winter season), in relation to fertilizer treatments, are shown in Fig. 5. The highest yields for both rice treatments and maize were obtained when recommended NPK rates were complemented by farmyard manure (FYM) application. The use of cumulative yield gaps indicated that K was the most yield limiting macronutrient in all crops with the exception of spring season rice when there was a stronger response to N than K, which resulted in a greater yield for the NP treatment than the control. The largest response to K application was observed in maize. These findings show that degraded soils were quickly depleted of K and required regular K fertilization

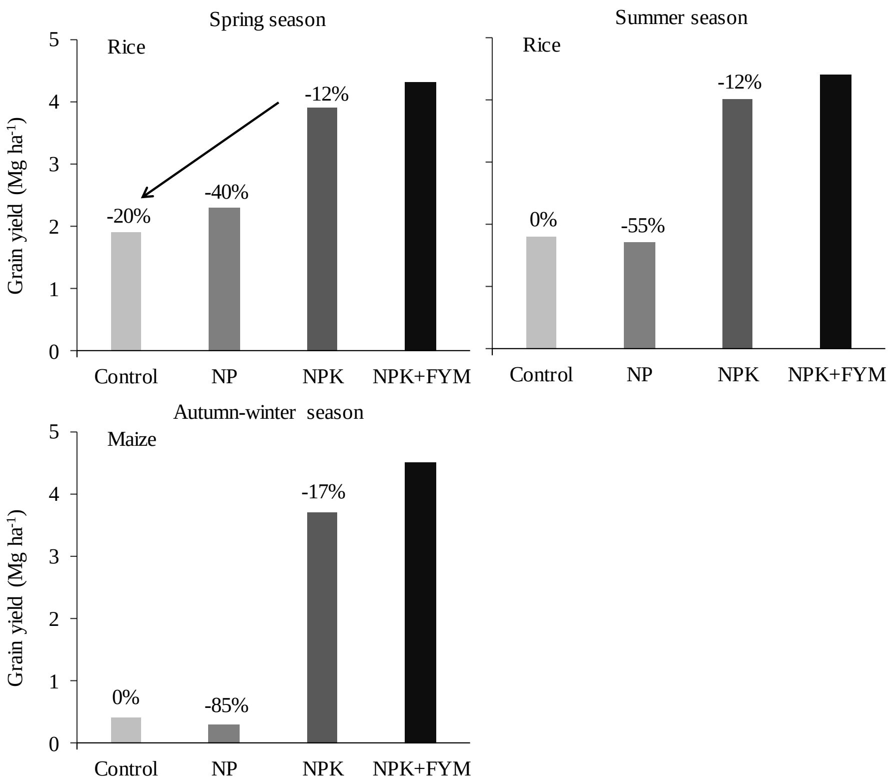

Fig. 5. Average yields (mean of five years) in a long-term cropping system experiment in the Red River Delta, Vietnam. Percentages indicate cumulative yield gaps. *Source:* Mussgnug *et al.*, 2006.

to meet crop demand for K and ensure yield responses to N and P. The authors suggest that the beneficial effect of FYM may possibly have resulted from the additional Mg input because of the extremely low levels of available Mg in these degraded soils.

Dietary mineral nutrient deficiencies (MND) are widespread throughout Africa and not easy to assess. Joy *et al.* (2014) estimated MND risks due to inadequate intakes of seven mineral nutrients in Africa, using food supply and composition data from 46 countries throughout the continent, to determine per capita supply for various mineral nutrients and phytate. Deficiency risks were quantified using an estimated average requirement. Highest MND risk was found for Ca (54% of the population) followed by zinc (40%), selenium (28%), and iodine (19%). Copper (1%) and Mg (>1%) deficiency were low. Deficiency of iron (Fe) was lower than expected (5%). Under conditions of low bioavailability of Fe, however, as with a high phytate and low animal-protein diet, commonly occurring in many areas, an estimated value of 43% was obtained.

Nutrient, water and energy use efficiency

Nutrient use efficiency

Balanced nutrient supply is a key factor in crop fertilization. This is especially the case for the closely interrelated nutrients K and N where increasing the K application rate can increase nitrogen use efficiency (NUE) and the resulting economic returns of K input can be large. This relationship was investigated in the cultivation of winter wheat and maize on the North China Plain in response to K fertilization (Niu *et al.*, 2011; Niu *et al.*, 2013). Field experiments were set up comparing three levels of K fertilization (K0 = no K, K1 = medium K rate (75 kg K_2O ha^{-1}) and K2 = high K rate (150 kg K_2O ha^{-1})) at an application rate of 225 kg N ha^{-1} for wheat and 240 kg N ha^{-1} for maize. On average, in the wheat experiments, K fertilization significantly increased all three yield components, namely kernel number per spike, spike per hectare and kilo-grain weight. The beneficial influence of K fertilization on NUE in wheat can be seen in enhanced N uptake in the grain (%) with increasing rates of K application, with similar results also being obtained for maize (Fig. 6). Maize grain yields increased by 15.7 and 21.0% with medium and high K rates respectively. Numerous other examples can be cited showing similar benefits of balanced N and K supply in crop nutrition (Brar and Imas, 2014). The benefits of balanced fertilization are particularly relevant to nutrient poor soils as in SSA where responses to fertilizer in increased yields and biomass can be particularly high. Residual biomass can be returned to the soil to augment organic matter thereby improving moisture retention and soil productivity as well as reducing the risk of soil erosion. Well managed and balanced fertilizer use thus has the advantage of increasing both food production as well as reducing soil degradation in nutrient poor fragile soils.

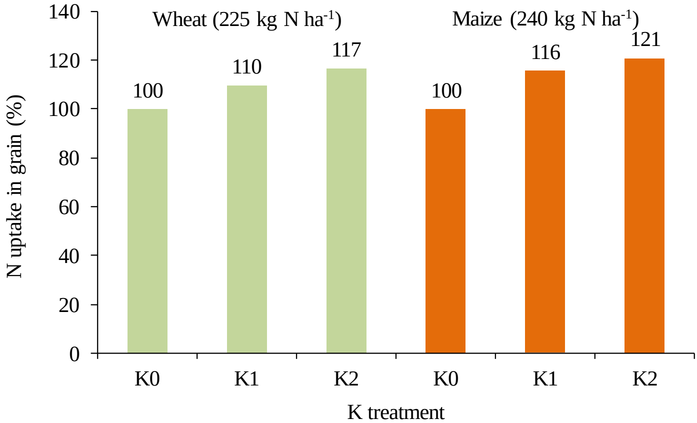

Fig. 6. Improving nitrogen use efficiency by better K application. Data calculated from: Niu *et al.*, 2013 (wheat) and Niu *et al.*, 2011 (maize).

In the above experiments, profits increased up to the highest rate of K application. Profits were measured in terms of Yuan per hectare (economic profit) and by value cost ratio i.e. the increase in grain yield in kg ha^{-1} above the treatment without K application x price of the grain per kg/F_k (the amount of fertilizer applied in kg ha^{-1}) x P_k (the price of the fertilizer at the specific site per kg). In general, in order to maximize profit, efficient farmers need to produce a given crop output at minimum cost. As proposed by Lingard (2002), this implies that marginal productivity (MP) or agronomic efficiency per Dollar spent is the same across all nutrient inputs in keeping with the Sprengel-Liebig Law of the Minimum. Thus $MP_N / P_N = MP_P/P_P = MP_K/P_K$, where MPs are the marginal productivities of the various nutrients (and the contribution to yield of the last 10 kg unit applied) and Ps are the relative prices for 10 kg of N, P and K. Interrelationships between nutrients have to be taken into account as is the case for the remedial inputs of K to increase NUE to produce large economic returns, as demonstrated above in the experiments of Niu *et al.* (2011) and Niu *et al.* (2013) with maize and wheat respectively on the North China Plain.

Water Use Efficiency

Water scarcity is one of the major global constraints to the increased food production required by the expanding population over the next 50 years. Only 3% of the world's water is freshwater and 70% of that is present in glaciers and permanent snow cover. The remainder is mostly groundwater, so surface water represents only a very small fraction of global freshwater (Laegrid *et al.*, 1999). Water resources throughout the world are unevenly distributed with large parts of Africa, including SSA, likely to experience or expect chronic shortage. Irrigation must be carried out with care under these conditions. Nutrient acquisition by crops is closely dependent on soil moisture regimes, so judicious water and fertilizer use is also needed in increasing and stabilizing yields of dryland crops. The beneficial effect of K fertilization in alleviating drought stress in wheat, as measured by higher rates of photosynthesis in K treated plants, is very clear from the work of Cakmak (2005).

Irrigation systems vary greatly in their efficiency, and the impact they have on crop water use efficiency (Rangely, 1987). Losses of water in transport and application to fields can be in the range of 10-70%. On the other hand more sophisticated techniques have very much higher percentage efficiencies, including sprinkler systems (60%) and drip irrigation (85%). Crops also differ in their needs for irrigation and forms of irrigation. The yields of some crops, such as potatoes and maize, can be particularly increased by irrigation, although marked differences between experimental sites can occur. This is evident from average grain yields between 2008 and 2010 in relation to water use efficiency reported in experimental data from Israel and China. In Israel 20 mt ha^{-1} grain was obtained with 400 mm water, i.e. 200 kg water per kg grain. By contrast in China, only half the yield was obtained with twice the amount of irrigation water applied, 800 kg water being required per kg of grain produced (Magen, 2013).

Energy Use Efficiency

With a rapidly rising global population, unprecedented demands are being placed on agriculture to meet the world's needs for food production, security and sustainability. To achieve these goals, increasing fertilizer use and its efficient application in food production, is paramount. Agriculture, including deforestation, contributes to 30-35% of 'greenhouse gas' (GHGs) emissions, producing carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The global warming potential (GWP) of these gases are detailed in an Intergovernmental Panel on Climate Change (IPCC) report (2001). Global warming potential is a relative measure of how much heat is trapped by GHGs in the atmosphere. Over a 100 year period, CO_2 GWP is given as 1; in comparison to CO_2, the GWP increases to 23 for CH_4 and 296 for N_2O.

Deforestation and conversion to agricultural land accounts for approximately 12% of global GHG emissions (Bellarby, 2008), and is the second largest global source of anthropogenic CO_2 to the atmosphere after fossil fuel combustion (van der Werf *et al.*, 2009). Methane is generated in high amounts in cattle production as a result of bacterial digestion in the rumen. Large CH_4 quantities are also released during rice cultivation. Nitrous oxide is an intrinsic component of the nitrogen (N) cycle and is produced in the soil by nitrification in the conversion of ammonium to nitrate, as well as by denitrification of nitrate. Nitrous oxide is released from the soil by applications of mineral and organic N fertilizers, but there is no clear relationship between N fertilizer application rate and nitrous oxide emission (IFA/FAO, 2001).

Global food production, as we have seen, is critically dependent on the manufacture of NH_3 based fertilizers by the Haber Bosch process in which N from the atmosphere combines with H. The energy to drive this process is provided by natural gas which also acts as a source of methane as a feeder of H_2. The primary steam reaction with methane produces H_2 and CO_2 which is released into the atmosphere. According to Bellarby *et al.* (2008) this CO_2 release amounts globally to 410 million mt eq per year to make up 0.8% of global CHG emissions. As considered earlier, approximately 100 million mt ammonium derived N fertilizer are consumed annually on a global scale which implies that every kg of N applied to the crop represents the release of somewhere in the region of 4 kg CO_2 eq. The industrial manufacture of ammonia is extremely energy efficient but requires a high net energy consumption of approximately 34.6 GJ mt N (Jenssen and Kongshaug, 2003). Upgrading the ammonia to urea or urea ammonium nitrate requires even more energy (41.8 GJ mt N and 36.6 GJ mt N respectively). Additional energy costs are involved in transport and application. For maize this amounts to about 0.53 MJ per kg N for transport and 0.48 MJ per kg N for application. By contrast the energy required in manufacturing P and K fertilizers is very low. The consumption of the net energy in manufacturing potash (muriate of potash) is 2.5 GJ mt K_2O, mainly arising from mixing and drying. In maize cultivation the equivalent cost of application is also considerably lower than that of N (Sawyer *et al.*, 2010). The very small energy contribution of K to the total energy used in N and K fertilization of six crop species, ranging between 0.1-2.5% is evident in Table 2 (Pimental and Pimental, 2008).

The very high energy costs in producing and applying N fertilizers (in comparison with P and K) means that N fertilizers must be applied judiciously so that greatest benefit to crop yield and quality can be obtained from their use by nutritionally balanced fertilization. Over the past 50 years, although food production overall has hugely increased, consumption of N P and K has been skewed towards N, causing K depletion in soils and reduction in yields. Furthermore, excess N fertilization, as well as being a waste of money, is a cause of pollution by increasing N_2O emissions from the soil as well as nitrate leaching from the soil profile to induce eutrophication.

Table 2. Energy inputs and costs in various crops.

Crop	Country	N fertilizer	K fertilizer	Total energy	$Energy_K$/ total
mt ha^{-1}		----------*Energy input, MJ*		-----------	*%*
Maize (8)	US	11,246	749	29,485	2.5
Wheat (2.67)	US	5,342	29	17,805	0.1
Rice (6.7)	US	11,714	769	49,720	1.5
Soybean (3)	US	290	202	10,085	2.0
Potato (39)	US	18,035	1,520	71,845	2.1
Cassava (12.4)	Thailand	3,591	588	54,647	1.0

Adapted from Pimentel and Pimentel, 2008. Food, Energy and Society. 3rd edition. CRC Press.

Photosynthesis of carbohydrates by higher plants underpins higher life on the planet. In considering energy use of fertilizers it has to be taken into account that fertilizers, as suppliers of essential plant mineral nutrients, significantly increase solar energy capture by plants. The use of fossil energy required particularly in the production of N fertilizers thus enables the capture of considerably larger quantities of solar energy as discussed in Dawson's (2008) thought provoking essay. Figure 7 taken from his presentation illustrates the energy involved in growing and fertilizing a hectare of wheat and the energy contained in the increased biomass as a result of the fertilizer. The extra energy captured is more than six times greater than that involved in the manufacture and application of the N fertilizer used. During photosynthesis five times as much CO_2 is removed from the atmosphere in the production of carbohydrate than is released during the manufacture of N fertilizer used. The carbon in the carbohydrate is current CO_2 as opposed to the 'fossil' carbon in the methane used in the manufacture of the fertilizer. This hugely enhanced amount of carbohydrate attained is urgently needed for food production, and as pointed out by Dawson (2008) the use of fertilizer to produce the extra carbohydrate required is neither optional nor an irresponsible use of fossil fuel.

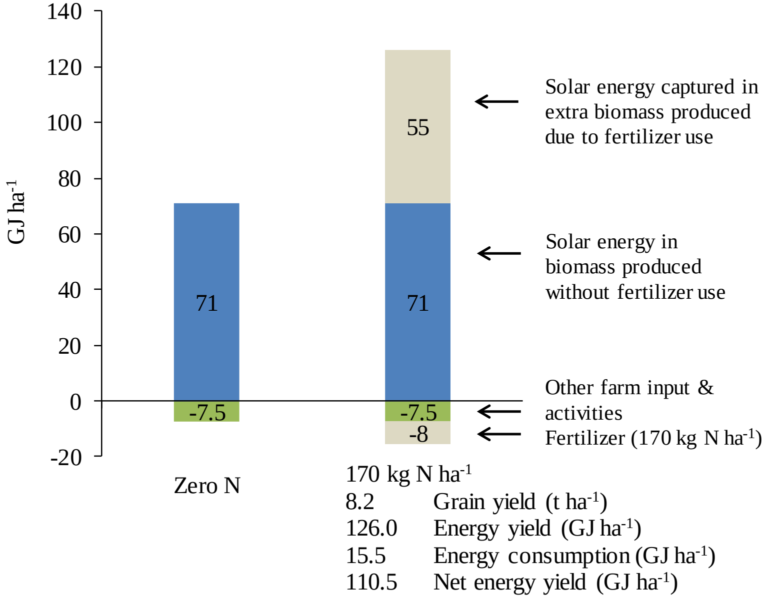

Fig. 7. Illustration of the solar energy captured by a hectare of wheat (8.2 t ha^{-1}) and the energy invested in its production (after EFMA, 2006).

Conclusions

1. Fertilizers frequently account for more than 50% of yield produced. In soils with low nutrient reserves, as in SSA, attributable yields can be much higher.
2. Fertilizer use in Africa and particularly in SSA is very much lower than other regions of the world.
3. Using fertilizers efficiently and judiciously is financially beneficial to the farmer and advantageous to the environment.
4. In order to feed the world, intensification is required. It is a basic principle of plant nutrition that those nutrients removed from the soil by a harvested crop must be replaced. In this respect the Potash Development Association fertilization recommendation calculator (phosphate and potash deficiency correction and nutrient offtake calculator) should be used.
5. Efficiency in water and nutrient use is an important area of development. In particular a balanced supply of N and K fertilizer should be supplied to crops to improve both yield and quality of crops and to avoid the damaging effects on the environment as a consequence of excess N supply.

6. Use of fertilizers for food production enables the capture of solar energy. In efficient wheat cultivation, for example, more than five times the amount of energy used in manufacture, transport and application of fertilizers (particularly N) can be found in the increased biomass of the harvested crop as a result of the fertilizer applied. The crop also removes five times as much CO_2 from the atmosphere while growing, as is emitted during the production of the fertilizer that it uses.

7. Fertilizer demand will continue to rise to meet the corresponding demands of an increasing world population.

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Chapter 2

What Can the Potash Industry Learn from Ethiopia's Agricultural Growth Experience[1]

John W. Mellor[2]

Abstract

The almost universally poor record for agricultural growth in African countries has led to pessimism about the potential of the sector and arguments for directing more agricultural investment towards large-scale farms (e.g. Stevan Dercon, Paul Collier). Yet that makes little sense given the dominance of small-farms in most African countries.

Ethiopia dramatically demonstrates that an African country can have a high agricultural growth rate and that it can come from the small commercial farmer. Ethiopia has sustained a growth rate faster and longer than any Asian country in agricultural production generally, and in cereal production in particular. That success, as is always the case, required a high growth rate in fertilizer use from a substantial base. And as always potash becomes of increasing importance over time; in Ethiopia, based on the numerous demonstrations and validation tests conducted during the last couple of years and the significant increase in crop yield due to potash, it has been decided that the fertilizer should become part of the fertilizer extension package. This is an advantage since several global companies are currently engaged in potash exploration and mining, which will make Ethiopia a global potash fertilizer supplier in the near future.

Dominance of the Small Commercial Farmer

Eighty four percent of the production increase of about 7 percent per annum over the past decade came from the small commercial farmer. They are the farmers with 0.75 to 5 hectares of land and comprise about half the rural population. Less

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than 10 percent came from large scale farms. The small remainder of the increase came from the rural families with less than 0.75 hectares of land. Thus we need to distinguish the small commercial farmer from those who have a small plot of land but who draw the bulk of their living from off the farm.

By this definition, the small commercial farmer is not poor, is not a subsistence farmer, is commercial, buying and selling, and is sufficiently employed on the farm to see increasing farm income as the way to improving his standard of living. Most of these farmers have sufficient income and capital to invest in what they see as profitable innovations and to take risks to innovate. On risk taking, it is important not to see unwillingness to take up unprofitable innovations as risk aversion. They of course face a credit constraint in the face of large investment opportunities.

Importance of the Ethiopian Success to the Potash Industry

As the potash industry expands its efforts in Africa including Ethiopia, it is important to know that there is a major success story in the context of generally poor performance in African agriculture, including slow rates of growth of fertilizer use. Knowing how Ethiopia achieved this success will enable other countries to replicate it by highlighting policies and investments governments need to implement, and how to encourage governments to pursue these. Foreign aid organizations (which generally show little understanding of the reasons behind agricultural growth) may also be encouraged to pursue policies that will help get recipient countries on a successful track.

The Cereals Production Growth Rate

For the 16 year period from 1995-96 to 2012-13, the cereals growth rate was 6.3 percent, rising to an average of 7 percent in the last 12 years due to growth policies coming fully into play. It is important to recognize that these are solid numbers. The basic data sets for the growth rates discussed in this paper are from the Ethiopian Central Statistical Agency (CSA). The Central Statistical Agency website (www.csa.gov.et) provides detailed information on their methodology and internationally recognized standard procedures. This reveals that the data are from regular sample surveys. Plots are selected randomly and yields are determined by crop cutting. CSA has been doing this for close to two decades with continuity in professional leadership and management and well trained and supervised staff. The data were cleaned and analyzed by standard linear regressions and also by the Sen Method which is better for removing the impact of weather fluctuations. In fact, the two approaches provided very similar results.

The data show differences in growth rates among cereals and overtime that are fully consistent with weather changes and differences in technology among crops and overtime.

What are the Sources of Ethiopia's Rapid Growth

Five points stand out in the Ethiopian success story.

First, Ethiopia started from a low base of crop yields. Very fast growth rates are almost always substantially catch-up growth. But most of Africa has similar low yields and is not catching up. And, despite the success so far, yields are still well below those of advanced countries. Ethiopia therefore has another two decades of potential for present growth rates.

Second, was a widely publicized commitment from the government at the highest level to agricultural growth as the means for transforming the economy. Prime Minister Meles set a vision in 2000 for Ethiopia to reach middle income status in 25 years. The Agricultural Development Led Industrialization (ADLI) strategy focused initially on cereals production, a set of commodities that occupy 90 percent of the farmed area and dominate the consumption patterns of those below the poverty line. The vision and the strategy have been so widely publicized that essentially everyone, including farmers, know of it and are at least somewhat motivated by it. Concurrently, there was a significant increase in the number of extension workers – currently reaching 63,000. Although not well-trained, farmer surveys and focus groups consistently show that farmers have a good opinion of the extension workers. They helped publicize the need to increase production and were helpful in encouraging farmers even with respect to traditional practices.

Third, was a large commitment of the national budget to agricultural growth. The Africa-wide strategy for agriculture (Comprehensive Africa Agriculture Development Programme, CAADP), signed off on by all African heads of State (AU), stated that a minimum of ten percent of total government expenditures should be on agriculture. Tanzania, at four percent, is typical. At times Ethiopia has spent 15 percent but has consistently been above the minimum of ten percent. No more than one or two other African countries have met the target even for a year or two. Compliance with the thoughtfully developed target shows whether or not a country is committed to agricultural growth. The target is important because governments must build a wide variety of critical agricultural services, many of which would not traditionally be provided as part of an agricultural growth strategy. The targets for agricultural growth set out in a country strategy will not be met if the overall allocation of funds to agriculture is grossly inadequate, but if the necessary funds are provided they must then be optimally allocated to a few priorities.

Fourth, is continuous and growing investment in rural physical infrastructure. Agriculture in all African countries is greatly disadvantaged by lack of roads as well as access to electricity. Ethiopia stands out with large scale investment in trunk roads, rural roads and to some extent rural electrification.

Minton *et al.* (2014) provides a definitive statement of the impact of a set of changes of which rural roads were central. Transport costs and marketing margins declined precipitously from 2000. That had a large impact on relative prices farmers faced which increased incentives to invest and intensify. Between major markets and central cities costs halved, which enabled the initial investments. However, there is a long way to go in connecting farmers and villages with central markets. Much of the road system is still made up of gravel roads and International Food Policy Research Institute (IFPRI) data show that it is all weather roads that bring development (Ahmed, 1975).

The focus here is on the economic impact of infrastructure investment. It is important to realize that the rapid growth rates in agriculture have built market towns, much of which are defined in CSA data as rural. There has also been migration to central cities but despite this, the rural population will continue to grow for a considerable time to come. Thus a concern for social welfare must give emphasis to rural education and rural health. Those require improved roads. Why would the health worker or the teacher bring a family to a place without all-weather road access? That is why investment in rural roads must be extensive and justified only in a small part by the impact on agricultural growth even though the effect on agriculture is very large. Note that CAADP, in defining government agricultural investment, does not count rural road investment even though it says it is important to agricultural growth.

Fifth, was a major change in agricultural growth strategy and the changing components of strategy as the effort proceeded. That is discussed in the next section.

Changing Sources of Rapid Growth in Agriculture

Dividing sources of growth into three distinct periods is a useful simplification. The first period from 1995 to roughly 2008 saw the intensification of traditional processes. Next came seed, fertilizer intensification from 2008 to the present. The third period looks forward, from the present to another decade or two of seven percent growth and outlines a few key priorities. As the first two periods developed it was easy to see a system that was working well, giving the required growth. It is necessary to predicting the need for change otherwise it is unlikely to occur and the growth rate will slow. Without understanding why the required adjustments may not be implemented.

Phase I - Intensification of Traditional Practices

The growth rate in the first period must be understood in terms of the remaining potential for recovery after disruptions caused by the past military regime (Dergue) and then in terms of the potential to increase intensification in a traditional context. Prior to the present government taking office in 1952, Ethiopia went through a horrendous period of deeply misguided policies, a declining agricultural sector in both cropped area and intensity, and disruptions from civil war. In the first few years after accession of the present government, growth from recovery could be expected. It is likely that the recovery of area and quality of husbandry continued beyond 1995 helping explain the early high growth rate.

The Policy and Investment Framework (PIF) for the current growth plan analyzed the growth rate for several years from the early 1990's,[3] and concluded that the growth rate had been about seven percent at that time. Further analysis made it clear that that growth could not be explained by modern technology. The base and the growth rates for improved seed and inorganic fertilizer were simply too small to explain even a small percentage of that growth rate (Government of Ethiopia, 2010).

The conclusion in the PIF was that the growth was from area expansion, some of which was recovery from the decline during the Dergue period, intensification of traditional labor intensive practices, and a large increase in the road network as explained above. Initially, the expansion of the cultivated area was rapid and then slowed somewhat. By that time, the expansion of the road network was underway and would be expected to bring additional intensification with markedly improved price relationships (Minton *et al.*, 2012), however another factor came into play.

The extension service was expanding at a phenomenal rate on the way to the present 63,000 extension officers. Because these agents were based at the peasant association or Kebele level they met the bulk of the farmers in their area. Farmers have a good impression of the extension agents[4]. They are poorly trained, but they are dealing with farmers at a very low level of productivity as well. And they worked in a context of national exhortation with respect to the Prime Ministers vision for the country and the strategy for implementing it.

Thus, in that early period, the infrastructure investment, the national drive, and the extension agents made a difference, and modern technology must have had an attitudinal impact as well. As a reference point, in India, in the early years after

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[3]That analysis of trends was an unsophisticated inspection of graphs and drawing trend lines from visual judgments, not the sophisticated approach reported here. Nevertheless the result was similar.

[4]Focus group studies for the AMDe USAID project corroborate this as do as yet unpublished IFPRI studies.

independence, the agricultural growth rate accelerated sharply, the area expanded and yields increased (Mellor *et al.*, 1968). During that period, modern technology was at the same stage as in Ethiopia during phase one. Technology was being pushed and must have affected attitudes, but the base was too low to allow much impact. India expanded its extension service but it was far smaller than the large effort in Ethiopia but the expansion of the road network was not nearly as big. The Ethiopian commitment to an agricultural strategy and greater current knowledge of agricultural development (as later represented in CAADP) also favored more rapid growth for Ethiopia. Thus, it is logical that Ethiopia would have grown much faster than India at a similar stage of development even though the mechanism was similar but the emphasis more in Ethiopia.

Phase II - Seed/Fertilizer Based Growth

The PIF made a powerful argument that while the growth rate up to 2010 had been exemplary it was based on processes that would soon run out. It was essential that the strategy change. The central element of that change would be a very rapid (15 percent growth rate recommended) rate of increase in fertilizer usage. It was clear that would also require a major change in the seed supply system – with encouragement of the private sector as well as public sector hybrid seed production and growth of community-based, relatively small-scale efforts to develop and disseminate open pollinated seed.

There was considerable controversy about this change in strategy. The past growth had been cheap in resources and successful. Yet despite some opposition, both locally and within the donor community, the government did swing towards PIF-recommended very high fertilizer target and a radical change in the size and institutional structure of the seed industry. These changes were imperfect but worked.

Fertilizer use expanded from the modest base of 200,000 tons in the mid-nineties to 900,000 tons by 2013-2014, expanding by about 80,000 tons per year. Government control of imports and their commitment to meet the fertilizer target resulted in a push (see Desai, 1988, IFPRI for its importance) to supply fertilizer to primary cooperatives, pressuring them (under duress) to move fertilizer on to farmers. This push, together with an expansion of the extensions system, brought the rapid growth.

To explain all of the increase in yields with fertilizer and seed would assume a response coefficient of 8.8 to one. Fertilizer has been somewhat inefficiently used, but farmers would not use it at less than a 7 to 1 ratio and with the increase in seed availability that average of 8.8 to one is not unreasonable. Thus, the growth rate in yield seems not only reasonable but it is explained almost entirely by the seed and fertilizer input. The success seen by teff after rapid acceptance of improved seed shows that the potential of open pollinated seed multiplication had increased greatly. The increased area planted to improved seeds would also have increased the productivity of the base use of fertilizer, further emphasizing the power of the seed fertilizer strategy.

Phase III - Key Priorities for the Next Phase

The seven percent growth rate is catch-up growth. In the long run, when Ethiopia has caught up to more advanced countries, land as a source of growth will lose its position and yield growth will be similar to the rate generated in research stations in advanced countries, e.g. around two percent. The questions should be: 1. For how long can the current rate be maintained? 2. What are the requirements for doing so?

Simplistically, data from the UN Food and Agriculture Organization (FAO) reveals that cereal yields in France are over three times those in Ethiopia. Assuming France's yields increase at two percent per year as a result of continued research, Ethiopia could maintain a seven percent rate for another 20 years before it caught up. Of course, on the other hand, increasing the growth rate of livestock to meet the growth in demand (a doubling of the present growth rate for livestock) and with export potentials of live animals to the Middle East and for leather reinforces the plausibility of that growth potential. The structure of livestock growth would change greatly. Twenty years would see the proportion of the rural population under the poverty line diminish to a negligible level and the economic transformation proceed sufficiently to allow the farming population to commence its slow decline allowing increased farm income from increased area per farm. The economic transformation implicit in the ADLI strategy would be fulfilled.

A simple seed/fertilizer strategy cannot maintain the seven percent growth rate indefinitely. That becomes clear by looking at future requirements and one way to determine those needs is to note conditions in which all high productivity agricultures have a large complex structure and strong value chain in which Ethiopia is now markedly deficient. Six such areas stand out. Briefly stating these makes the point, first, that simple seed and fertilizer without other institutional support cannot maintain levels of growth; second that the requirements for continuing the seven percent growth rate are currently known; third that efforts are underway to meet them; and fourth that the requirements although feasible are not trivial.

1. *Livestock Sector*. Domestic demand for cereals for human consumption has largely kept up with the seven percent growth rate in cereals production. Real prices have trended neither up nor down. That has had a tremendous impact

on food security. However, that large increase in human consumption of cereals is driven by relatively high income elasticities (0.72) of demand on the part of the poorer half of the rural income distribution. Those elasticities will become more inelastic and the population growth will also decline. As the growth rate in demand for human consumption slows with decreasing poverty the scope for intensive livestock production built on high grain feeding rates will gradually increase. The present livestock growth rate is only about half the rate of demand growth. The PIF noted that this problem would arise and recommended the creation of a new position of Minister of State for livestock - a recommendation that was implemented. The required changes, including transforming smallholder agriculture into commercialization and industry, and the need to strengthen natural resource conservation are underway. Put simply, the time is near when the size of the public support for the livestock sector will need to be as great as for the crop sector.

2. *Finance.* Failure to understand the dominant role of the small commercial farmer and their financial needs has resulted in virtually a complete lack of access to credit to meet rapidly increasing investment requirements. Those requirements already go well beyond financing fertilizer and that dispersion will accelerate in the next round of growth. All countries with high productivity agriculture have a specialized agricultural finance system suitable for the bulk of their farmers (Desai and Mellor, 1998). It is only in Africa that the lack of such institutions is endemic. International experience is clear (Desai and Mellor, 1998) that the two requirements of a finance system for the small commercial farmer are convenience of access, requiring thousands of branches, and a loan officer able to assist in making profitable loans for agricultural production and following up for on time repayment. In that context, the institutional structure depends very much on national culture and institutional history. There are currently discussions within the government on how best to meet this need.

3. *Fertilizer.* A huge advance is being made in tailoring plant nutrient provision to agro-ecological differences. That is essential and admirable. However, the lack of competition to the cooperatives is not only detrimental to cooperative development, as discussed below, but constrains the current level of fertilizer use and restricts growth to a much smaller base than is necessary. The success with fertilizer was due to putting the most effective cooperatives in overall charge, pushing large inventories on the cooperatives with a consequent pressure to move fertilizer, and a massive extension effort. For the future, growth will have to move much closer to the optimal and hence lower margins. Maintaining the current rate of growth in fertilizer use will require greater efficiency as farmers move further out the response curve - meaning

they will not get as much from their investment in fertilizers. There needs to be competition to identify cooperatives that are under performing and pressurize them to increase efficiency. Cooperatives define non overlapping geographic areas and hence do not compete with each other. In 1996 the government barred the private trade from fertilizer distribution, presumably to foster the growth of cooperatives. The grain traders want to return to fertilizer distribution because it complements the grain trade – it is traded during different season, opportunity for use of warehouse space, working capital, and management. While IFPRI studies show the operating margins of cooperatives to be too low, private traders in focus group studies are happy with those margins - underlining the complementarity. Opening to the private trade will bring competition, clarity as to where the deficiencies of the cooperative lie, and service to now under serviced areas. It is now time for that to happen.

4. *Primary Cooperatives.* Ethiopia is committed to multi-purpose cooperatives being at the core of servicing the farmer. They occupy such a role in a large number of high and middle income countries. The advantage of cooperatives over private traders is a loyal membership. Farmers, in focus groups, are consistently clear that they prefer cooperatives to private traders. Unfortunately, the reality is that the primary cooperatives, to which farmers are members and see as the object of their loyalty, rarely have a paid manager and as a result offer poor services. The basic problem is that the primary cooperatives are, correctly from an ease of access point of view, targeted at the Kebele level. They are in fact not multi-purpose cooperatives but are solely distributors of fertilizer. The size of business is insufficient to cover a paid manager. The question then is how to increase the scale sufficiently. The principle argument against such expansion of scale is that the cooperatives cannot even manage what they have and should not be complicated by adding activities. The obvious solution with the ten percent of cooperatives that are operating well (unpublished Agricultural Transformation Agency study) is to add activities to get scale, hire a paid manager, build membership and then expand from there.

5. *Irrigation.* The PIF allocated over half of the investment in the plan to irrigation. There is substantial rainfall that is seasonal, charging water tables and rivers. Irrigation protects against poor rains and allows for a second crop. But to be effective irrigation requires a much larger institutional structure than now exists. The time is coming when the decline in area expansion has to be compensated by increased irrigated area, with an emphasis on a second crop. But the institutional structure in high productivity agriculture is far more complex and larger than now exists in Ethiopia. A major effort is required.

6. *Coffee.* Ethiopia stands out in lacking an institutional super-structure to manage the coffee sector. Being in an international market requires that rapid advances be made in productivity including disproportionately large expenditure on a fully integrated research/extension system. A host of quality related measures need to be instituted from the farm through the export markets. A government committee looked at this without finding a solution. That effort is continuing. But there is urgency in reaching that decision.

Agricultural Growth and Poverty Reduction

From the agricultural growth success has come radical decline in rural poverty and increase in food security of the poor. The proportion under the World Bank-defined poverty line fell by almost a half from the early 1990's to the present and calorie consumption of the rural poor increased greatly with a consequent increase in food security.

The resources for agricultural growth are often justified by expected impact on poverty reduction. The international cross-section data are consistent with that. Where agriculture grows rapidly poverty declines rapidly[5] and where it does not, poverty declines little or not at all. Timmer (1997) shows that large scale, e.g. Latin American style, agriculture is not associated with such declines in poverty. But we make the point above that Ethiopia's agricultural growth, as for most low income countries, is driven by the small commercial farmer who is not poor. How is that connection between incomes accruing to non-poor small commercial farmers getting into the hands of the poor? It is not for this paper to spell this out in detail. However a recently published paper by Dorosh and Mellor (2013) based on Ethiopian data does document that connection.

Briefly, small commercial farmers spend half of the increments to their income on the employment of intensive, non-tradable, rural non-farm sector. Obvious examples are increased size of house and improvements in house quality, locally made furniture, at least for women some increase in local tailoring, and most important increased services ranging from retail clerks, to transport services (bus conductors, drivers, and repair facilities), and personal services at the farm level. The demand for such goods and services is elastic – that is the sector grows faster than farm incomes. Over time those activities move increasingly to the market towns, creating vibrant towns many of which become small cities, providing a dispersed pattern of urbanization.

[5]See for example Timmer (1997), Ravallion (2002), Thirtle (2001).

Thus as long as there is a large stock of rural underemployment, concentrated mostly in the rural non-farm population, the growth in incomes of the small commercial farmer will have a major impact on poverty reduction.

Conclusion

Ethiopia demonstrates that a growth rate in cereals production faster than the Africa wide target in CAADP is feasible and for decades. That growth is based on the not-poor small commercial farmers who require a wide range of public goods and services if they are to increase production rapidly. Ethiopia has succeeded because it has a clearly stated vision and a strategy that explicitly places rapid agricultural growth at the forefront of the growth and economic transformation process. The high growth rate started with recovery after a long period of stagnation and retrogression, intensification of traditional processes enhanced by a significant extension service and large-scale investment in roads. Next a seed fertilizer strategy was followed with a major push to ensure a high growth rate in fertilizer use. Now that approach is also running out and the government is tooling up to advance six major institutional structures for the next round. The changes needed for that next round are feasible but difficult.

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Chapter 3

Fertilizer Use Trends in Ethiopia

Teshome Lakew[1]

Fertilizer use and potential demand in Ethiopia

Ethiopian farmers traditionally use fallowing, crop rotation, farmyard manure and forms of compost to improve soil fertility. These traditional practices used to maintain soil fertility have been gradually reduced due to high population pressure and limited availability of cultivable land. The use of manure to add organic materials to the soil is also hampered by the increased use of dung and crop residues as a source of energy. Thus, in order to restore plant nutrients to the depleted soils, provision of chemical fertilizer to farmers has been one of the major activities of extension programs in Ethiopia. Since the inception of the agricultural extension program in Ethiopia, promoting the use of chemical fertilizer has been the major work of extension personnel.

Inorganic fertilizer was first introduced to Ethiopia following three years (1967-1969) of simple fertilizer demonstration carried out by the government with the assistance of FAO's Freedom from Hunger Campaign. The objectives of this program were to create awareness among smallholder farmers on the use of inorganic fertilizer, to conduct field trials to determine the optimum rate of application, and to define sound policies, strategies and institutional set up that would help introduce an efficient fertilizer distribution system. The crops under trials were cereals and the introduced inorganic fertilizers were diammonium phosphate (DAP) and Urea (Techane, 2002). Since then, the application of chemical fertilizers has gained popularity and consumption of the two types of fertilizers (DAP and Urea) has greatly increased. Accordingly, the total consumption of chemical fertilizer has increased from 107,457 mt in 1993 to 729,244 mt in 2013 (Table 1). In the last 20 years, an average of 11.6% annual fertilizer consumption growth rate was recorded.

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Although the total consumption of chemical fertilizers has shown an increasing trend, its actual per hectare application by farmers is very little due to various institutional, economic and physical factors. For example, the amount consumed in 2013 corresponds to only about 59.4 kg per ha of major crops in that season. This shows that the current level of fertilizer application is too little to support a sustainable yield increase. Hence, the major challenge facing the country remains how to increase fertilizer consumption necessary to attain a sustainable increase in yield (GTP (Growth and Tansformation Plan) target).

More than 90% of all fertilizers are used by smallholder farmers, with the remaining 10% used by private commercial farms, state farms and research centers. Four regions (Amhara, Oromia, SNNPRS and Tigray) combined accounted for more than 90% of the country's total fertilizer consumption.

Annual sales volume data shows that only 15 to 20% of fertilizer is consumed during the short rainy season (BELG) starting from February through March, while 80 to 85% of average annual fertilizer sales are consumed during the main season (MEHER) starting June to September. Consumption of fertilizer is insignificant in September and virtually nil between October and January. Fertilizer application under irrigation is also insignificant, though some improvement has been observed in recent years.

There is a big gap between estimated potential demand and the actual annual consumption of chemical fertilizers in Ethiopia. The potential demand for fertilizer in Ethiopia can be calculated by multiplying the area under annual/temporary crops (crops receiving more than 90% of annual fertilizer used) by the existing application rate recommended by the national extension program (i.e. 100 kg of DAP/NPS and 100 kg of Urea). According to CSA (Central Statistics Agency) data for the year 2013, the total area under temporary crops by snall holder farmers during the main season was about 12.3 million hectares. Multiplying this by the recommended application rates, the potential demand for chemical fertilizer in Ethiopia is estimated at about 2.5 million mt. This shows that there is wider scope to convert the potential demand for fertilizer to effective demand in Ethiopia, as the current highest record of fertilizer consumption in the country is 729,244 mt, only 29.7% of the estimated potential demand.

There is no domestic production of inorganic fertilizer in Ethiopia. Chemical fertilizers are imported from abroad in the form of DAP, Urea and recently NPS. The foreign exchange required for fertilizer import is allocated by the National Bank of Ethiopia (NBE) from the government treasury.

Fertilizer policies and strategies

Taking into consideration the limited scope for increasing the area under cultivation, diminishing soil fertility and population increase, the Government of Ethiopia saw the use of chemical fertilizer as a fundamental pre-requisite for achieving its goal of food security in the country. In order to create an enabling environment for the fertilizer sub-sectors and to make it instrumental in achieving the national goals of food self-sufficiency and food security, the government issued the comprehensive national fertilizer policy in November 1993 with the following goals:

- Promoting farmer's effective demand for fertilizers;
- Ensuring adequate supply of fertilizer through domestic production and import;
- Effective fertilizer marketing through the private and public sector and cooperatives;
- Developing appropriate pricing, subsidy and credit systems;
- Strengthening agricultural research and extension services; and
- Undertaking measures to protect fertilizer quality and the environment.

In order to achieve the aforementioned goals, the national fertilizer policy encompasses the following main objectives:

- Promoting competitive fertilizer marketing systems;
- Developing farmers’ effective demand for fertilizer;
- Ensuring that fertilizers are available to smallholders in the required quantity, product mix, at a time needed and at reasonable price; and
- Provision of the necessary support to the national research and extension system to generate packages of technologies (National Fertilizer Policy, 1993).

The policy envisages that distribution and marketing will be made more efficient by encouraging the private sector to participate fully in the importation, distribution, wholesale and retailing of fertilizer to promote competition and efficiency in the fertilizer market. Moreover, farmers’ service co-operatives will be promoted, organized and encouraged to participate in fertilizer distribution.

The national fertilizer policy also gave rise to the establishment of the National Fertilizer Industry Agency (NFIA) in 1994 to strengthen the institutional aspect of the sector and to better coordinate activities aimed at the development of the fertilizer sub-sector. With the objective of putting a systematic coordination of agricultural inputs in place, the National Agricultural Input Authority (NAIA) was established. During the restructuring of agricultural sector institutions in 2004, NAIA was dissolved and its duties and responsibilities were transferred to the Ministry of Agriculture to better coordinate and guide the input sub-sector under an umbrella organization.

Since the inception of the national fertilizer policy, the Government of Ethiopia has taken important measures towards the liberalization of the fertilizer market. Notable among these measures include:

- The deregulation of the fertilizer retail price, which took effect in January 1997;
- Withdrawal of the government subsidy for fertilizer in the same year;
- Issuance of fertilizer manufacturing and trade proclamation in 1998; and
- This issue of fertilizer import, transport and distribution guidelines in 2006, with the main objective of creating a system that ensures timely supply of fertilizer at a competitive price to smallholder farmers. The guidelines clearly outline duties and responsibilities of each key stakeholder in fertilizer marketing.

Although participation of private dealers in the fertilizer business is not expected for various reasons, since the inception of the national fertilizer policy:

- Annual fertilizer supply has been secured;
- Consumption was annually increased, though it is below the GTP target;
- Weight and quality has improved;
- Extension and research systems are strengthened; and
- Farmer's organizations come into the picture of fertilizer import and distribution, hence smallholder farmers get fertilizer on time at accessible places for relatively lower prices (1.5-2% profit margins compared with 5-10% margins for Indian cooperatives, and 6-7%, 2-10% and 7-14% for agro dealers in Kenya, Tanzania and Malawi, respectively.[2]

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[2]Insights on Agro-Dealer Programs in Africa and Possible Implications for Ethiopia. ATA Confidential Draft Report. 2012.

The process of fertilizer demand estimation

The approaches and procedures of fertilizer demand assessment in Ethiopia emanate from the overall fertilizer system prevailing in the country along with the key actors involved in the system. Fertilizer demand is assessed using a bottom up approach (from kebele to national level). The assessment is done ten months before fertilizer is needed to allow time for procurement, import and distribution to sales centers on time. The demand at woreda, zone, region and national levels are adjusted based on trends in the previous years and development plans. The actors in the demand assessment are public experts from kebele level (development agents) to the Agricultural Inputs Marketing Directorate of the Federal Ministry of Agriculture.

Under the current fertilizer demand assessment system the whole task of fertilizer demand assessment is done by Ministry of Agriculture experts from the development center to federal levels. The participation of fertilizer importers/distributors in fertilizer demand assessment and promotion task is generally weak.

The time when demand is assessed is critical as the information required demand is dynamic and depends on the time of the year (season). Information about weather conditions that will prevail during production seasons is normally determined at the time of assessment, which is closer to the appropriate season. Although Ethiopia’s weather forecasting capacity is increasing, its application to crop production in general and fertilizer demand assessment in particular, is still in its infancy. Similarly, information on market conditions for the produced crops is generally available after harvest. These factors normally require the time of demand assessment to be as close as possible to the production season. However, the time required for fertilizer procurement, import and distribution forces actors to estimate the demand about ten months in advance. Due to this, in most years holding high leftover stock is common. Thus, applying better demand estimation techniques that consider factors which influence fertilizer demands shall be employed.

Foreign fertilizer procurement process:

After demand estimation and upon securing the required foreign exchange for fertilizer import, the fertilizer procurement operation has to go through the following steps, which normally takes from 3 to 4 months until the first fertilizer shipment reaches the country. The steps are:

- Preparation of bid document;
- Tender floating;

- Bid opening, evaluation and award notification for the successful bidder;
- Supply contract signing between the importer and the supplier;
- Essential documents preparation and L/C opening by the importer;
- Follow up shipment, unloading at Djibouti port, transport and store arrangement.

Evaluation of offers includes:

- Technical specification;
- Price;
- Documentation (bid bond, various certificates); and
- Shipment terms and quantities.

Procurement option:

- Open tender: International Competitive Bidding (no short listing of suppliers and single supplier selection).

Shipping and logistics:

- 25,000 mt or above (in most cases): to obtain economies of scale in shipment;
- Bulk with bags: to reduce the relatively high labor cost of bagging at the supplier's country;
- C&F liner out: to avoid demurrage risk.

Inspection:

- Both at loading and unloading ports.

Delivery:

- About 95% direct delivery from vessel to trucks, to avoid additional port charges due to the keeping of the fertilizer in the stacking area.

Fertilizer marketing channels

From 1970 to 1984, several institutional reforms took place in fertilizer promotion and marketing in Ethiopia, including in the following institutions: the Agricultural and Industrial Development Bank, the Agricultural Inputs Marketing Service, and the Agricultural Marketing Corporation (which handled fertilizer procurement and distribution). From 1985 until 1992, all fertilizer imports, distribution and retailing was monopolized by the parastatal Agricultural Inputs Supply Enterprise (AISE).

Following the national fertilizer policy, six private importers/distributors joined the public parastatal that is AISE. These were: Ambassel Trading House, Dinsho Trading Company, Ethiopia Amalgamated Limited, Fertiline Private Company, Guna Trading House and Wondo Trading Company. As a result, the share of private companies in the total import increased from 19% in 1995 to 52% in 2000. Similarly, the share of private importers/distributors in the total sales of fertilizer increased from 19% in 1995 to 69% in 2000. In the early period of fertilizer market reform (1993-1996) many private wholesalers and retailers were also attracted to the fertilizer business and their number was more than 2,300 in 1996. However, the number of importers, wholesalers and retailers has dropped since 1999. Currently the participation of private retailers in fertilizer marketing is very limited. Even if they are operational, they act informally and deal with small quantities. These private dealers run other businesses besides retailing fertilizers (NFIA, 2001).

The major reasons of the decline in the number of private dealers could be shortage of working capital, lack of fertilizer business know-how, competition from importers in fertilizer retailing, the seasonal nature of the fertilizer business and hence unattractive profit margin compared to other businesses (Techane and Mulat, 2000; NFIA, 2001).

Similarly some private importers have ceased participation in fertilizer marketing due to various reasons. Studies sponsored by the World Bank and conducted by consultants in 2001 and 2005/2006 have indicated that private importers were not comfortable with the existing fertilizer procurement and distribution system. First, the import procedure was too long (it takes up to 7 months) and hence makes Ethiopian markets unattractive to foreign suppliers: secondly, a 100% counterpart fund which has to be deposited during the opening of L/C is very expensive for importers, as the fertilizer business requires huge capital. Thirdly, there was no level playing field as some local authorities were alleged to favor regional based companies.

Due to the above-mentioned problems and reasons associated with the entrepreneurial capacity of each importer, the share of private importers in the total fertilizer import declined to 20% in 2005/2006. On the other hand, the share of agricultural cooperative unions came on the scene of fertilizer imports in 2004/2005 with the main objective of ensuring timely fertilizer supply in the right quantity and at a reasonable price for their member farmers. Presently with the exception of one public enterprise and few private dealers, the fertilizer import and distribution task is handled by cooperative unions (95%).

Currently the importance of agricultural cooperatives has obtained a lot of recognition from the government of Ethiopia due to the fact that cooperatives can enhance farmers' group bargaining power to withstand unfair trading practices and thereby contributing to the improvement of agricultural input and output marketing.

The existing fertilizer marketing channel comprises one public enterprise and many cooperative unions as importers, wholesalers (farmer’s cooperative unions) and retailers (farmer’s primary service cooperatives and few private dealers).

There are more than 8,000 primary cooperatives that are distributing fertilizer to their member farmers. Farmer's service cooperatives mainly distribute fertilizer on cash and credit basis to their member farmers. Apart from the participants mentioned above, the federal and regional governments are also involved in providing facilitation services including demand forecasting, credit guarantee, provision of training and information to market participants, and coordinating transport operations.

The federal government consolidates regional demand and makes foreign exchange available to importers. The regional governments mainly provide facilitation services through the agricultural bureaus, departments and development agents in the area of demand assessment, and follow up timely distribution of fertilizer. In addition, they guarantee the input credit delivered by banks to farmers.

Latest developments in the fertilizer supply system

The major factors that affect fertilizer use in Ethiopia include: high price of fertilizer; limited types of fertilizers available in the market (only DAP and Urea); lack of crop and soil specific fertilizer recommendations; delays in timely distribution mainly due to shortage of trucks; an unsustainable input credit system; and irregular rain fall in some years. To address these problems the following major developments are being implemented:

- **Combined fertilizer procurement**
  Since the 2009/2010 cropping season, the government imports its total annual fertilizer requirements through one representative company/union in one or two tenders. This is to get price advantages from economics of scale, both from combined fertilizer purchase and port-to-central-warehouse transport. In this arrangement every year one company is elected to buy fertilizer on behalf of other importers and hand over the fertilizer at agreed central warehouses.
- **Reducing the dependency of smallholder farmers on regional government guaranteed credits**

Recently, regional agricultural bureaus are working to reduce the dependency of farmers on regional government guaranteed credits, in this regard bureaus are:

- o Encouraging farmers to buy fertilizer and other inputs with cash;
- o Strengthening rural saving and credit cooperatives and micro finance institutions, so that they can give input credit for farmers;
- o Introducing voucher credit systems; and
- o Encouraging the introduction of new financial products like weather index insurance in pilot werades/Kebles.

- ▪ **Promoting the use of organic fertilizers**
Recently the extension system is strongly promoting the use of organic fertilizers and scaling up best practices.

- ▪ **Training agro dealers**
In collaboration with the COMESA Regional Agro-input Program, fertilizer dealers and cooperatives were trained in agricultural inputs marketing and input dealer's accreditation criteria were developed.

- ▪ **Conducting trials on new fertilizers**
To introduce new fertilizers (other than DAP and Urea) in to the country, trials are under way in different agro-ecologies. Based on these trials recently new fertilizers like NPS and three types of micro nutrients have been introduced.

- ▪ **Treating acidic soils with limes**
To increase the return from fertilizer use in acidic soils, treating acidic soils with limes is gaining increasing attention and is implemented mainly in the four high fertilizer consuming regions. For this, lime mills were established in representative sites.

- ▪ **Developing crop and soil-specific fertilizer recommendations**
Soil calibration and apping is under way to come up with soil and crop specific fertilizer recommendations.

- ▪ **Establishment of fertilizer manufacturing plants**
is under way. Moreover, five small fertilizer blending plants at cooperative level are under construction.

- ▪ **Preparation of agricultural cooperatives sector development strategy**
To strengthen the participation of cooperatives in input and output marketing a five year cooperative development strategy was prepared. This strategy applies the experiences and lessons of both domestic and international best practices relating to cooperative enterprise promotion, while responding to

perspectives raised by stakeholders within the cooperative movement itself, the government, the private sector, and civil society. In particular, the strategy aims to address government's special development goals to improve smallholder farmers' productivity and income by leveraging a cooperative enterprise.

Table 1. Fertilizer consumption/sales (1993-2013).

Year	DAP	Urea	Total (Mt)
1993	90,109	17,348	107,457
1994	170,000	20,000	190,000
1995	202,312	44,410	246,722
1996	209,883	43,269	253,152
1997	168,623	51,808	220,431
1998	193,395	87,976	281,371
1999	195,345	94,919	290,264
2000	197,345	100,562	297,907
2001	181,545	98,057	279,602
2002	155,941	76,329	232,270
2003	157,955	106,394	264,349
2004	210,837	112,105	322,942
2005	224,819	121,735	346,554
2006	251,156	124,561	375,717
2007	259,020	129,121	388,141
2008	265,768	138,988	404,756
2009	278,239	148,437	426,676
2010	352,309	201,576	553,885
2011	350,233	200,345	550,578
2012	401,817	233,526	635,343
2013	456,618	272,625	729,244

Source: Ministry of Agriculture, Agricultural Input Marketing Directorate.

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Chapter 4

Fertilizer Financing in sub-Saharan Africa: The Case of Ethiopia

Gezahegn Ayele[1]

Abstract

The consumption of fertilizer in sub-Saharan Africa (SSA), in particular in Ethiopia has been increasing over time. Fertilizer consumption has risen since the beginning of the 1970s, although fertilizer use in region is still amongst the lowest in the world. The international price of fertilizer has also increased in correlation with fertilizer consumption. Fertilizer use and adoption has been promoted through various policy mechanisms in SSA; some countries have financed fertilizer with subsidies and some other countries without. Fertilizer financing in SSA is predominantly accessed through government credit systems, acquiring finance through banks. In some Eastern African counties, farmers are able to secure fertilizer on credit on the basis of area under cultivation and anticipated earnings from crop sales. There are specific initiatives for financing fertilizer in Africa. These initiatives have achieved some formidable steps in terms of securing funding, although the initiatives are at very rudimentary stages. Fertilizer import financing in Ethiopia is accessed predominantly via government budget through commercial bank credit facilities.

Agriculture and fertilizer financing in sub-Saharan Africa (SSA)

Introduction

The agriculture sector is the dominant sector in most African countries, especially in SSA. It provides employment to the majority of the population in rural areas and makes significant contributions to gross domestic product (GDP) and foreign exchange earnings. In SSA, agriculture employs 62% of the population (or around half a billion people) and generates 27% of GDP. Nevertheless, 226 million Africans are chronically undernourished and 5 million die of hunger every year. African agriculture is based on smallholder farming (less than 2 hectares): 80% of all farms are small and family-based. Because of its dominant role in the

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economy of African countries, agriculture has been called the engine of economic growth. In spite of its dominant role, agricultural productivity is low and the population dependent on agriculture is generally poor. Technological innovation is what is needed at the forefront of productivity in Africa. Although other inputs are necessary, this paper's main focus is on fertilizer financing because fertilizer use is low and nutrient depletion from soils is causing serious soil fertility degradation. Africa's soil is rapidly losing the nutrients essential for growing crops and protecting the environment, due in large part to the continent's low use of fertilizer. African farmers apply only 5–10% of the fertilizer amounts used by their counterparts in other developing regions, such as Asia. And even this amount is projected to decline in the near future due to the rapid increase in global fertilizer prices. Financial capital is a panacea for input use and growth in agriculture.

Fertilizer financing in SSA

Although other inputs are equally necessary to boost African agriculture, this paper's main focus is on fertilizer financing as fertilizer use is low and nutrient depletion from soils is causing serious soil fertility degradation. Many factors affect both demand and supply of fertilizers. The issues related to financing deserve special attention as inadequate and untimely supply of fertilizers at the farm gate itself is a manifestation of inadequate supply of fertilizer in SSA.

Many factors are believed to be responsible for low fertilizer use in Africa. One of the problems for low adoption of fertilizer is lack of finances related to credit. The underdeveloped and fragmented nature of the fertilizer market in rural areas is caused by many factors including policy, institutional, infrastructural, political, and economic (predominantly lack of finance).

Improving the supply of fertilizers requires alleviating all constraints that affect the fertilizer supply chain at both national and regional levels in Africa. Cooperative systems may or may not be equivalent to private-sector channels in terms of effectiveness or efficiency. The system where government agencies take complete responsibility for the supply of fertilizer and other inputs is rapidly disappearing as markets are liberalized. In Ethiopia, the input marketing directorate in the Ministry of Agriculture is responsible for the coordination of imports although it is no longer responsible for actual procurement. Imports are handled through the Agricultural Input Supply Enterprise (AISE), another agency responsible for importing fertilizer. In many countries though, government agencies or ministries are responsible for implementing national fertilizer programs, e.g. the targeted input program in Malawi and the fertilizer support program in Zambia. Implementation of these programs is still frequently non-market friendly and disruptive to liberalized markets; for example, in Angola and Nigeria, subsidy schemes and donors' supplying fertilizer undermines commercial activities. To address fertilizer costs in Kenya, the government recently implemented a subsidy program and price controls aimed at bringing prices down. Before market liberalization, these vertically integrated systems were generally poorly implemented and were neither effective nor efficient; with the most frequent faults being pan-territorial pricing and late arrival of fertilizer to meet market demand.

There are two common forms of commercial procurement practices: (a) procurement by tender and (b) procurement by direct negotiation with suppliers. Both procurement routes are used by the public and private sectors. Tenders are competitively bid for and, there is adequate and timely information available on international price formation from trade publications in traditional and electronic formats. Products can be purchased in various ways: Free on Board (FOB); Cost and Freight (CFR); Cost, Insurance & Freight (CIF); and on various other terms. Advantages and disadvantages for these various sales contracts vary depending on the circumstances and the skills and experience of the purchasers. In SSA countries, procurement is undertaken by both the private sector and governments; often by both sectors within a country. This happens when governments procure on behalf of donors or through government distribution agencies and the private sector imports commercially. These combined efforts of procurement are usually disadvantageous for the private sector due to uncertainty over the level of government procurement. Fertilizers are bulky materials and vary in nutrient content. International freight costs are an important consideration in keeping import prices down. Virtually all fertilizer materials can be shipped in bulk, but at a considerable freight. Vessels of 20,000 to 25,000 Mt are frequently used for fertilizer shipments, but there are many ports in SSA that cannot accommodate such vessels for bulk unloading. Exceptions include Beira, Dar es Salaam, Djibouti and Lagos. Smaller vessels of approximately 10,000 tons add to shipping costs by a premium of between 10% and 15% over more suitable larger vessels. Because African markets require bagged product, a considerable cost saving is realized by bagging bulk cargoes on port arrival (Gregory and Bumb, 2006). Other considerations affecting import costs include port charges, inspection fees, discharge costs, agents' fees, bank and finance charges, duties and taxes, clearance fees, and demurrage/dispatch. In congested ports, such as Lagos, Nigeria, it is often difficult to determine in the charter party contract a fair port and discharge time because berthing delays are frequent. When delays occur, demurrage costs can be as high as $10,000 to $20,000 a day for a 10,000 Mt ship, which can add $1-$2/Mt for each day's delay.

Finance is the lifeblood of fertilizer use and any business development for that matter, but limited access to finance resulting from high interest rates, underdeveloped financial infrastructure~~s~~, stringent collateral requirements, and the risk-averse attitude of commercial banks toward agriculture and agribusiness make it difficult to obtain the necessary funds for business development. Equally difficult is to get a Letter of credit (LC) for importing inputs.

Since capacities are limited and direct negotiations with trading partners are restricted; the reliance on importers who are general traders also reduces the possibilities for supplier finance handled through an opening LC. Regional procurement arrangements may offer opportunities for securing supplier credit on favorable terms. The promotion of business linkages between importers, wholesalers, and retailers could open the door for suppliers' credit for business development. Most credit programs in SSA have attempted to deal with the credit needs of small farmers, and little attention has been paid to the needs of the importers, wholesalers, and retailers. Three distinctive credit products should be recognized: importer credit, wholesaler credit, and retailer credit. Imported fertilizer is financed through US$-denominated irrevocable LCs. Access to foreign exchange is essential. Importers require transport and handling internal transport costs to be high in SSA because of long transport distances and very poor infrastructure. The poor condition of feeder roads in rural areas adds significantly to the transportation cost of supplying inputs, especially fertilizers, in rural areas.

Fertilizer import and consumption: multi-country approach

Ethiopia imports one of the highest volumes of fertilizer of the COMESA countries, particularly compared with Mozambique, Uganda and Rwanda. In Ethiopia, commercial fertilizer imports, including consumption, have reached about 1.2 million tons, with Diammonium Phosphate (DAP) fertilizer commanding the lion's share (MoA, 2012). In 2010 and 2011, fertilizer consumption was 553,885 and 550,530 Mt respectively, representing a 30% increase from 2006 levels; made up of DAP and UREA fertilizers. Compared to the rest of the SSA, Kenya has relatively high fertilizer use per hectare. Fertilizer use is estimated at 35.3 kg per ha of arable land; higher than the average of 12.74 kg for the SSA region, or 0.95 kg in Uganda, and 35 kg in Ethiopia (World Bank, 2001). Following Ethiopia, in 2011, Kenya's fertilizer imports stood at around 500,000 Mt an increase from 245,000 Mt in the early 1990s. Over the last decade, fertilizer consumption has grown by over 50% from 230,000 Mt to 500,000 Mt respectively, with DAP commanding the highest share followed by 25:5:5+5s. Potential consumption is estimated to be over 1 million Mt, implying that only 30%, of this potential has been realized, on average. This Fig. is comparable to Ethiopia; with current actual supply around 1.1 million Mt. The tendency is that Kenya and Ethiopia enjoy more economies of scale for bulk purchasing and selling. On a lateral scale, the two countries use more fertilizer and as a result, import almost 2/3 of fertilizer compared to other COMESA counties - including Malawi, Rwanda, Tanzania and Uganda combined. Although import and consumption of fertilizer has increased in other COMESA countries (Malawi, Mozambique, Rwanda, Uganda, Zambia and Zimbabwe), the level of fertilizer use is still low, below the 50 kg per ha target (Table 1).

Table 1. Level of fertilizer use (Mt) in 2011 in COMESA countries.

	2005/06	2006/07	2007/08	2008/09	2009/10	2010/11
	--------------	--------------	----- *Mt* -----	--------------	--------------	--------------
Ethiopia	346,554	375,717	388,141	404,756	553,885	550,000
Kenya	383,285	410,214	390,740	470,508	503,174	500,000
Malawi	291,982	302,547	305,605	328,580	328,580	330,828
Mozambique	28,000	28,000	32,000	33,000	33,000	55,000
Uganda	-	-	-	-	-	115,000
Zambia	-	158,208	134,558	-	-	260,000
Zimbabwe	240,000	250,000	200,000	230,000	300,000	350,000
Rwanda	6,593	-	-	-	13,000	-

Source: COMESA/ACTESA, 2012.

Fertilizer use in Uganda is amongst the lowest in the world. For instance, between 1996 and 2000, fertilizer use in Uganda was estimated at just 1Kg per ha, which is 0.2% of the required quantities. The annual import and consumption of fertilizer in Uganda is almost negligible - from 2006 until 2008 it ranged from 25,000 Mt to 30,000 Mt; a single lot shipment for Ethiopia. This is also less than the fertilizer consumption of one Ethiopian region, SNNPR. Similarly, fertilizer consumption in Rwanda was 1.11 kg per ha as of 2009. Its highest value over the past 5 years was registered close to 8.33 in 2008. Despite the many fertilizer projects (FAO trials and demonstration plots as well as efforts by bilateral donors), aggregate consumption reached a peak of only 6,593 Mt. Although consumption and import data are scarce, just before the war in 1993, imports reached an all-time high of 13,192 Mt. Because over 50% of COMESA countries import less than 10,000 Mt, there are little economies of scale in import and transport of fertilizers. In this respect, single shipment is considered as bulk on 25,000 Mt.

Blended fertilizers

The supply side of the fertilizer market represents part of the value chain challenges in SSA. The supply of fertilizer nutrients for agriculture requires raw materials - natural gas, phosphate rock (PR), sulfur, and potassium salts - for fertilizer production. SSA is deficient in raw material resources. SSA is essentially deficient in supplies of natural gas; exceptions are Angola, Democratic Republic of Congo, Ethiopia, Equatorial Guinea, Madagascar, Mozambique, Namibia, Nigeria and Tanzania. Substantial commercial PR deposits exist in Senegal and Togo although there are numerous smaller deposits throughout SSA including in Ethiopia (Gregory and Bumb, 2006).

The situation is very different in North Africa and South Africa. Morocco is the largest producer of phosphate fertilizers in Africa and ranks at number six in world production, and Algeria, Egypt and Tunisia are producers of both phosphates and nitrogen fertilizers. In South Africa, there are significant PR deposits and production of phosphate fertilizers. Nitrogen production in South Africa is based on coal as the hydrocarbon source rather than natural gas. Approximately 80% of potash fertilizer production is concentrated in five countries: Belarus, Canada, Germany, Israel and Russia. There was potash fertilizer production in the Congo from 1969 to 1977, but annual production never exceeded 285,000 nutrient tonnes compared with the world production of 25.8 million nutrient tonnes. There are potash reserves in Ethiopia, which are yet to be exploited and used for fertilizer production.

Blended fertilizers developed in the North American market and production has spread around the world, but these are not a primary production source. These products use solid finished fertilizer materials such as urea, diammonium phosphate, and muriate of potash blended to form various grades of NP, PK, and NPK fertilizers. Blending plants have been established in SSA notably in Kenya, Malawi, Nigeria, Zambia and more recently, in Ethiopia. By using soil testing, it was possible to blend fertilizers to suit the requirements of individual fields and crops. Blending was facilitated by information and communications technology and global positioning technology; this approach has been further refined to “precision farming”. Small bulk blending plants allowed retailers to bring in finished products in bulk and distribute prescription bulk blends in response to local market areas. These bulk-blending plants average about 5,000 t in annual sales and distribute and apply the bulk-blended product directly to farms within a 50 km radius.

Highlights of fertilizer financing initiatives

Recognizing the critical role that fertilizers play in the effort to boost African farm production, the African Development Bank (ADB) called for the establishment of the Africa Fertilizer Financing Mechanism (AFFM) as one of the major resolutions of the June 2006 African Union's (AU) Africa Fertilizer Summit in Abuja, Nigeria. At the Summit, African heads of state and high-profile individuals decided it was necessary to establish an AFFM for the purpose of increasing fertilizer use in Africa to boost agricultural productivity. This would contribute to economic growth, food security, and sustainable management of natural resources in Africa.

With the support of the UN Economic Commission for Africa and the AU Commission, the AFFM was established in March 2007, and is hosted and managed by the ADB in Tunis, Tunisia. On 4 December 2007, the ADB’s board of directors endorsed the legal instrument and framework for the establishment of the AFFM. The AFFM secretariat has been operational at the ADB with bank support. The aim of the AFFM is to support Africa's agricultural sector. Key areas of intervention and support include: Facilitation activities including policy formulation, technical assistance, information dissemination, law reform, and project preparation; development of Africa's fertilizer manufacturing capacity; support for the establishment of regional fertilizer procurement and distribution facilities; and, to establish financing mechanisms in support of fertilizer production, distribution, and agriculture generally.

At the 2006 African Fertilizer Summit in Nigeria, African heads of state met and signed the Abuja Declaration, in which they pledged to work together to address the continent’s soil fertility crisis by boosting the production and availability of fertilizers throughout the continent. Since the Abuja meeting, the ADB, and other experts from the public and private sectors have developed a series of proposals for an AFFM to serve as a vehicle for financing activities to address the soil fertility crisis and increase access to and affordability of fertilizers in Africa. The AFFM’s specific target is to achieve at least a six-fold increase in fertilizer use. This would mean boosting the current average of 8 kg per ha to at least 50 kg per ha by 2015.There is also some effort to harmonize input procurement with COMESA and facilitate funding mechanisms for joint procurement. The AFFM will work multilaterally with African governments, regional institutions, the private sector, other development banks, and international donors. The AFFM will assist African public and private sectors to conduct feasibility assessments and secure financing for promising fertilizer production ventures, including agricultural lime. The mechanism is also expected to improve the economies of scale of fertilizer production, procurement and distribution; for example, by creating holding warehouses at ports of entry that make fertilizers available in the region throughout the year, and make them accessible to farmers in time for planting.

So far there has been no operational achievement although the AFFM secretariat was established at the ADB in March 2007. The bank has also received and is considering proposals for possible AFFM support including: a) a feasibility study to establish a fertilizer production plant for the East African Community (EAC); b) a fertilizer procurement facility pilot for the EAC; c) exploitation of phosphate rock deposits in DRC and Mali; and d) bio-fertilizer production in Cameroon.

Fertilizer procurement and imports in Ethiopia

Fertilizer imports

At present, Ethiopia depends wholly on imports to meet its annual fertilizer demand. The foreign exchange needed for fertilizer importation is financed through loans, donor assistance (grants) and government treasury. Hence fertilizer supply relies on Forex and valuations of fertilizer in global markets. However, aware of the strategic role of the fertilizer sector in achieving self-sufficiency and alleviating poverty, the government of Ethiopia is heavily involved in the sector and ensures foreign exchange is available to importers through bidding, whilst encouraging more fertilizer use at farmer level. Fertilizer procurement is handled through the Ministry of Agriculture (MoA) input marketing directorate. The process starts with opening up a tender document in the National Bank of Ethiopia (NBE). According to the agricultural input and marketing directorate, the fertilizer procurement process begins with a demand assessment from the end users of last mile distribution; primarily individual farmers facilitated by farmers organizations. The MoA aggregates regional demand data, combined with the previous year leftover stock available in each regional warehouse, and compiles the volume of fertilizer to be procured and passes it on for decision. The ministry, in consultation with AISE, then prepares tender documents and invites the board of trustees to approve the documents for bidding of fertilizer imports. The trustees are drawn from the Ministry of Finance and Economic Development, NBE, Commercial Bank of Ethiopia (CBE) and the Quality and Standard Authority. The tender specifies quantity, often in the range of 20,000-25,000 Mt. Tenders are priced at the ruling price at the time of tender. For the 2012 season, for example, the first tender floated and negotiated to secure the annual requirement for DAP of 750,000 Mt was called in September 2011. The balance was retendered in January at prices in the $645 to $650/Mt range with a reduced price. The DAP tender of January 17, 2012 for 232,000 Mt for March/April delivery, attracted offers of a oversubscribed 1.4 million Mt, with a band of reduced price. With such flexibility of tendering, with netbacks to Morocco estimated in the high $550’s, just on the high side of the trading band for that week outlined in

"Fertilizer Week", but the important point is the landed cost is competitive (see DAP fertilizer monthly price - US$ per ton July 2010-July2015).

There are some advantages and disadvantages of setting large contracts for future deliveries particularly with increased price volatility observed in fertilizer commodity pricing since 2008. There could be some win-win situations particularly with regards to increasing domestic food grain supply and price volatility. In volatile markets often it is advisable and beneficial to pay the market price, rather than predicted market price (Bumb and Ayele, 2010). Nevertheless, studies need to be conducted before decisions are made to arrive at a reasonable cost-benefit especially when we have price volatility in both input and output markets.

Since 2005, a number of cooperative unions have been involved in direct import and distribution of fertilizer to members and non-members alongside AISE. For a few years starting in 2006, cooperative unions were provided with credit to import and distribute fertilizers. Their market shares grew rapidly, reaching 75% of total fertilizer imports (about 300,000 t) in 2007/2008. However since 2009, it was recommended by government that fertilizer imports be held by a sole importer, AISE, as bulk procurement in fertilizer lowers the cost by about 4%. In addition it allows for timely delivery of inputs before the cropping season starts. This policy change in fertilizer marketing means that AISE, as the sole importer, is responsible for issuing tenders and arranging for international procurement of fertilizer for the country's needs, as well as shipments from Djibouti port to the central warehouse. The role of unions is limited to fertilizer distribution from central warehouse to primary cooperatives and farmers or end users. The centralized procurement system may contribute to the timely allocation of foreign exchange and fertilizer procurement, reducing transaction costs (World Bank, 2011). Such types of sole procurement may be advantageous in countries where foreign exchange supply is restrictive and where market forces do not operate. Although, a single import system creates a monopoly in fertilizer marketing thereby eliminating fertilizer importing business; overall, it has improved efficiency in coordination of fertilizer and timely distribution. The overall procurement period has been estimated to take on average 220 days starting from the date of the bid. But in the current sole importing arrangement, the period was reduced by about 20 days. Currently, over 90% of domestic marketing is handled through cooperatives.

It is clear from Fig. 1 that fertilizer imports have historically increased linearly, particularly post-1993 in the liberalization period. Imports shot upwards drastically in 2008/2009 and reached a level of total supply (import and carryover) of more than 800,000 mt in 2010/2011. This Fig. was more than 1 million t in

2011/2012. As a result, total carryover stock was about 300,000 mt in 2010. Over 550,000 mt of fertilizers have been imported to the country (MoA, 2012).

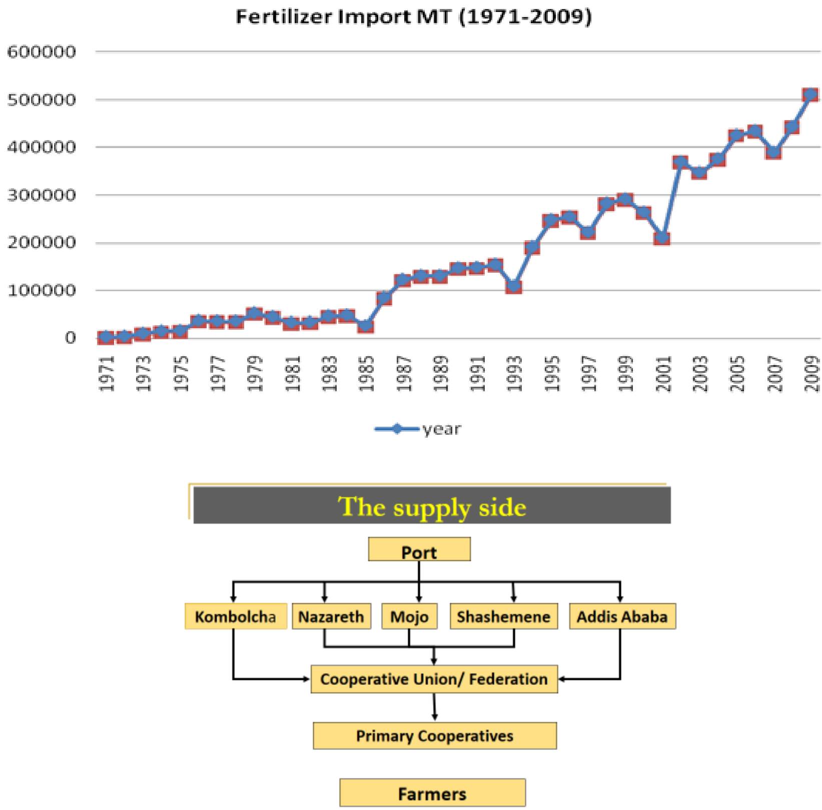
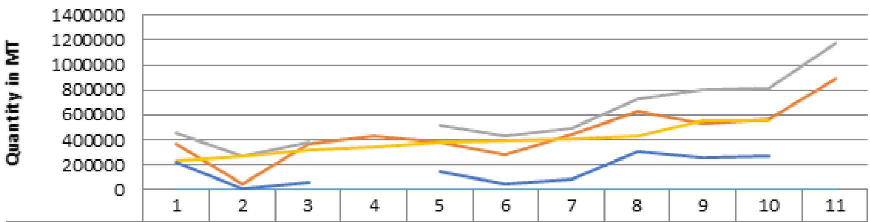


Fig. 1. Fertilizer import.

The average national fertilizer application per hectare of cultivated land remained negligible from the 1970s to the mid–1980s, ranging from 0.1 kg per ha in 1971 to 4 kg per ha in 1985/1986. Beginning in 1986, it started to grow steadily and then declined again in 1993 as result of devaluation. Fertilizer application grew from 22.1 kg per ha to 35.4 kg per ha from 1991/1992 to 1999/2000, with a spurt in growth with the initiation of the Professional Alliance for Development in Ethiopia in 1995/1996. However, due to the sharp increase in international prices in 2008, fertilizer imports have declined by about 28%. In particular, imports of urea have dropped from 153,000 t in 2005/2006 to 50,000 t in 2006/2007. Another estimate between 1995 and 2005 also indicated that the average fertilizer use increased from 250,000 t (21 kg per ha) to 323,000 t (32 kg per ha) of product. In fact, weighted average c.i.f. import prices of urea at Djibouti port have increase by 32.2% in 2008 compared to 2006, while prices of DAP have increased only by about 14%. At aggregate level, total fertilizer availability amounted to about 433,000 t in 2006/2007, comprising about 277,000 t of new imports and about 157,000 t of carryover stocks. Despite significant increases in base prices of DAP to around 420-440 Birr per quintal ($511/t) and to around 380-390 Birr per quintal ($444/t) for urea, DAP sales went up or at least remained stable. During the small rainy season, commonly known as “belg season”, fertilizer consumption and use comprises less than 20% of the total consumption of fertilizer; the highest proportion (or consumption) is during the main rainy season “meher” and thus Ethiopia requires contingency reserves for the small season.



	1	2	3	4	5	6	7	8	9	10	11
year	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
import	368'42	46'041	374'68	424'52	385'57	276'72	442'10	626'73	525'27	568'67	888'00
Total aval	457'54	271'32	380'60		521'01	433'31	487'57	728'20	806'09	818'05	1'169'
sales	232'27	264'34	322'94	346'55	375'71	388'14	404'75	426'67	553'88	550'57	
carryover	225'27	6'973	57'665		145'30	45'174	82'818	301'52	252'21	267'47	

Fig. 2. Fertilizer import, supply and demand.

The MoA and AISE have slightly different estimate Fig. s for fertilizer supply data. Fertilizer consumption (or demand) was at one of its highest levels in 2010 during the closing of the Plan for Accelerated and Sustained Development to End Poverty, standing over 818,054 Mt. This has increased almost 23% over the 2009 period. The total carryover stock estimated from official Fig. s was 252,211 mt, which could be assumed to be excessive stocks in Ethiopia accumulated at the end of 2009/2010. The recent Fig. shows that there is close to 550,000 t of overstock, which equates to over 1 million mt when combined with new imports. With this trend, the future supply is expected to increase by more than half a million mt.

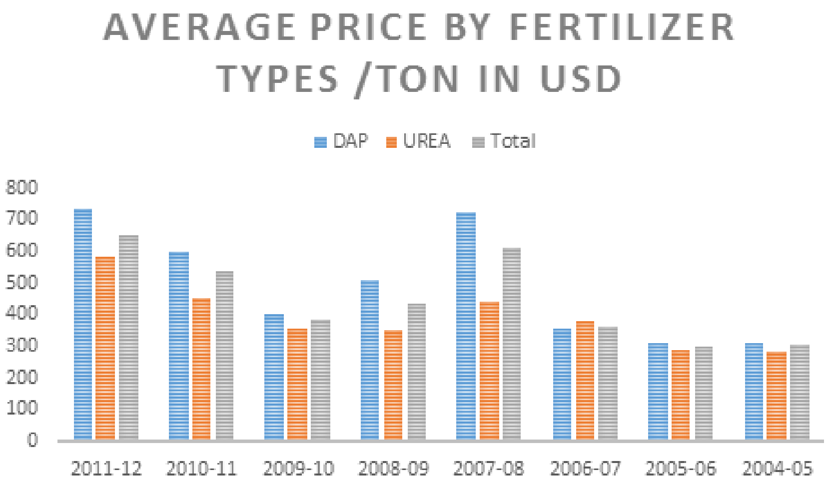


Fig. 3. *Source:* MoA Input directorate.

Fertilizer financing

In general, fertilizer import financing in Ethiopia is predominantly accessed through government budget. However, relying on government budget becomes unsustainable because of foreign exchange shortages. Under the condition of foreign exchange constraint the government has to depend on other sources of financing, for example donors and multilateral agencies such as the World Bank. The fuel, food and fertilizer crisis of 2007/2008 for instance, followed by the financial crisis, created severe foreign exchange shortages in Ethiopia. The availability of foreign exchange was reduced from the normal level of three months import requirements to less than one month's import needs. To ensure adequate supply of fertilizer under such conditions, in 2008 the Government of Ethiopia requested that the World Bank approve an emergency loan of $250 million to support the import of fertilizers for 2009 and 2010 cropping seasons. Due to the emergency nature of the loan and urgency of the situation, a detailed project appraisal was not conducted nor any policy, organizational, or technical changes solicited during the implementation of the project. The bank took nearly six months to approve the loan (International Development Association credit) and it was finally approved in May 2008. The project was meant to only provide foreign exchange support for fertilizer imports. The World Bank has only financed such a unique project for emergency purposes a few times over the last fifty years (from 1960 until 2010). There has also been very limited financing from AfDB for fertilizer imports.

The market structure for fertilizer imports and distribution is closely tied to credit programs. In the import market, the importer is required to deposit 100% of the value of fertilizer to be imported, at the time of opening a line of credit. To ensure uptake of technological packages, regional governments started a 100% credit guarantee scheme in 1994. In the early 90s about 90% of fertilizer was delivered on credit as part of technological packages, displacing what had previously been retail sales, including a substantial cash-based share from the private sector. The credit is extended by CBE through cooperatives, local government offices, and more recently micro-finance institutions and one cooperative bank, to farmers to finance extension packages (of fertilizer and seed). Since 1994, the number of active cooperatives, cooperative unions, and micro-finance institutions has increased, gradually assuming part of the guaranteed credit program. Record-keeping and collection of interest and principal is done by regional authorities and cooperative unions. Thus, CBE only serves as distributor of funds with virtually no transaction and risk costs. As a result of the credit guarantee, the number of defaults has been nearly non-existent in the past two decades from the federal government block grants to each of the regions. This has created a burden on the budgetary resources of regional governments. However, there are two developments that took place recently changing the pattern of fertilizer financing. Firstly, fertilizer credit guarantee burden is shifted from regional government to cooperative unions or federations and secondly, instead of financing through credit most fertilizer sales shifted to cash-based sales, which led to a decrease in local fertilizer credit default rate. Currently, fertilizer import is handled through the government institution AISE on behalf of unions. The recent attempt to move into ICT-based financing mechanisms is expected to improve fertilizer financing and the availability of credit on time. For domestic financing, overall the role of the private sector and its participation in the bidding process has declined in the international market for importing fertilizer. Nevertheless, many unions and federations were participating in the bidding process, which is considered to be an agglomeration of farmers' organizations.

The role of the private sector has declined due to several factors. At the import level, import licenses are allocated by a tendering process in lots of 25,000 mt; the private sector is not interested in the bidding and importers prefer to invest different areas. On the second level up, foreign exchange supply is limited, linked to the post-1992 partial liberalization of the input market. The private sector gradually became dominated by holding companies (for example Ambasel, Dinsho, Guna, and Wondo) which were given relatively favorable access to input markets. Consequently, there was increased competition among public, private, and endowment companies from 1997 until 2000, with private companies dominating followed by endowment companies taking over from 2001 until 2006. From 2007 onwards following global price hikes, the number of holding companies diminished and the entrance of many farmers' cooperatives increased, with AISE playing a dominant role as sole importer on behalf of cooperatives. Over 90% of the current import and distribution is handled through cooperatives, with the remaining amount import and distribution is handled by the public sector, primarily AISE. Nevertheless, the role of cooperatives has been limited to distribution. All import is handled through AISE on behalf of cooperatives, by pooling together their demands. This procedure was thought to be efficient, as assessed in 2010 (World Bank, 2010). Overall emergency financing during crisis may have its own risks and shortcomings, for two major reasons: First and foremost, such unprecedented increases in fertilizer prices reduces the use of fertilizers by smallholder farmers, leading to a reduction in food production, thereby leading to hunger and malnutrition for both rural and urban populations. Secondly, the fertilizer crisis may force national governments to introduce drastic measures like price and marketing controls, thereby compromising long-term development efforts. Hence it is very important to have alternative sources of financing mechanisms; to reduce the risks associated with financing and, to increase the sustainability of importing fertilizer without compromising development.

The current trend suggests that Ethiopia will move towards importing various sources of fertilizer and blending its own fertilizer; this move, towards importing various fertilizer and blending, will provide alternative forms of fertilizer mechanisms based on the latest communication technologies. The recent move to establish a cooperative-managed fertilizer blending facility at Tullu Bolo is one step forward. Based on scientific study of soil fertility mapping, more urea and other fertilizer products are being imported and blended to meet specific crop and soil demands. This provides an impetus and is also a major advance in the use of balanced fertilizer to increase agricultural production and productivity, a culmination of over four decades of blanket fertilizer advisory work. Nevertheless, a very sustainable financing mechanism is needed for fertilizer. This could be managed through a business model, for example using a 70:30 ratio of credit.

Conclusions

Innovative approaches are needed to alleviate financial constraints to business development. Business models based on risk-sharing fund mechanisms are needed to improve access to finance for importers and dealers. In most of SSA, agricultural input import funds are managed and maintained for foreign exchange supply by central banks, which would be accessible for any importer licensed for importing fertilizers to get a LC from the bank. This arrangement could be with 70:30 business credit. This will help to reduce the cost of imported fertilizers by lowering the funds needed to acquire an LC. Although operational activities have not yet commenced on the ground, much has been achieved in terms of preparatory work, including hosting and operationalizing the ADB-AFFM secretariat, as well as mobilization of support for the AFFM through consultation with stakeholders. The mechanism enjoys strong support from African political leadership. In accordance with the instrument establishing the AFFM, for it to become legally operational, the mechanism needs financial contributions and/or instruments of commitment from African governments and donors. In Ethiopia, although the financing mechanism is not institutionalized and is in place, there are various on-going initiatives to modernize the financial mechanism, equipping modern IT systems and linking financing input through banks. There is an important shift occurring and tremendous progress being made in terms of fertilizer blending and consumption. The current practice of introducing new types of fertilizer usage into farming systems call for new organization and financing mechanisms of fertilizer. The need for Triple Superphosphate fertilizer and potassium fertilizer demands more funding and financial systems. The benefit of bringing such fertilizer into the cropping system is obvious, in that farmers will benefit from increased productivity and higher level of income that lead to a reduction of poverty. Overall, fertilizer financing requires African-wide strategic thinking for sustainable fertilizer financing.

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Chapter 5

Potassium Fertilization: Paradox or K Management Dilemma*

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and Ernest A. Kirkby[4]

Abstract

In 2014, Khan *et al.* presented evidence that soil exchangeable K (Exch-K) increases over time without addition of potassium (K) to the soil despite the removal of K in crops on a soil rich in montmorillonite and illite. The authors term this behavior 'The potassium paradox'. From their review of the literature, the authors also report a lack of crop response to potassium chloride (KCl) fertilization. Close evaluation of these findings reveals that their observations can be interpreted and predicted using current knowledge of K in soil chemistry and its uptake by plants, and there is no paradox in K behavior in the soil-plant system. There is also no evidence of a detrimental effect of KCl on crop yield or quality. Their conclusion that the widely used Exch-K soil test is inadequate for managing K fertilization is discussed and some possible modifications to improve its performance are included. We believe that measurement of Exch-K is an essential and valuable tool and its use should be continued, along with improvements in recommending K fertilizer application.

Keywords: Exchangeable potassium; capacity/intensity; chloride; potassium fertilizer recommendations; non-exchangeable potassium.

Background

In 2012, Mueller *et al.*[1] reported in Nature a global study of fertilizer and irrigation needs to close yield gaps for the three most important world cereals -

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maize, wheat and rice - in relation to an approximate doubling in human food requirements by 2050. Their findings showed that in 73% of the underachieving areas worldwide, yield gaps could be closed with acceptable yields obtained (a 29% global increase), solely by focusing on the nutrient inputs. The required increases in nitrogen (N), phosphorus (P) and potassium (K) application relative to baseline global consumption were evaluated as 18, 16 and 35%, respectively. In light of this work, the required increases in nutrient supply in low-yield regions on the one hand, and the current trend of reducing fertilizer use in high yielding regions on the other, the study by Khan *et al.* is timely. Although the authors indicate a need for a reassessment of our ability to manage potash fertilization using existing K soil tests, their reports of little response to K fertilization on many soils and the adverse effects of potassium chloride (KCl), the most commonly used K fertilizer, on crop yield and quality must be questioned.

The main concerns raised by Khan *et al.*[2] are twofold. First, they argue that soil exchangeable K (Exch-K), the main K soil test for predicting crop requirement, is inadequate to evaluate soil K availability. They support this claim from the analysis of soils from the long-term 'Morrow Plots' experiment at the University of Illinois sampled in 1955 and 2005. After 51 years, the Exch-K in the K-unfertilized plots exceeded that of the initial value, and the K uptake in low soil K plots exceeded the K uptake predicted by Exch-K tests. A 4-year field study further showed that Exch-K estimation was dependent on the water content of the analyzed soil samples (field moisture versus air dryness). Second, they conclude that KCl fertilization is unlikely to increase crop yield and, moreover, that it is predominantly detrimental to the quality of major food and fiber crops. The authors support this claim on the basis that only in about 24% of the approximately 300 published papers they reviewed was there a beneficial effect of KCl supply on crop yield, and only in 8% was there an improved crop quality. This commentary evaluates the authors' assessments, statements and conclusions.

Data Evaluation and Discussion

Evaluating the suitability of Exch-K for estimating soil K supply to plants

The authors reconfirm the known effects of soil moisture content and seasonality on Exch-K test values (Figs. 1 and 2[2]). As the Exch-K test involves a strict protocol of sampling (soil depth and timing) and preparing for analysis (soil moisture content and sieve size), the importance of the above factors in determining Exch-K is low as long as sampling and preparation follow prescribed instructions.

The data in Fig. 1 in Khan *et al.*[2] indicate an increase in Exch-K over a 4-year period (1986-1990) in a silty clay loam soil, with montmorillonite and illite as major clays, without K addition and despite crop uptake. Such a result could be predicted from the studies by Galadima and Silvertooth[3], Jalali and Zarabi[4], and Ghiri *et al.*[5], which showed that in arid soils, the rate of release of fixed K to the soil solution is 12-75 μmol K kg^{-1} $soild^{-1}$, depending on the soil type and the length of extraction. This value can be compared with a rate of release of 20 μmol K kg $soil^{-1}d^{-1}$ for a crop absorbing 200 kg K ha^{-1} in 100 days from the 0 to 20 cm soil layer. The fact that the quantity of fixed K in the 0-20 cm soil layer ranges from 5 to 27 t ha^{-1}, depending on soil minerals and climate[6] and annual intake is about 0.2 ton (t) ha^{-1}, proves that in many cases K released from fixation sites may cause an increase in soil Exch-K over several years.

As further evidence, in support of the findings in Fig. 1[2] the authors also cite the results from the Morrow Plots (montmorillonite and illite containing soil) showing that Exch-K increased by more than 50% between 1955 and 2005, particularly in low K treatments, and despite a K removal estimated at 1.4 t K ha^{-1}. In addition to the contribution of fixed-K release, the authors interpret the increase in Exch-K as a consequence of root uptake of K from below 20 cm in the soil profile and its release from plant residues in the top 0-20 cm soil, a mechanism also investigated by others, including Barraclough and Leigh[7] and Singh and Goulding[8]. Considering these facts, the results from the Morrow Plots cannot be regarded as a paradox. Moreover, Nafziger[9] reported that soils sampled frequently in the Morrow Plots (in the continuous corn experiment) between 1967 and 2008 did not show an increase in Exch-K (except for a short time following deep tillage), which raises doubts regarding the long-term K balance estimation in this historic experiment. A similar result of apparent steady Exch-K over time in the Broadbalk experiment in England between the years 1856 and 1987 was reported by Singh and Goulding[8], but not cited in Khan *et al.*[2].

Bar-Tal *et al.*[10] studied K transformations in a montmorillonitic silty loam loess soil over one growing season of sweetcorn in a pot experiment. Under zero K fertilization they found that fixed-K contributed to about 35% of the K consumed by plants, and under KCl application of 10 mmol K kg^{-1}soil the K uptake increased and fixation of 12% of the added K was observed. The long-term Exch-K balances were also checked in a montmorillonite-illite clay soil in the permanent plots experiment at Bet Dagan, Israel, over 30 years[11]. The initial (in 1963) cation exchange capacity (CEC) and Exch-K were 380 and 13.7 mmolc kg^{-1} soil (0-20 cm), respectively. In 1993, the Exch-K in the unfertilized plots was 20.9mmolckg-1, with no change in CEC, whereas in treatments receiving 30 and 60 g Km^{-2} once every 3 years, the final Exch-K was 19.5 and 14.3 mmolc kg^{-1}, respectively. In 2009, treatments receiving high N, and thus taking up more K, fixed-K was released from soil-illite to furnish the enhanced K consumption[11]. These results, which are not included in the Khan *et al.*[2] paper, confirm their findings. The uptake of K by the crop exceeded the change in Exch-K plus the applied K, and also there was an increase in Exch-K over time where no K was applied; the results also prove, however, that all the data can be quantitatively interpreted and theoretically explained without recourse to a ‘potassium paradox’.

Evaluating the claim that KCl fertilization is unlikely to increase crop yield, impairs yield quality and deteriorates soil productivity

Numerous field experiments with K fertilization are compiled by Khan *et al.*[2] in Table 4, from which they claim that K fertilization has no positive effect on yield. Unfortunately, those studies that showed no benefit from added K were not evaluated to ensure that the yield limitation was specifically the effect of K, rather than some other factor restricting growth. The most important factors are the level of Exch-K in the soil, lack of water, climate and a deficiency or excess of another mineral nutrient, particularly N. Potassium is required in highest amounts by the plant as an osmoticum to maintain cell turgor and, in this respect, it interacts with N because, by applying N, both cell number and cell size increase and thus also the water content of a crop. The need for K is thus closely dependent on N supply. Additionally, climate, lack of water and disease all affect yield and response to K. Khan *et al.*[2] did not separately assess till versus no-till, and rain versus irrigated systems, so the agrotechnological factors may have masked the unique effect of K on yield. Consequently, we believe that the authors’ statement that K fertilization is detrimental to yield has not been proven. This comment is strengthened by the fact that the authors’ database lacks many response studies carried out in regions with semi-arid climates. For example, in a long-term rotation experiment in Australia, Li *et al.*[12] showed that there was a wheat-yield response to K when Exch-K ranged from 2.5 to 3.4 mmolc kg^{-1} (depending on soil type). A similar result was obtained in two Rothamsted long-term fertilization experiments, where wheat and barley responded by enhanced grain yield to K application of 70 kg K ha^{-1} in starved soils, but not on previously K-enriched plots. The same result was obtained in potatoes[13].

However, despite these reservations, there is still evidence in Table 4[2] showing lack of yield response to KCl. A closer investigation of these data show, however, that all cases can be accounted for by one or more of the following factors: excess available K in soil; rapid K fixation of fertilizer K; and accumulation of K in the surface soil under no-till due to slow K transport down the profile toward the center of the root volume. Cases of reduced yield and quality due to K fertilization most probably resulted from K-Mg and K-Ca antagonism in plant uptake and utilization (in tomato[14] and in forage[15,16]).

The possibility of yield reduction due to soil structure deterioration as a consequence of KCl application, as suggested by Khan *et al.*[2], can be disproved by the studies of Chen *et al.*[17] and Levy and Torrento[18]. Chen *et al.*[17] demonstrated that increasing the contribution of Exch-K to the CEC [Exch-K percentage (EPP)] in clayey soils up to ~20% had a negligible effect on clay dispersion and aggregate stability, the major factors involved in hydraulic conductivity reduction. A significant reduction in hydraulic conductivity (>50%) did not occur until the EPP approached 50-70%[17] a value greatly in excess of that of (EPP <10%) found in most cultivated soils. Thus there is virtually no possibility that KCl application adversely affects soil structure.

Khan *et al.*[2] have attributed adverse effects of KCl fertilizer on yield to chloride (Cl) toxicity in the plant and increased salinity in the root zone, but with scant evidence in support of this statement. Their suggestion to replace KCl by potassium sulfate (K_2SO_4) would be expensive due to the difference in the unit price of K in these two fertilizers. Additionally, there could be problems in rain-fed agriculture as, under such conditions, KCl is the only source of Cl for plants. Chloride, as an essential plant nutrient, is required by crops in the range of 4-8 kg Cl ha^{-1} and is particularly important at sites distant from the sea[16]. Indeed, the most well-documented example of agricultural Cl deficiency is in the wheatgrowing regions of the Great Plains of the USA[19]. The global increase of irrigated crops (currently estimated at 24% of the total cultivated land[20]) will no doubt increase the use of fertigation. Potassium sulfate cannot be added via the water because of the low calcium sulfate ($CaSO_4$, gypsum) solubility, whereas KCl has no practical solubility constraints and is therefore more suitable for K fertigation.

Required improvements for measuring soil K availability

The results presented by Khan *et al.*[2] show no evidence of a 'potassium paradox' but rather draw attention to the need for an understanding of the chemistry of soil K and soil-plant K interaction in relation to K fertilization. This could involve defining soil K in terms of intensity and capacity factors[21,22], as well as taking into account the transport of K in the soil, which mainly takes place by diffusion and which generally constitutes the limiting step in the acquisition of K by crop plants[23]. This approach avoids the uncertainties associated with the Exch-K test, and improves K management decisions by considering those effects that determine K uptake by the crop, namely: growth conditions, soil water content, K-Ca exchange, K transfer between soil K pools, root distribution in soil and clay content and mineralogy. Such an approach is incorporated into the dynamic soil-crop-K model of Greenwood and Karpinets[24,25] successfully field-tested in predicting K fertilizer requirements of ten different vegetable crops to increasing rates of K application. Unfortunately, however, this approach requires the determination of too many parameters for its regular use by extension services or private consultants. A simpler approach would involve defining K needs by both capacity and intensity factors. This could be achieved by relatingKextracted by 0.01 M $CaCl_2$ soil extract (which is another important K availability soil test, particularly in calcareous soils; the intensity factor) with the K extracted by 1 M ammonium acetate (the capacity factor). Another approach is to relate plant uptake with Exch-K. Leigh and Johnston[26] showed that for cereals, the concentration of K in tissue water remained essentially constant throughout growth at about 200 mmol kg^{-1} tissue water in soil well supplied with K but only 50 mmol kg^{-1} tissue water in K-deficient soils. Thus it is possible to assess whether soil K supply is adequate based on the concentration of K in the tissue water.

Whatever tool is used to manage the plant-available K status, the principles of environmental sustainability prohibit mining soil K below the critical level required to achieve optimum crop yields now and in the future. This requires replacing the K removed in a crop by an amount at least equal to that removed by the crop, so that the critical level of plant-available K is maintained[27–30]. The amount of K applied may exceed that removed in the crop where leaching or fixation occur, or may be less than that removed in harvested crops where large amounts of structural K are released annually from soil minerals. In both these cases, regular soil sampling and analysis for Exch-K every 3-5 years will ensure that the critical level is being maintained. On deep soils where crops have an appreciable amount of root in the subsoil, it may be necessary to sample the 0-20 and 20-40 cm soil layers separately. In the case of cereal crops, as much as 50% of the roots may be present in the subsoil[7] and K taken up from the deeper soil layers can also be cycled within the soil profile[31].

Conclusions

There is no paradox in the behavior of K in soil. Khan *et al.*[2] generalize as to the lack of suitability of Exch-K as a soil test from their findings from one particular soil, high in non-exchangeable reserves of K. In many soils, the Exch-K soil test is the simplest, but it is generally recognized that the response of the crop to Exch-K and applied K fertilizer can be affected by many factors, e.g., climate, water deficit and limiting nutrient supply other than K. The reliability of the Exch-K soil test may be increased by sampling not only the 0-20 cm but also the 20-40 cm soil layer because K is acquired from both. The claim that zero or negative yield response to KCl application is widespread has not been substantiated, and in cases where it was correctly observed it was most probably due to the result of excess K application, K immobilization in the soil, and K-Mg and K-Ca antagonisms in the soil and in plant uptake and utilization. Until an easily operated computerized capacity/intensity-based system for K management in soil is developed, the Exch-K soil test will remain the best tool for recommending K fertilization.

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Chapter 6

Crop K Response in Southern Ethiopia

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Abstract

There has been a longstanding perception among professionals that Ethiopian soils were rich in potassium (K). However, with time, it is likely that K could have been depleted in some Ethiopian soils. Based on this hypothesis, several on-station and on-farm experiments were conducted to test and validate the response of potato, wheat and barley to K in the highlands of southern Ethiopia over five years (2007-2011). In the early years of the research, the effect of K was investigated as a component of integrated soil fertility management (ISFM) and liming trials (2007-2009). However, in the later years (2008-2011), K effect on crops was investigated as an independent treatment. The data from ISFM experiments revealed that nitrogen (N) and phosphorus (P) treatment did not significantly increase the yield of the test crops compared to that obtained from the control plot in both locations. However, dramatic increases in yields of these crops were obtained when NP was applied with K and/or farm yard manure (FYM). NP + K and NP + FYM increased the tuber yield in the ranges of 71-100 percent over the mean yield obtained from the control and NP treated plots in Chencha. The effectiveness of lime in improving the yields of the test crops was increased when it was applied with NP + K compared to NP only. The result of the K rate trail conducted in Chencha for two years (2007-2008) indicated that the yield of potato rose significantly with increasing levels of K, and biological and economic optimum yield of potato was obtained from K applied at 150 kg ha^{-1}. On average this rate increased the yield by over 194 percent (36 t ha^{-1}) compared with the control (18 t ha^{-1}) that only received the optimum amount of NP. Similarly NP + K increased the grain yield of wheat by 296 and 123 percent over the control at Chencha and Hagere Selam locations respectively. The results of an on-farm K verification trial conducted in Hagere Selam on potato and wheat revealed that NP + K treatment increased the marketable tuber yield

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by 252 and 56 percent over that obtained from the control and NP treatments. Similarly NP + K treatment increased the grain yield of wheat by over 106 percent over that obtained from NP treatments. All these results obtained across locations and crops proved that soils in the study sites are low in levels of K required for optimum crop production. Thus, introduction and application of K fertilizer to soils in Chencha and Hagere Selam areas to enhance crop production is strongly recommended.

Keywords: Soil fertility decline, soil acidity, NPK fertilizers, potato, wheat, barley.

Introduction

Declining soil fertility is one of the major, if not the first challenges to crop production and productivity in Ethiopia (www.ata.gov.et). According to the International Food Policy Research Institute (IFPRI) (2010), as many as or more than 5-7 million people in Ethiopia are chronically food insecure which is mainly caused by soil degradation. Crop nutrient removal, inadequate use of organic and inorganic fertilizers, nutrient losses through soil erosion and depletion of soil organic matter coupled with poor inherent soil fertility are some of the causes contributing to declining soil fertility in Ethiopia (IFPRI, 2010). In general, the crop production system in Ethiopia is based on nutrient mining, aggravating the depletion of the soil nutrient reserve. This is substantiated by the finding of Stoorvogel and Smaling (1990) who reported that on average 41, 6 and 26 kg ha^{-1} nitrogen (N), phosphorus (P) and potassium (K) respectively are removed from Ethiopian soils every year and the nutrient depletion rate is among the highest in sub-Saharan Africa, after Malawi and Rwanda.

Aimed at determining the fertility status of Ethiopian soils and if fertilizers were required as an input to increase crop productivity, extensive on-station and on-farm fertilizer experiments across diverse locations and crops have been conducted, beginning the late 1960’s (NFSAP, 2007). The results of these experiments revealed that crops responded appreciably to N and P fertilizers indicating that these nutrients were the major limiting factors to crop production. Thus, following filed demonstrations of fertilizers (Urea and DAP), farmers were convinced about the fertilizers and started using them as inputs to crop production. Dramatic increases in the productivity of several crops across diverse ago-ecologies of Ethiopia have been obtained due to the use of N and P fertilizers. Consequently, the adoption of fertilizers by farmers was faster than any other technology, potentially with the exception of improved seeds. Even if the amount of N and P fertilizers being applied by farmers is not sufficient to counter the soil N and P depletion rate, consumption of these fertilizers has increased from year to year. According to the World Bank (2008), the consumption of fertilizers increased from 3,500 tons in 1967-1972 to over 450,000 tons in the 2007/2008 cropping season. However, with time, the yield gains from this practice are decreasing. In line with this, IFPRI (2010) reported that despite a five times increase in fertilizer application, the yields of cereals have increased by only 10 percent since 1980. Depletion of soil organic matter, soil acidity, soil salinity and depletion of other essential nutrients which were once assumed to exist in sufficient amounts in Ethiopian soils are some the causes that account for decreasing gains from N and P fertilizers.

Depletion of essential nutrients other than N and P, such as K, could be one of the major factors for decreasing response of crops to N and P fertilizers. So far in Ethiopia, there is no practice of K fertilizer application based on research by Murphy (1968) who reported that Ethiopian soils were rich in K and therefore there was no need for its application. This notion persisted in the minds of the scientists and professionals until recently didn't give attention from investigating the K status of Ethiopian soils and K fertilizer response. However, with time, it is natural and likely that deficiency of K and other essential nutrients could occur to various degrees depending on the agro ecology, climate, farming systems and history of cultivation in a particular location in the country. Some of the possible causes of soil reserve K depletion could be widespread deforestation that occurred in the last four decades in Ethiopia (Bishaw and Abdulkadir, 1990; Pound and Jonfa, 2005), severe soil erosion in the highlands, crop nutrient removal, and leaching loss which are common phenomena in the highlands (Wassie and Shiferaw, 2011). This argument can be substantiated with what was found in Bangladesh in 1951 where only N was a limiting nutrient but in 1957 N and P became limiting nutrients. The picture changed in 1960 when NPK became limiting nutrients, and by 2010 more than half of the essential plant nutrients became limiting. Thus, to ensure adequate crop production, application of fertilizers containing these nutrients was found to be a must (Rajpma and Islam, 2003). Similar to this, Schneider *et al.* (1994) reported that Nepalese soils used to be rich in available K due to the high content of silt, but continuous cropping of heavy feeder crops have exhausted these reserves and soil K became deficient, ultimately resulting in reduced yields of crops. Moreover, most soils in the tropics are low in their total K content due to high intensity of weathering which in turn decreases the K supply of the soil to crops (Yawson *et al.*, 2011). In Ethiopia where until recently, land degradation has been among the worst in the world, there is no reason that similar or more severe depletion of nutrients including K would not occur. This is also substantiated by a report by the UN Food and Agriculture Organization (FAO, 2003) that indicated the average NPK balance for Ethiopian soils was estimated to be -41, -6 and -26 kg ha^{-1} for the period ranging from 1982 to 1984 respectively. The projected balances for the same nutrients for 2000 were -47, -7 and -32 kg ha^{-1} respectively. Accordingly, even among the three nutrients, the rate of depletion was relatively higher for K compared to N and P.

Despite the earlier report that K was not a limiting nutrient in Ethiopian soils, few enthusiastic scientists recently started to make soil K assessments and study K-response at different times and in different locations in Ethiopia and found indications of soil K depletion. For instance, Abegaz (2008) studied the K content of three soil types from Atsbi-Wonberta district of Tigray, northern Ethiopia in 2003 and found that K was deficient in Luvisol for barley production. Kassahun (2012) reported that the soil K level under cultivated lands of Bezawit watershed, in north-western Ethiopia, was in the low range to support adequate plant growth. Similarly, Deressa *et al.* (2013) collected 353 soil samples from five districts of east Wollega, western Ethiopia and found that the K and calcium (Ca) contents of all soils were below optimum level for adequate crop production. However, most of the reports indicating that K is deficient in different parts of the country are based on the result of soil test K levels and comparing the results with different ratings found in literature. Classifying soils as low, medium or high with respect to K based on such comparisons could be misleading as K in soils is found in different forms which are in dynamic equilibrium with each other (Mutscher, 1995). This in turn is affected by the clay content of the soil, the parent material from which the soils are made from, the type of crop grown, and so on. Thus, soil K ratings based on crop responses to K fertilizers are absolute indicators for determining whether K is deficient in a particular soil or not. In this regard, about ten years ago, a few findings came out with results that K was deficient in some Ethiopian soils. The notable examples include that of the work of Abiye *et al.* (2004) who reported that K applied in the form of K_2SO_4 has significantly increased the grain and straw N uptake of wheat and then increased grain yield in the Vertisols of central Ethiopia whose soil exchangeable K levels show higher values.

In southern Ethiopia, in the early 2000’s, multi-location experiments on different crops were conducted with the objective of determining the optimum NP rate for crop production. The results from some areas with acidic soil indicated that there was little or no response by crops to NP fertilizers. This inspired researchers to pursue further research on the effect of liming along with NP application on different crops. It was found that the yields of crops improved due to liming and NP application but the improvements were not as high as expected (Wassie *et al.*, 2009). On the contrary, the results of an experiment conducted for two years (2006-2007) on the acidic soil of Chencha in southern Ethiopia comparing the effects of NP, NPK, farm yard manure (FYM), NP + FYM and NPK + FYM on potato, revealed that over two years, NPK treatment dramatically and significantly increased the fresh total tuber yield of potato from 6.27 and

8.09 t ha^{-1} in the control and NP treated plots to 30.9 t ha^{-1}. In other words, applying K along with NP increased the tuber yield of potato by 392 and 282 percent over the control and NP treatments respectively (Wassie and Shiferaw, 2009). These results strengthened the suspicion that K could be a limiting nutrient in these areas and it was decided to conduct extensive on-station and on-farm research on the response of potato, wheat and barley to K along with the usual NP (Urea and DAP) fertilizers in many areas of the south with acidic soil. The role of K in integrated soil fertility management (ISFM), and enhancing crop yield and land sustainability was also investigated in the same period.

The objective of this paper is to present the findings on the responses of potato, wheat and barley to K fertilizers through experiments conducted for five years (2007-2011) in the acidic soils of Chencha and Hagere Selam in southern Ethiopia. The paper also makes recommendations for scientists and policy makers about the use of K fertilizers as an important additional input for crop production in these and other similar areas, and indicates future directions that research into soil K in Ethiopia should take.

In this review paper, the findings on the response of crops to K are divided into three parts. The first part presents the effect of K on crops, which was studied as an integral component of ISFM and lime (informal K effect study). The second part presents the results of on-station experiments in which the effect of K on crops was applied as an independent treatment (formal K research), and the third phase presents the results of an on-farm K effect study on crops.

Brief description of the study sites

The experiments were conducted in Chencha and Hagere Selam for five years (2007-2011). Both Chencha and Hagere Selam are found in southern Ethiopia (Fig. 1). Chencha is located at 37°60’E and 6°13’N, with an altitude ranging from 2,500-3,005 meters above sea level (masl) and a mean annual rainfall of 1,325 mm. Hagere Selam is located at 37°31’E and 6°25’N, with an altitude of 2,750 masl. The mean monthly rainfall and temperature pattern of Chencha and Hagere Selam are shown in Fig. 2 and 3 respectively. Crops such as potato, wheat, barley and hose beans are predominantly grown in both areas.

The soil of Chencha is classified as Allisol whereas the soil in Hagere Selam is classified as Nitisol. Some of the soil physicochemical data show that the soils of both areas are strongly acidic, and low in available P and exchangeable K (Table 1).

Table 1. Some of the physicochemical properties of the soils of the study sites.

Location	Texture	pH	Exch. Al	SOM	TN	Av.P	CEC	Exchangeable bases			
								K	Ca	Mg	Na
			cmol kg^{-1}	--------%--------		*mg kg^{-1}*		--------------*meq 100 g^{-1} of soil*-----------			
Chencha	CL*	**4.8**	**3.21**	3.5	0.31	3.20	13.5	0.03	4.3	1.10	0.10
Hagere Selam	CL*	**4.7**	**0.21**	3.7	0.19	2.12	14.8	0.28	4.4	0.75	0.45

Note: *CL = Clay loam.

Part I: K interaction with other soil amendments

The Role of K in integrated soil fertility management

The effects of NP/NPK fertilizers applied alone and in combination with FYM were studied on potato, wheat and barley in factorial treatment combinations in Chencha and Hagere Selam, southern Ethiopia for three years (2007-2009). The fertilizer treatments were 0:0:0 (control), 55:20:0 (half dose), 0:55:20:50 (half dose), 110:40:0 (full dose) and 110:40:100 (full dose) kg ha^{-1} N:P:K. The corresponding doses of N:P:K fertilizer used for wheat and barley were 0:0:0, 23:20:0, 23:20:25, 46:40:0 and 46:40:50 kg ha^{-1} N:P:K. Nitrogen, P and K fertilizers were applied as urea, TSP and KCl respectively. FYM rates were 0, 10 and 20 Mt ha^{-1}. The experiment was laid out in a randomized complete block RCB) design with three replications. The plots were maintained permanently for three years and FYM was applied only in the first year (2007) whereas NP and NPK were applied as per the treatment continuously every year for up to three years.

The results revealed that NP applied at both half and full rates did not significantly increase the tuber yield of potato at Chencha (Fig. 1). However, supplementing K at 50 and 100 kg ha^{-1} by half and full NP doses respectively resulted in a dramatic increase in the tuber yield of potato.

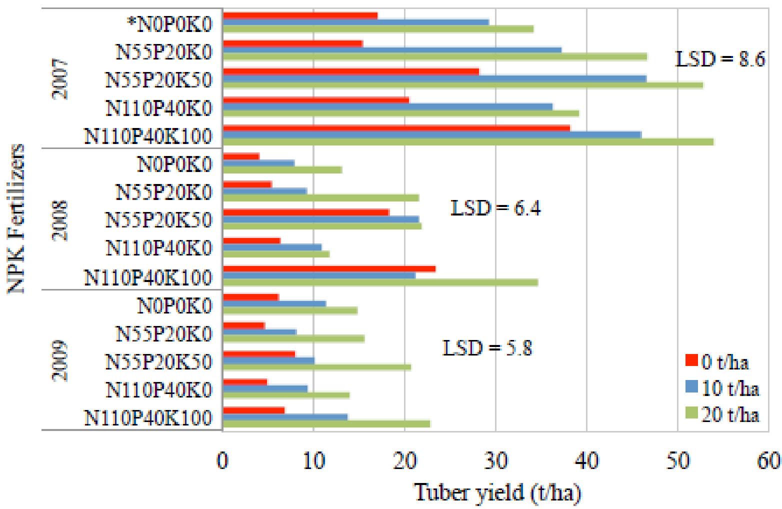

Fig. 1. The effect of NP and NPK fertilizers with and without FYM on potato in Chencha. *Source:* Haile, W. *et al.*, 2009.

Half and full doses of NPK increased the tuber yield by 86 and 90 percent compared to half and full NP rates respectively in 2007. On the other hand, applying both half and full doses of NP along with 10 and 20 Mt ha^{-1} of FYM resulted in a significant increase in the yield of potato compared with the control and was greater yield than that obtained with the sole application of the corresponding NP doses. This implies that FYM served as a source of K, among others. From these results, it is inferred that K is deficient in Chencha soil. But half and full doses of NP with 10 or 20 Mt ha^{-1} of FYM did not significantly differ in the yield of potato produced. However, interestingly, the tuber yield of potato was significantly increased further when half and full doses of NPK were applied along with 10 or 20 Mt ha^{-1} of K. This suggests the benefit of FYM is beyond supplying NPK alone.

Table 2. The effect of integrated application of FYM and NPK fertilizers on the yield of Irish potato (t ha^{-1}) in acidic soils of Hagere Selam.

Treatment	Year	
	2007	2008
	---------------------*Mt ha^{-1}*----------------------	
$N_0P_0K_0$ + 0 Mt ha^{-1} FYM	8.7^{e}	18.1^{b}
$N_0P_0K_0$ + 10 Mt ha^{-1} FYM	10.1^{d}	2.4^{b}
$N_0P_0K_0$ + 20 Mt ha^{-1} FYM	11.6^{cd}	3.2^{b}
$N_{55}P_{20}K_0$ + 0 Mt ha^{-1} FYM	9.6^{e}	5.1^{ab}
$N_{55}P_{20}K_0$ + 1 0 Mt ha^{-1} FYM	21.0^{c}	5.4^{ab}
$N_{55}P_{20}K_0$ + 20 Mt ha^{-1} FYM	21.0^{c}	7.8^{a}
$N_{55}P_{20}K_{50}$ + 0 Mt ha^{-1} FYM	29.0^{b}	5.0^{ab}
$N_{55}P_{20}K5_0$ + 10 Mt ha^{-1} FYM	34.0^{b}	8.5^{a}
$N_{55}P_{20}K_{50}$ + 20 Mt ha^{-1} FYM	38.0^{ab}	7.3^{a}
$N_{110}P_{40}K_0$ + 0 Mt ha^{-1} FYM	26.0^{bc}	5.0^{ab}
$N_{110}P_{40}K_0$ + 10 Mt ha^{-1} FYM	30.0^{abc}	7.5^{a}
$N_{110}P_{40}K_0$ + 20 Mt ha^{-1} FYM	36.0^{b}	7.5^{a}
$N_{110}P_{40}K_{100}$ + 0 Mt ha^{-1} FYM	35.0^{b}	8.6^{a}
$N_{110}P_{40}K_{100}$ + 10 Mt ha^{-1} FYM	45.0^{a}	7.8^{a}
$N_{110}P_{40}K_{100}$ + 20 Mt ha^{-1} FYM	42.0^{ab}	9.4^{a}
LSD (0.05)	7	4.0
CV (%)	39	41

Means within column followed by the same letter(s) are not statistically significant from each other.

The yield of potato was also significantly affected by different treatments in Hagere Selam and the responses had a similar pattern to that obtained in Chencha (Table 2). Significantly, higher yields were obtained from treatments involving NPK and NPK + FYM. Still, NP treatments didn't significantly increase the yield of potato in Hagere Selam, compared to the control.

Similar to potato, NP fertilizers didn't improve the yield of barely in any year in Chencha (Table 3). However, NP applied along with K significantly and appreciably improved the grain yield of barely at Chencha. NPK applied at 23:20:25 kg ha^{-1} and 46:40:50 kg ha^{-1} increased the grain yield by 95 and 120 percent over their respective NP treatments (23:20 and 46:50 kg ha^{-1}). But still the integrated application of NP/NPK + FYM gave a significantly superior grain yield of barely compared with either source applied alone.

Table 3. The effect of integrated applications of inorganic fertilizers and FYM on grain yield of barely (t ha^{-1}) at Chencha.

Treatment	Year		
	2007	2008	2009
	----------------------*Mt ha^{-1}*----------------------		
$N_0P_0K_0$ + 0 Mt Mt FYM	0.57^{f}	0.8^{e}	0.36^{def}
$N_0P_0K_0$ + 10 Mt FYM	1.14^{def}	1.08^{de}	0.28^{def}
$N_0P_0K_0$ + 20 Mt FYM	1.52^{bcde}	1.15^{de}	0.36^{def}
$N_{23}P_{20}K_0$ + 0 Mt FYM	0.977^{ef}	1.36^{cde}	0.4^{def}
$N_{23}P2_0K_0$ + 10 Mt FYM	1.32^{cde}	1.94^{abcd}	0.4^{def}
$N_{23}P_{20}K_0$ + 20 Mt ha^{-1} FYM	1.65^{bcd}	1.70^{bcde}	0.33^{ef}
$N_{46}P_{40}K_0$ + 0 Mt ha^{-1} FYM	0.92^{ef}	1.64^{bcde}	0.42^{cdef}
$N_{46}P_{40}K_0$ + 10 Mt ha^{-1} FYM	1.7b^{cd}	1.66^{bcde}	0.56^{bcdef}
$N_{46}P_{40}K_0$ + 20 Mt ha^{-1} FYM	2.17^{abc}	1.92^{abcd}	0.81^{abcde}
$N_{23}P_{20}K_{25}$ + 0 Mt ha^{-1} FYM	1.9^{abcd}	1.72^{bcde}	0.92^{abcde}
$N_{23}P_{20}K_{25}$ + 10 Mt ha^{-1} FYM	1.9^{bcd}	2.08^{abcd}	1.04^{abcd}
$N_{23}P_{20}K_{25}$ + 20 Mt ha^{-1} FYM	2.17^{abc}	2.42^{abc}	1.14^{ab}
$N_{46}P_{40}K_{50}$ + 0 Mt ha^{-1} FYM	2.03^{abcd}	2.83^{a}	1.08^{abc}
$N_{46}P_{40}K_{50}$ + 10 Mt ha^{-1} FYM	2.4^{ab}	2.4^{abc}	1.28^{a}
$N_{46}P_{40}K_{50}$ +20 Mt ha^{-1} FYM	2.8^{a}	2.58^{ab}	1.25^{a}
LSD	0.97	1.1	0.69
CV (%)	35	36	58

Means within column followed by the same letter(s) are not statistically significant from each other.

The effect of applying an integrated application of NP/NPK fertilizers on the grain yield of wheat in Chencha and Hagere Selam is presented in Tables 4 and 5. In 2007, even if the grain yield obtained from applying 10 and 20 Mt ha^{-1} FYM was higher than the control, the increment was not statistically siginificantly different. With regard to NP fertilizers, both doses of NP fertilizers (23:20 and 46:40 kg ha^{-1}) did not significantly increase the grain yield relative to the control. However, both half and full doses of NPK fertilizers (23:20:25 and 46:40:50 kg ha^{-1}) significantly increased the grain yield of wheat compared to the control and NP treatments. These treatments increased the grain yield by 272 and 431 percent respectively over the control. Application of NP/NPK fertilizers with FYM also significantly increased the grain yield relative to the control and NP treatments.

Table 4. The effect of combined applications of FYM and different fertilizers on the grain yield of wheat (t ha^{-1}) in Chencha.

Treatment	Year	
	2007	2008
	----------------------*Mt ha^{-1}*----------------------	
$N_0P_0K_0$ + 0 Mt FYM	0.61^{e}	0.26^{d}
$N_0P_0K_0$ + 10 Mt FYM	$1.3b^{cde}$	0.36^{cd}
$N_0P_0K_0$ + 20 Mt FYM	1.4^{cde}	0.42^{cd}
$N_{23}P_{20}K_0$ + 0 Mt FYM	1.21^{bcde}	0.34^{cd}
$N_{23}P_{20}K_0$ + 10 Mt FYM	1.65^{bcde}	0.47^{bcd}
$N_{55}P_{20}K_0$ + 20 Mt ha^{-1} FYM	2.08^{abcd}	0.75^{cb}
$N_{46}P_{40}K_0$ + 0 Mt ha^{-1} FYM	8.5^{cde}	0.36^{cd}
$N_{46}P_{40}K_0$ + 10 Mt ha^{-1} FYM	2.12^{abcd}	0.26^{cd}
$N_{46}P4_0K_0$ + 20 Mt ha^{-1} FYM	3.38^{a}	0.42^{cd}
$N_{23}P_{20}K_{25}$ + 0 Mt ha^{-1} FYM	2.27^{abcd}	0.68^{cbd}
$N_{23}P_{20}K_{25}$ + 10 Mt ha^{-1} FYM	2.35^{abc}	0.75^{cd}
$N_{23}P_{20}K_{25}$ + 20 Mt ha^{-1} FYM	2.70^{ab}	1.46^{a}
$N_{46}P_{40}K_{50}$ + 0 Mt ha^{-1} FYM	3.24^{a}	0.68^{bcd}
$N_{46}P_{40}K_{50}$ + 10 Mt ha^{-1} FYM	2.03^{abcd}	0.78^{bc}
$N_{46}P_{40}K_{50}$ + 20 Mt ha^{-1} FYM	2.60^{abc}	0.89^{ab}
LSD	1.4	0.45
CV (%)	23	45

Means within column followed by the same letter(s) are not statistically significant from each other.

There were significant differences among treatments in their effect on the grain yield of wheat in the second cropping seasons in 2008. However, there was a sharp decline in the yield of wheat for all treatments. Generally, higher grain yields of wheat were obtained from plots that received continuous applications of half and full doses of NPK fertilizers along with the residue of FYM.

Table 5. Effect of NP/NPK fertilizers and FYM and its combination on the grain yeild of wheat (t ha^{-1}) in Hagere Selam.

Treatment	Year	
	2007	2008
	-----------------------*Mt ha^{-1}*-----------------------	
$N_0P_0K_0$ + 0 Mt FYM	2.4^{bcd}*	2.8^{f}
$N_0P_0K_0$ + 10 Mt FYM	2.0^{d}	3.0^{ef}
$N_0P_0K_0$ + 5 Mt FYM	2.9^{abcd}	3.4^{ef}
$N_{23}P_{20}K_0$ + 0 Mt FYM	2.7^{abcd}	3.8^{bcde}
$N_{23}P_{20}K_0$ + 10 Mt FYM	2.76^{acd}	4.2^{bc}
$N_{23}P_{20}K_0$ + 20 Mt ha^{-1} FYM	2.94^{abc}	4.5^{abc}
$N_{46}P_{40}K_0$ + 0 Mt ha^{-1} FYM	2.0^{cd}	4.4^{abc}
$N_{46}P_{40}K_0$ + 10 Mt ha^{-1} FYM	3.46^{a}	5.0^{ab}
$N_{46}P_{40}K_0$ + 20 Mt ha^{-1} FYM	2.94^{abc}	3.8^{bcde}
$N_{23}P_{20}K_{25}$ + 0 Mt ha^{-1} FYM	2.8^{abcd}	3.9^{bcd}
$N_{23}P_{20}K_{25}$ + 10 Mt ha^{-1} FYM	2.9^{abc}	3.9^{bcd}
$N_{23}P_{20}K_{25}$ + 20 Mt ha^{-1} FYM	3.4^{a}	4.4^{abc}
$N_{46}P_{40}K_{50}$ + 0 Mt ha^{-1} FYM	3.3^{ab}	4.8^{ab}
$N_{46}P_{40}K_{50}$ + 10 Mt ha^{-1} FYM	3.4^{a}	4.8^{ab}
$N_{46}P_{40}K_{50}$ + 20 Mt ha^{-1} FYM	3.5^{a}	5.4^{a}
LSD	9.5	11
CV (%)	19	16

Means within column followed by the same letter(s) are not statistically significant from each other.

Review of the role of K applications in enhancing the effectiveness of lime in boosting crop productivity

The effect of NP/NPK fertilizers with and without lime on the yield of potato was studied in Chencha and Hagere Selam for three years. The treatments were 0:0:0, 110:40:0, 110:0:100, 0:40:100 and 110:40:100 kg ha^{-1}, with and without lime.

Lime was applied at 3.5 t ha^{-1} one month ahead of planting the test crop. The experiment was laid out in a RCB design with three replications.

Under unlined condition, NP and NK treatments did not significantly increase the tuber yield over the control in 2007 at Chencha (Fig. 2). However, PK treated plots gave an appreciable and significant increase in tuber yield of potato compared with the control, NP and NK treatments. PK treatment increased the yield by 187, 94 and 94 percent over that obtained from the control, NP and NK treated plots respectively. This implies that the soils are starved of both P and K. The tuber yield was also dramatically increased when NPK was applied, suggesting that balancing the application of NPK is important for increased productivity of potato in the area.

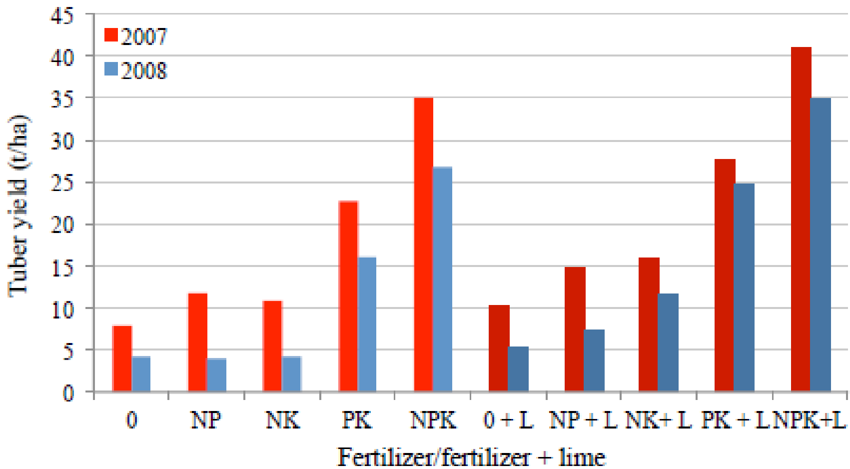

Fig. 2. Effect of NP/NPK fertilizer and lime on the tuber yield of potato in Chencha (2007-2008).

Part II: Review of on-station crop response to K research findings

Effect of K on potato in Chencha

The effect of different K fertilizer rates (0, 30, 60, 90, 120, 150, 180, 210, 240, 270 and 300 kg ha^{-1}) on potato in Chencha's soil was studied for two years (2007-2008). KCl was use as the K source and N and P were applied to all plots at 110 and 40 kg ha^{-1} respectively in the form of Urea and TSP respectively. The experiment was laid out in an RCB design with three replications.

Application of increasing levels of K significantly and dramatically increased the total and marketable tuber yield of potato in both years (Table 6). Increasing levels of K from 30 kg ha^{-1} significantly increased the tuber yield up to 300 kg ha^{-1} but the highest total and marketable tuber yield was obtained at K level applied at 150 kg ha^{-1}. In the 2007 cropping season, K applied at 150 kg ha^{-1} increased the marketable tuber yield from 13.4 Mt ha^{-1} in the control to 55.9 t ha^{-1} in 2007. The corresponding increase in the 2008 cropping season was from 21.3 t ha^{-1} to 49.2 t ha^{-1}.

Table 6. The effect of different K levels on the tuber yield of Irish potato on the acidic soil in Chencha.

K levels	Tuber yield			
	2007		2008	
	Total yield	Marketable yield	Total yield	Marketable yield
kg ha^{-1}	*Mt ha^{-1}*			
0	15.6^{d}	13.4^{d}	24.5^{c}	21.3^{d}
30	21.7^{d}	19.7^{d}	25.7^{bc}	22.8^{cd}
60	38.0^{c}	34.63^{c}	29.7^{c}	26.5^{cd}
90	40.0^{c}	36.9^{c}	35.7^{abc}	32.9^{abcd}
120	50.8^{ab}	41.8^{ab}	36.5^{abc}	34.6^{abcd}
150	57.2^{a}	55.9^{a}	50.3^{a}	49.2^{a}
180	49.3^{abc}	47.5^{ab}	42.8^{bc}	41.4^{abc}
210	54.8^{a}	51.8^{a}	45.2^{ab}	42.7^{ab}
240	52.3^{ab}	49.7^{a}	44.9^{abc}	42.6^{ab}
270	51.4^{ab}	48.8^{a}	33.3^{abc}	31.6^{abcd}
300	51.3^{ab}	48.5^{ab}	44.1^{abc}	41.6^{abc}
LSD (0.05)	12.3	11.7	20.3	19.2
CV (%)	16.0	16.7	32	32.3

Means within column followed by the same letter(s) are not statistically significant from each other.

Source: Haile, W. and T. Mamo, 2013.

NP/NPK fertilizers effect on wheat at Chencha and Hagere Selam

Application of K along with NP fertilizers has significantly improved the grain and straw yield of wheat in both locations relative to the control and NP treated plots (Table 7). The highest grain and straw yields of wheat were obtained from NPK applied at 46:40:50 kg ha^{-1}. This treatment increased the grain yield by 296 and 123 percent over the control at Chencha and Hagere Selam respectively. However the yield gain from this treatment was not significantly different from that produced by the half dose of NPK (23:20:25 kg ha^{-1}). In line with the current finding, Khan *et al.* (2007) reported that the application at 60 kg ha^{-1} of K_2O significantly increased the grain yield of wheat by over 13 percent relative to the control in the arid zone of Pakistan, where soil has an ammonium acetate extractable K value of 80 ppm (0.2 me 100 g^{-1} of soil).

Table 7. The effect of NP/NPK fertilizers on the grain and straw yield of wheat on acidic soils in Chencha and Hagere Selam (2007).

Treatments	Chencha		Hagere Selam	
	Grain yield	Straw yield	Grain Yield	Straw yield
	------------------------------*Mt ha^{-1}*-------------------------------			
$N_0P_0K_0$	0.58^{b}	0.78^{c}	1.3^{c}	1.8^{d}
$N_{23}P_{20}K_0$	0.97^{b}	1.2^{bc}	1.9^{bc}	2.1^{c}
$N_{46}P_{40}K_0$	0.91^{b}	1.4^{b}	1.7^{bc}	2.0^{cd}
$N_{23}P_{20}K_{25}$	1.8^{a}	2.4^{a}	2.2^{ab}	2.5^{a}
$N_{46}P_{40}K_{50}$	2.3^{a}	2.8^{a}	2.6^{a}	2.9^{a}
LSD (0.05)	0.5	0.4	0.6	2.3
CV (%)	21	17.3	12.8	7.0

Means within column followed by the same letter(s) are not statistically significant from each other.

Effect of K fertilizer on the biomass and grain yields of wheat in upper Ganna, Lemmu, southern Ethiopia

The effect of different rates of K fertilizer on the grain and biomass yield of wheat was studied on two farmers' fields in upper Ganna, Hadya Zone, southern Ethiopia during the 2013/2014 cropping season.

The results revealed that K has significantly affected the grain and biomass yields of wheat in one of the farmer's field (Aregash), but not in the other (Kifle) (Table 8). In Aregash's field, the highest grain and biomass yields of wheat were obtained from the K treatment applied at 15 kg ha^{-1}. However, K treatments of 30, 40 and 60 kg K ha^{-1} were statistically on par with K applied at 15 kg K ha^{-1}. However, K applied at 75 kg K ha^{-1} produced significantly lower grain and biomass yields in wheat. K applied at 15 kg ha^{-1} increased the grain yield by 58 and 28 percent over that obtained from the absolute control and that obtained from plots that received NPK fertilizer respectively.

Table 8. Effect of K fertilizer on the grain and biomass yields of wheat in Upper Gana, Hadya, southern Ethiopia, 2013.

K-rate	Aregash		Kifle	
	Grain yield	Biomass yield	Grain yield	Biomass yield
kg ha^{-1}	---------------------------*Mt ha^{-1}*---			---------------------------
0 (absolute control)	2.7^{d}	9.6^{c}	2.5^{b}	4.8^{b}
0 (NPS applied)	3.2^{dc}	10.6^{bc}	3.8^{ab}	11.1^{a}
15	4.1^{a}	12.3^{a}	3.9^{ab}	12.3^{a}
30	3.8^{ab}	12.8^{a}	3.6^{ab}	10.9^{a}
45	3.7^{abc}	11.7^{ab}	4.1^{a}	11.5^{a}
60	3.8^{ab}	12.8^{a}	3.9^{ab}	11.1^{a}
75	3.4^{bc}	11.3^{ab}	4.2^{a}	12.1^{a}
LSD (0.05)	0.53	1.18	1.46	2.44
CV (%)	8.7	6.0	22	13

Means within column followed by the same letter(s) are not statistically significant from each other.

Part III. Review of on-farm crop response to K in southern Ethiopia

On-farm K fertilizer application effect on potato at Hagere Selam

The experiment was conducted on 24 farmers' fields in different peasant associations of Hagere Selam districts in 2010 to verify and demonstrate the role of K in improving the yield of potato. Composite soil samples from fields of participating farmers were collected and analyzed for selected physicochemical properties. The treatments were control, 110:40:0, and 110:40:100 NPK kg ha^{-1}. Urea, TSP and KCl were used as sources of N, P and K respectively. The experiment was laid out in an RCB design replicated across 24 farmers' fields. Four different varieties of Irish potato namely, Zengena, Guassa, Jalleni and Tolcha, were planted as a test crop.

Application of K fertilizer significantly increased the total and marketable tuber yields of potato on farmers' fields at Hagere Selam in the 2010 growing season (Fig. 3). When averaged over the 24 fields, K applied at 100 kg ha^{-1} in the form of KCl increased the total and marketable tuber yields by 208 and 252 percent over the control respectively. The corresponding increases over NP treatments were 52 and 55 percent respectively.

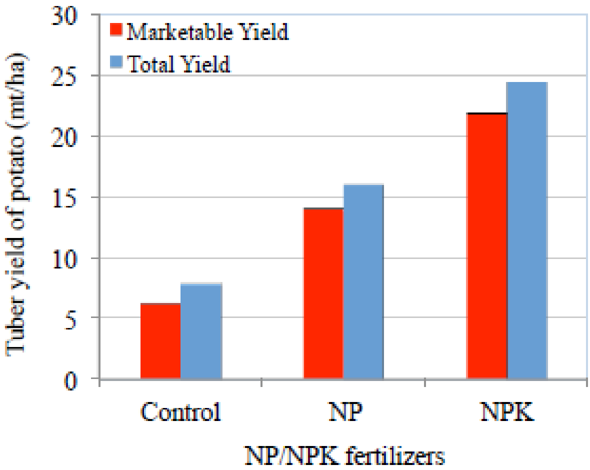

Fig. 3. Effect of NP/NPK fertilizer on the marketable and total tuber yield of potato in Hagere Selam (averaged over 24 farmers' fields). *Source:* Haile, W., 2009.

The partial budget analysis data of various treatments showed that the highest net benefit (35,521.73 birr) with a marginal rate of return (MMR) of 197 percent was obtained from the NPK treatment, while the next highest net benefit (25,485.73 birr) with a MMR of 340 percent was obtained from the NP treatment (Table 9).

The effect of K and sulfur (S), applied singly or in combination, on the yield of wheat on farmers' fields in Hagere Selam in 2011

The grain and biomass yields of wheat were found to be significantly affected by different treatments (Table 10). The highest biomass and grain yield of wheat was obtained from 50 Urea + 100 DAP + 43.33 KCl + 50 $CaSO_4$. The next highest yield was obtained from 50 Urea + 100 DAP + 50 $CaSO_4$. However, there was no difference among the rest of the treatments on their effect on the grain yield of wheat, indicating that S is also becoming a limiting nutrient in the study area.

Table 9. The results of partial budget analysis data of treatments.

Partial budget	Treatment		
	Control	NP	NPK
Average yield (kg ha^{-1})	7,900	16,000	24,400
Adj. yield (kg ha^{-1})	7,110	14,400	21,960
Gross benefit in birr	14,220	28,800	43,920
N	0	1,814.27	1,814.27
P	0	1,500	1,500
K	0	0	5,084
TVC (birr)	0	3,314.27	8,398.27
Net benefit USD ha^{-1}	14,220	25,485.73	35,521.73
MRR (%)	-	340	197

Adapted from Wassie, 2009.

Table 10. The effect of K and S, applied singly or in combination, on the yield of wheat grown on different soil types in southern Ethiopia in 2011 (Wassie and Tekalign, 2013).

Treatment	Yield	
	Mean biomass yield	Mean grain yield
kg ha^{-1}	------------------*Mt* ha^{-1}-------------------	
50 Urea + 100 DAP	5.23^{c}	1.82^{c}
50 Urea + 100 DAP + 50 K_2SO_4	9.44^{b}	3.76^{ab}
50 Urea + 100 DAP + 43.33 KCl	10.11^{b}	2.74^{b}
50 Urea + 100 DAP + 50 $CaSO_4$	10.597^{b}	4.02^{ab}
50 Urea + 100 DAP + 43.33 KCl + 50 $CaSO_4$	13.1^{a}	4.87^{a}
CV (%)	9.6	29.1

Means within column followed by the same letter(s) are not statistically significant from each other.

The observed significant increase in the biomass and grain yields of wheat on farmers' fields in Hagere Selam confirms the previous findings from on-station experiments, indicating a significant response of wheat to K fertilization.

Conclusion and recommendations

It is concluded that potato, wheat and barley, grown on the acidic soils of Chencha and Hagere Selam in southern Ethiopia, have consistently responded to the application of K, suggesting that the soil K levels in these areas are low for optimum production of these crops. This was substantiated by very low soil test exchangeable K values in both locations.

Furthermore, integrated application of NPK + FYM resulted in significantly higher yields of the test crops than those obtained from NP + FYM suggesting that it is critical to include K as an integral component of ISMF in these locations. The effectiveness of lime also increased when applied with NP, compared to NPK. This implies that the requirement for lime in these soils may be decreased with the balanced application of NPK fertilizers.

These results present strong evidence to disprove the longstanding conclusion that Ethiopian soils are rich in K. Thus, there is a need to revise the fertilizer package for potato, wheat and barley production in these areas and introduce K fertilizers in Chencha and Hagere Selam to enhance and sustain crop production. Application of K fertilizers at 150 and 100 kg ha^{-1} is recommended for optimum production of potato in Chencha and Hagere Selam respectively. For barley and wheat, application of K at 25 kg ha^{-1} is recommended in both locations.

The way forward/future research directions

- Establishment of potassium critical levels for soils in Chencha and Hagere Selam and other locations is recommended.
- K dynamics (K-sorption/desorption, Q/I relationships, interaction among the various K forms in soils, etc.) needs to be studied.
- Further intensive investigation on the status of soil K levels in conjunction with crop response to K should be conducted in other areas of Ethiopia, especially the highlands which receive high annual rainfall and have acidic soil reaction (for example, most areas of south and southwestern Ethiopia, and the highlands in the south-east).
- Investigation of the relationship between K content and soil clay mineral types is needed to have a basic understanding of K availability.
- The interactions between K and P with acidity and lime in the soils of Chencha and Hagere Selam needs to be studied.

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Chapter 7

Response of Wheat to Phosphorus and Potassium Fertilization on Vertisols of Central Highland of Ethiopia

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Abstract

Field experiments were established in 2012 and 2013 cropping seasons on two rainfed locations in the central highland Vertisols of Ethiopia to determine the response of bread wheat (*Triticum aestivum* L.) to P and K fertilization. A total of 16 treatments were tested in a 4*4 factorial design involving four P (0, 10, 20 and 30 kg ha^{-1}) and four K (0, 26, 39 and 52 kg ha^{-1}) fertilization levels with three replications. Analysis of variance revealed a significant difference ($p < 0.01$) between treatments in yield and nutrient (N, P and K) uptake of wheat at both sites over the two cropping seasons. In addition, the study showed that concurrent use of P and K significantly increased the yield and the nutrient uptake of wheat (N, P and K) from the level obtained with either P or K applied alone. The fertilization treatments had no significant effect on grain size. In Cheffe Donsa site, the highest grain yields, 6.4 and 7.6 t ha^{-1}, were exhibited by a combination of 10 kg P ha^{-1}) and 26 kg K ha^{-1} in 2012 and 2013 cropping seasons, respectively. In Akaki site the highest grain yields, 2.8 t ha^{-1} (2012) and 4.8 t ha^{-1} (2013), were acquired with 30 kg P/ha and 26 kg K ha^{-1}. In conclusion, the concurrent use of P and K fertilizers enhanced the yield and nutrient uptake of wheat in the studied sites.

Keywords: Wheat (*Triticum aestivum* L.), phosphorus, potassium, yield, nutrient uptake.

Introduction

Wheat (*Triticum aestivum* L.) is one of the major cereal crops of the world ranking second after paddy rice both in area and production among the cereal crops. It

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provides more nourishment for the nations of the world than any other food crop (Curtis, 2002).Ethiopia is one of the largest wheat producer among the countries in the sub-Saharan Africa (Hailu, 1991). Wheat is the second most widely produced crop after teff (Eragrostis tef) on the Vertisols of Ethiopian highlands (Getachew, 1991). Ethiopia's current annual wheat production of approximately 3.24 million tons is insufficient to meet the domestic needs (CSA, 2010). The low mean national yield for wheat is primarily due to depleted soil fertility, low fertilizer usage, and the unavailability of other improved crop management inputs (Asnakew *et al.*, 1991; Getachew, 1991).

Vertisols are considered suitable for producing cereals like wheat. They cover about 12.61million ha of land in Ethiopia and the country ranks third in Vertisols abundance in Africa after Sudan and Chad. Majority of the Ethiopian Vertisols, about 8 million ha, are located in highlands (Berhanu, 1985). Generally, nitrogen (N) and phosphorus (P) are the most limiting nutrients in Vertisols (Finck and Venkateswarlu, 1982) and this holds true for the Ethiopian soils as well. The lack of response to fertilizer P application on Vertisols could be attributed to various factors including high P sorption capacity of the soil, soil moisture conditions and, perhaps, P transformation into sparingly soluble forms (immediate fixation) (Hubble, 1984).

In Ethiopia, potassium (K) status of agricultural soils is generally found to be adequate for crop production though a few studies show acutely deficient soil K levels (Tekalign and Haque, 1988; Tariku and Tekalign, 1999). Fixation of K is correlated with percentage of clay and is highest in the Vertisols. K fixation is enhanced by the presence of smectite and amorphous materials. The limited response of crops to applied K and the often high levels of exchangeable K found in most of the Ethiopian soils, have led researchers and development agents to conclude that the K fertilization need in these soils is minimal. However, continuous cropping, in which fertilizer responsive varieties and improved management practices are used, results in K mining from the soil. Wheat crop can remove more than 400 kg K_2O $ha^{-1}year^{-1}$ (IFA, 1986). Total absence or low application level of K fertilization combined with intensive continuous cropping leads to the depletion of soil K reserves. Even soils which are initially well supplied with K will become deficient under such management system. Total consumption of K from soil by wheat producing10 t yield ha^{-1} varies from 160 to 242 kg K ha^{-1} (Kemmler, 1983). In Ethiopia, reports which indicate crop response to applied K on Vertisols have started to emerge. A study conducted by Abiye *et al.* (2004) found that wheat responded significantly to K application on Vertisols at Chefe Donsa, east Shoa of Ethiopia. They recommended the need to reassess the traditionally practiced system of not applying K fertilizer to Ethiopian soils. However, information concerning P and K fertilization for wheat grown on highland Vertisols is limited. Thus, this study was conducted with an objective to investigate the effect of different levels of P and K additions on yield and the yield components as well as on nutrient uptake of bread wheat (HAR 3116) on two central highland Ethiopian Vertisols.

Materials and methods

Experimental site description

The experiments were conducted on farmers' fields on two representative central highland Vertisols, Akaki and Cheffe donsa during 2012 and 2013 main cropping seasons. Basing the coordinates (longitudes and latitudes) of the experimental areas, the specific location of each sites are constructed in the map using Arc GIS 9.3 software. The Akaki site is located 25 km south east of Addis Abeba (08˚49'40.5''N lat. and 38˚49'17.9''Elong.) at an altitude of 2,400 m a.s.l. (Fig. 1). Akaki receives mean annual rainfall of 930mm; mean annual minimum and maximum temperatures are 8 and 27˚C, respectively (Table 3). The Cheffe Donsa site is positioned at about 80 km east of Addis Abeba (08˚57'59.6''N lat. and 039˚06'28.4''E long.) at an altitude of 2,444 m a.s.l. (Fig. 1). Cheffe Donsa receives mean annual rainfall of 1,098 mm; mean annual minimum and maximum temperature are 10 and 25˚C, respectively (Table 1).The soil characteristics of the experimental sites are given in Table 2.

Experimental design

The experimental design was a randomized complete block design in a factorial combination of P and K. A plot size of 3m by 3m was used and adjacent plots and blocks were 1m apart. Both experiments contained the following treatments; four rates of P as triple super phosphate (0, 10, 20 and 30 kg ha^{-1}) and four rates of K as murate of potash (0, 26, 39 and 52 kg ha^{-1}) (Table 3). There were three replications. N as urea (60 and 92 N Kg ha^{-1} in the first and second cropping season, respectively), sulfur (S) as gypsum (20 S kg ha^{-1}) and zinc (Zn) as zintrac (700 Zn g ha^{-1}) were applied as a basal doze.

Experimental materials and procedures

The experimental fields were prepared using local plow (maresha) according to farmers' conventional farming practices. The fields were ploughed two times, after which broad bed and furrows were constructed by broad bed maker (BBM), which is an oxen-drawn traditional wooden plough, modified for the construction of raised beds and furrows to facilitate surface drainage through the furrows between the beds so that the crops are grown on the beds (Jutzi and Mesfin, 1986).

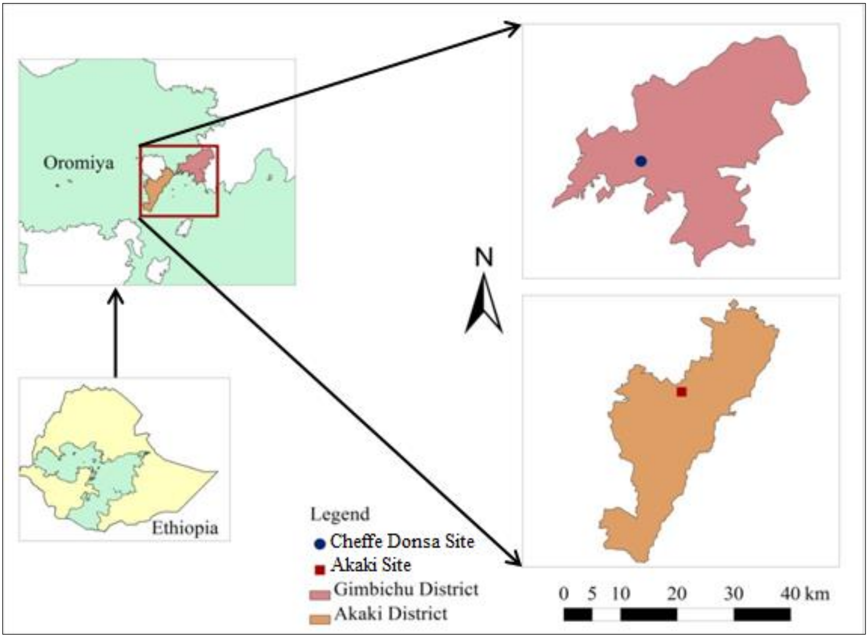

Fig. 1. Location of the experimental sites

Table 1. Climate data of Akaki and Cheffe Donsa area in the 2012 and 2013 cropping season.

	Akaki		Cheffe Donsa	
	2012	2013	2012	2013
Total annual rainfall (mm)	826	1,033	936	1,259
Mean annual maximum temperature (^oC)	27	27	25	24
Mean annual minimum temperature (^oC)	9	7	11	9

Source: National Meteorological Agency of Ethiopia.

Table 2. Physical and chemical properties of surface soil (0-15 cm) of the experimental sites (n=12).

Soil property	Experimental sites: Akaki (Akaki)	Experimental sites: Cheffe Donsa (Gimbichu)
Particle size distribution		
Clay (%)	67	54
Silt (%)	18	25
Sand (%)	15	21
pH (1:2.5 suspension)	7.4	7.8
EC (1:2.5 suspension) (dS m^{-1})	0.15	0.2
Total nitrogen (%)	0.1	1.1
Total carbon (%)	1.2	1.1
Soil organic matter (%)	1.9	1.9
Olsen's P (ppm)	5.9	7.5
Sulfate-S (ppm)	1.8	1.2
Ammonium acetate extractable		
Na ($cmol_{(+)}$ kg^{-1})	0.16	0.27
Ca ($cmol_{(+)}$ kg^{-1})	38	32.8
Mg ($cmol_{(+)}$ kg^{-1})	9.4	5.2
K ($cmol_{(+)}$ kg^{-1})	1.6	1.8
CEC ($cmol_{(+)}$ kg^{-1})	49.4	42.1
PBS (%)	99	95
AB-DTPA extractable		
Fe (ppm)	40.8	33.6
Mn (ppm)	34.8	46
Zn (ppm)	1.14	1.1
Cu (ppm)	3.86	3.5

Table 3. Details of the experimental treatments.

Treatment	Fertilizer dozes	
	P	K
	-------------------------*kg ha^{-1}*-------------------------	
T_1 (Control)	0	0
T_2	0	26
T_3	0	39
T_4	0	52
T_5	10	0
T_6	10	26
T_7	10	39
T_8	10	52
T_9	20	0
T_{10}	20	26
T_{11}	20	39
T_{12}	20	52
T_{13}	30	0
T_{14}	30	26
T_{15}	30	39
T_{16}	30	52

The test variety used in the study areas was improved bread wheat variety (HAR3116), which has been widely used by the farmers in the study areas. The wheat seed was sown at a rate of 80 kg ha^{-1} in 3 m by 3 m plots using 20 cm row spacing. The entire amount of P and S designed for each treatment was applied once at the sowing time, whereas N and K fertilization was split into two applications. One third of the N and half of the K were applied at the sowing time and the remaining was top dressed after 35 and 45 days, respectively. Zn was applied twice, at the tillering stage and again 14 days after. Weed control was done by hand 20 days after sowing and as needed throughout the growing season in all the treatments. Planting and harvesting were also done by hand.

Soil sampling and analysis

For assessing the fertility of surface soil, twelve composite soil (0-15 cm) samples, four per block, were taken from each experimental site before planting. Each composite soil sample comprised of 15 sub samples collected in a zigzag pattern within the replication and mixed thoroughly following a standard procedure for soil sampling and sample preparation (Andreas and Berndt-Micheal, 2005).

Laboratory analyses were conducted at Debre Ziet Agricultural Research Center (DZARC), Ethiopia and at Natural Resources Institute Finland (former MTT Agri-food Research Finland) using the following standard methods. Soil particle size distribution was determined by hydrometer method (Gee and Bauder, 1986). Soil textural class names were assigned based on the relative contents of the sand, silt and clay separates using the soil textural triangle of the USDA. Soil pH (McLean, 1982) and electrical conductivity (Rhoades, 1982) were measured in soil: water extract. Soil organic carbon (C) and total nitrogen (N) content were determined by dry combustion methods based on ISO 10694 (1995) and ISO 13878 (1998) protocols, respectively. Soil organic matter was calculated by multiplying soil organic carbon by 1.724 assuming that average C concentration of organic matter is 58%. Available phosphorus was extracted by 0.5N sodium bicarbonate solution as described by Olsen *et al.* (1954), and thereafter measured using Perkin Elmer Optima 8300 Inductively Coupled Plasma - Optical Emission Spectrometer (ICP-OES). Sulfate was determined in the soil extract by the turbidity method using spectrophotometer on transmittance at a wave length of 420nm according to Williams and Steinbergs (1959). The cation exchange capacity (CEC) of the soils was determined by the ammonium acetate method (Cottenie, 1980). One Molar neutral ammonium acetate (pH=7) was used to extract the exchangeable cations (Ca, Mg, K and Na) (Cottenie, 1980). Then the cations were determined using ICP-OES. Available micronutrients (Cu, Fe, Mn and Zn) were extracted by ammonium bicarbonate di-ethylene tri-amine penta-acetic acid (AB-DTPA) as described by Soltanpour and Schwab (1977) and were measured by ICP-OES.

Crop data collection and analysis

The wheat crop was harvested by collecting the above ground plant mass from the central 2 m^2 area of each plot when the plants showed clear signs of maturity (complete yellowing of leaves and spikes). The total plant biomass (biological yield) obtained was weighed, after which grains were separated and weighed to record the grain yield. Straw yield was determined by subtracting the grain yield from the biological yield. Thousand grain weights were recorded for each plot in five replicates by weighing 1000 randomly selected grains.

Grain and straw samples from each treatment were oven dried at 60-70°C to a constant weight and thereafter ground and analyzed for N, P and K contents. Total N concentrations of the samples were determined using modified Kjeldahl method (Jackson, 1958). For the P and K analyses, the samples were first re-dried in 60^0C and then ashed in 550˚C for 8 h. Thereafter, the ashes were digested in 20% HNO_3 (Zarcinaas *et al.*, 1987). P concentrations of the digests were measured with a spectrophotometer and the K concentrations with a flame photometer.

The uptake of nutrients (N, P and K) into straw and grain was calculated by multiplying the nutrient content (%) with the respective straw and grain yield ha^{-1} on dry weight basis. Total nutrient content in the biological yield was obtained by summing up the nutrient uptakes by grain and straw.

$$\text{Nutrient uptake of the grain} = \frac{\text{Nutrient content of the grain (\%) X grain yield (kg ha}^{-1}\text{)}}{100}$$

$$\text{Nutrient uptake of the straw} = \frac{\text{Nutrient content of the straw (\%) X straw yield (kg ha}^{-1}\text{)}}{100}$$

Total nutrient uptake = nutrient uptake of the grain + nutrient uptake of the straw

Statistical analysis

The data on crop yield and the yield related traits were subjected to analysis of variance (ANOVA) using SAS statistical software and the statistical procedures described by Gomez and Gomez (1984). The least significant difference (LSD) was used for comparing the means of grain yield and yield components of wheat obtained with the different rates of P and K applications

Results and discussion

The results of compound analysis of the two year experiments showed that the effect of year on the studied characteristics was significant. Accordingly, data of each year were analyzed separately for all characteristics.

Soil characteristics

The results of initial soil properties, as presented in Table 2, revealed that the particle size distribution of the surface soils (0-15 cm) of both experimental fields was dominated by clay fraction (above 53%). Berhanu (1985) and Tamirat (1992) also reported that Vertisols in Ethiopia generally contain more than 40% clay in the surface horizons. The surface soil (0-15 cm) analysis showed that prior to sowing the experimental soils had a pH of 7.2-7.8 (slightly to moderately alkaline), which is typical for Ethiopian Vertisols (Berhanu, 1985; Fassil and Charles, 2009). This pH range is favorable for most crops (Tekalign, 1991; FAO, 2000). The soil organic matter and available S contents, however, were in low ranges (Tan, 1996; Peverill *et al.*, 1999).According to the ratings of Cottenie

(1980), the available P (Olsen extractable) were low and moderate at Akaki and Cheffe Donsa, respectively.

Exchangeable Ca and Mg were the dominant cations in the surface soils of both experimental fields (Table 2). Ca comprised of 77 and 78% of the soil cation exchange sites of Akaki and Cheffe Donsa experimental fields, respectively. Similarly, Mg occupied 19 and 12.3% of the soil cation exchange sites of Akaki and Cheffe Donsa experimental fields. The exchangeable K was in the high range (<2 cmol kg^{-1}) (Hazelton and Murphy, 2007; Peverill *et al.*, 1999). Na had the lowest concentration (0.16-0.27 cmol kg^{-1} of soil) among the base forming cations found in the top soil cation exchange complex in both experimental fields. The CEC of the surface soils of Akaki and Cheffe Donsa were 49.4 and 42.1 cmol kg^{-1}, respectively. The CEC of the study area can be termed as very high according to the ratings given by Hazelton and Murphy (2007). The surface horizons of Ethiopian Vertisols have generally found to have very high CEC (Berhanu, 1985; Tamirat, 1992). These high CEC values might result from the dominant smectite clay mineral constituents of the Vertisols in the study area (Berhanu, 1985). The base saturation of the surface soil of the study area was in the very high range based on the ratings given by Hazelton and Murphy (2007). The high base saturation is explained by the very low rate of leaching due to the very low hydraulic conductivity and low infiltration rates of Vertisols (Pimentel, 2006). According to Soltanpour (1985) and Jones (2003), the AB-DTPA-extractable Cu, Mn and Fe contents of the surface soil of the experimental sites were rated as adequate, while Zn content was deficent and hence inadequate for plants growth (Table 2).

Biological yield

The above ground biomass of cereal crops (straw and grain) is an important agronomic parameter that is sensitive to soil and applied nutrients. Application of P and K significantly ($p \leq 0.01$) improved the aboveground biomass yield (Table 4 and Table 5).

At Akaki, the highest biological yields of 7.7 t ha^{-1} (1^{st} growing season) and 10.7 t ha^{-1} (2^{nd} growing season) were recorded from T_{14} (30-26 P-K kg ha^{-1}) and T_{11} (20-39 P-K kg ha^{-1}), respectively. These were statistically higher over P alone, K alone and the control (without P and K) treatments. In 2012 cropping season, the second highest biological yield of 6.5 t ha^{-1} was recorded from 39-30 P-K kg K ha^{-1} application. Results in 2013, however, indicated that a combined application of 26 kg K ha^{-1} with the highest P rate of 30 kg P ha^{-1} exhibited the second highest biological yield of 10.5 t ha^{-1} (Table 4).

In Cheffe Donsa the T_{15} (30-39 P-K kg ha^{-1}) treatment resulted in the highest biological yields of 17.2 t ha^{-1} and 11.7 t ha^{-1} in 2012 and 2013 growing seasons, respectively (Table 5). In similar manner, these were statistically higher than the control and other P and K alone treatments. In both cropping seasons, the second highest biological yields of 16.9 and 11.7 t ha^{-1} were recorded from 26 kg K ha^{-1} when applied with the lowest P rate, 10 kg P ha^{-1}. The biological yields were gradually decreased by increasing rate of P from 10 to 20 and 20 to 30 kg ha^{-1} when applied in combination with the low rate of 26 kg K ha^{-1} over the two cropping seasons. However, a gradual biological yield increment was recorded by increasing rate of P from 10 to 20 and 20 to 30 kg ha^{-1} when applied in combination with the highest K rate of 52 kg ha^{-1}. Generally, there were increases in biological yield at Akaki (48%, 50%) and Cheffe Donsa (20%, 48%) over the control, in the first and second cropping seasons, respectively.

Grain yield

Application of P and K significantly ($p \leq 0.01$) increased grain yield of wheat at both sites over the two cropping seasons (Table 4 and Table 5).

At Akaki, there were no significant grain yield differences in applying T_8, T_{11}, T_{12} T_{14} and $T_{15,}$ whereby T_{14} (30-26 P-K kg ha^{-1}) resulted the highest grain yield of 2.8 t ha^{-1}, were significantly higher over P alone and the control in the first growing season. In the same growing season, addition of P with K at the rates of 39 kg K ha^{-1} with 20 and 30 kg P ha^{-1}, however, didn't significantly increase yield over that with K alone treatments with the possible exception of K applied at the rate of 39 kg K ha^{-1}. In 2013 cropping season, grain yield was significantly increased over the control (without P and K) in all treatments but the magnitudes of responses were highest in three P and K rate combinations (T_{11}, T_{14} and T_{15}). Among these treatments the highest grain yield (4.8 t ha^{-1}) was recorded from T_{11} (30-26 P-K kg ha^{-1}).

The trend of response was different at Cheffe Donsa, the highest grain yields of 6.4 and 7.6 t ha^{-1} were obtained from P and K rate combination (20 kg P ha^{-1}, 26 kg K ha^{-1}) in 2012 and 2013 cropping seasons, respectively (Table 4). When the highest rate of both P and K (30 kg P ha^{-1} and 52 kg K ha^{-1}) were applied together, the resultant yield was apparently lower than the yields from P and K combinations (T_6 and T_{15}) though not significantly lower. A tendency to achieve significantly higher grain yields over the control were observed by two K alone treatments (26 kg ha^{-1} and 52 kg ha^{-1}) in the first growing season. In contrast, the apparent yield increment by all K alone treatments over the control (without P and K) were not significant in 2013 growing season.

Table 4. Wheat yield as affected by different P and K application rates at Akaki in 2012 (S1) and 2013 (S2) seasons.

Treatment	Biological yield		Grainy yield		Straw yield		Thousand grain weight	
P + K	S1	S2	S1	S2	S1	S2	S1	S2
	--------------------------------	*kg ha^{-1}*	--------------------------------				------------*gm*------------	
T_1 (0+0)	5,185	8,926	1,947	3,011	3,238	5,915	29	38
T_2 (0+26)	5,585	8,691	2,098	3,812	3,487	4,879	34	36
T_3 (0+39)	4,970	8,652	1,852	3,948	3,118	4,703	31	38
T_4 (0+52)	5,807	9,237	2,150	3,913	3,657	5,324	31	38
T_5 (10+0)	3,648	8,324	1,372	3,698	2,277	4,627	29	36
T_6 (10+26)	5,148	9,921	1,820	4,208	3,228	5,713	31	35
T_7 (10+39)	4,382	9,126	1,615	3,988	2,767	5,138	30	39
T_8 (10+52)	5,650	10,325	2,393	4,426	3,257	5,900	32	38
T_9 (20+0)	4,098	8,716	1,282	3,693	2,817	5,023	32	37
T_{10} (20+26)	5,013	9,340	1,973	4,061	3,040	5,279	34	39
T_{11} (20+39)	6,478	10,739	2,682	4,476	3,797	6,263	31	37
T_{12} (20+52)	5,308	8,821	2,232	3,997	3,077	4,824	32	39
T_{13} (30+0)	5,842	8,574	2,055	3,804	3,787	4,770	29	38
T_{14} (30+26)	7,662	10,497	2,815	4,797	4,847	5,700	32	39
T_{15} (30+39)	6,490	10,078	2,688	4,651	3,802	5,427	30	37
T_{16} (30+52)	5,423	9,878	1,992	4,339	3,432	5,539	31	38
LSD	1,224	600	857	1,123	1,335	653	4.2	2.3
SE	243	192	110	109	144	124	1.5	1.2
P value	**	**	**	**	**	ns	ns	ns

Note: **and 'ns' indicate significance at ≤ 1% probability levels and non significance difference, respectively. LSD: Least significant difference; SE: Standard error.

Table 5. Wheat yield as affected by different P and K application rates at Cheffe Donsa in 2012 (S1) and 2013 (S2) seasons.

Treatment	Biological yield		Grainy yield		Straw yield		Thousand grain weight	
P + K	S1	S2	S1	S2	S1	S2	S1	S2
	------------------------*kg ha*$^{-1}$	------------------------					------*gm*	------
T_1 (0+0)	11,450	7,910	4,370	5,520	7,080	2,390	39	41
T_2 (0+26)	14,695	10,120	5,545	6,197	9,150	3,924	39	46
T_3 (0+39)	13,383	9,283	5,183	6,328	8,200	2,955	38	42
T_4 (0+52)	14,998	10,362	5,725	6,395	9,273	3,967	38	44
T_5 (10+0)	13,283	8,834	4,385	5,962	8,898	2,873	38	41
T_6 (10+26)	16,955	11,668	6,380	7,568	10,403	4,100	39	44
T_7 (10+39)	14,525	9,951	5,378	6,164	9,147	3,788	38	43
T_8 (10+52)	15,173	10,518	5,862	7,069	9,312	3,449	39	44a
T_9 (20+0)	13,842	9,473	5,105	7,024	8,737	2,450	39	43
T_{10} (20+26)	16,152	11,118	6,085	7,223	10,067	3,896	37	45
T_{11} (20+39)	15,260	10,369	5,478	6,608	9,782	3,761	38	44
T_{12} (20+52)	15,995	10,938	5,880	6,701	10,115	4,236	40	44
T_{13} (30+0)	14,760	10,118	5,475	6,539	9,285	3,579	39	48
T_{14} (30+26)	15,965	10,981	5,997	7,217	9,968	3,765	38	44
T_{15} (30+39)	17,190	11,706	6,222	7,235	10,968	4,471	39	44
T_{16} (30+52)	16,553	11,352	6,150	6,935	10,403	4,417	39	46
LSD	1,907	836	1,315	1,403	1,317	886	2.4	4.4
SE	378	261	149	138	238	161	0.18	0.47
P value	**	**	**	**	**	ns	ns	ns

Note: **and 'ns' indicate significance at $\leq$ 1% probability levels and non significance difference, respectively. LSD: Least significant difference; SE: Standard error.

The combined analysis of variance in each location on grain yield are presented in Table 5.The significant difference in grain yield between the locations was caused by the difference between the sites. Even though the interaction of P and K rates didn't show significant difference in grain yield at Cheffe Donsa (both seasons) and second season in Akaki, their combination gave the highest grain yield and showing a significant ($p \leq 0.01$) difference in grain yield as compared to P alone, K alone and the control (without P and K). The highest grain yields (2.8, 4.8 t ha^{-1}) and (6.4, 7.6 t ha^{-1}) were obtained on the interaction of 30-26 and 10-26 P-K kg ha^{-1} in the first and second cropping season at Akaki and Cheffe Donsa, respectively. Generally, P and K fertilization induced grain yield of (45%, 59%) and (46%, 37%) over the control plots at Akaki and Cheffe Donsa in the first and second cropping seasons, respectively.

Table 6. Analysis of variance on grain yield of wheat for Akaki and Cheffe Donsa in 2012 (S1) and 2013 (S2).

Source of variance	Akaki		Cheffe Donsa	
	S1	S2	S1	S2
	------------------------*kg ha^{-1}*------------------------			
Phosphorus	ns	**	*	*
Potassium	ns	ns	ns	ns
P x K	**	ns	ns	ns
Mean yield of 0-0 P-K	1,947	3,011	4,370	5,520
Highest mean yield	2,815	4,797	6,380	7,568
P-K combination for highest yield	30-26	30-26	10-26	10-26

Note: *,**indicate significance at the 5 and 1% probability levels, respectively. ns- indicate non-significance difference.

Thousand grain weight

The fertilization treatments had no effect on ($p \leq 0.05$) the 1,000 seed weights in either of the either the seasons or sites. Heavier seeds were observed in the second season as compared to the first season at both sites. The interaction of P and K (T_{12}, T_{13}, T_7 and T_{10}) showed a trend towards heavier seeds as compared to P alone, K alone and the control (without P and K). Zero fertilization and applying T_5 (P-K 10-0 kg ha^{-1}) had lighter seed weight (Table 3 and Table 4) as compared to P and K interaction at both sites over the two cropping seasons. Although the mean 1000 grain weight appeared to be relatively similar under the various treatments at Akaki in the 2012 growing season, few differences (non-significant) were observed in 2013 growing season (Table 4). In 2013, the highest thousand grain weight of 39g was resulted from two P and K combinations ((10, 39) and (20, 26)) though statistically similar with the control (without P and K) and most other treatments.

At Cheffe Donsa, the trend was different; 1,000 grain weight appeared to be similar in 2012 but few differences were observed in the 2013 cropping season (Table 5). Increasing the rate of P from 10 to 20 and 20 to 30 kg ha^{-1} when applied with the various rates of K over the two cropping seasons didn't affect the 1,000 grain weights significantly.

Nutrient Uptake

The data shown in Tables 7 and 8 revealed that there were significant ($p \leq 0.001$) differences among treatments in total N, P and K uptake by wheat (kg ha^{-1}) during the first and second cropping seasons. At Akaki in 2012, the total N uptake was significantly increased over the control and P and K alone treatments on plots treated by combined application of P and K, with the possible exception of various K rates combined with low rate of P. The highest total P uptake of 12.3 kg ha^{-1} was found on plots treated with 26 kg ha^{-1} of K and 10 kg ha^{-1} of P and the lowest total P uptake was obtained from the control plot (without P and K). The total uptake of K under the various P and K combinations was either significantly higher or comparable to P and K alone treatments. In 2013, the pattern of total nutrient uptake and significance were nearly similar. In addition the magnitude of total nutrient uptake was more noticeable in this growing season.

Among the various treatments, T_{10} (20-26 P-K kg ha^{-1}) resulted in significantly highest total N uptake of 92 kg ha^{-1} at Chefe Donsa in 2012 cropping season. Likewise, significantly highest total P uptake of 21.6 kg ha^{-1} was exhibited by T_{11} (20-39 P-K kg ha^{-1}). The total uptake of K was generally increased on plots treated with P and K combinations compared to the control and K alone treated plots, but the differences were not significant in some of the cases. In 2013, increased uptake of N and K was noticed but total P uptake did not show a marked increase (Table 9, Fig. 2 and 3).

Generally, total N uptake was improved with P and K application and their combined use surpassed their application alone. This showed that the availability of extra K in these soils improved the extraction of nitrogen by the wheat crop. Sharma and Ramna (1993) indicated that the application of K released the fixed $NH4^{+}$ ion from the soil and helped the crop for better uptake of N. Total P uptake with P+K were highest followed by P alone, and both showed significantly higher P uptake as compared with K alone and the control. Total K uptake with P+K were highest followed by K alone, and both showed significantly higher K uptakeas compared with P alone and the control (without P and K) (Table 9, Fig. 2 and Fig. 3).

Total nutrient uptake and yields varied significantly between the experimental years. In fact, maximum yields and total uptake were recorded in 2013 cropping season at both study sites. This may be mainly attributed to the relatively high

Table 7. Total N, P and K uptake (kg ha^{-1}) of wheat as affected by application of P and K at Akaki during 2012 (S1) and 2013 (S2).

Treatment	Akaki					
	S1			S2		
P + K	Total N	Total P	Total K	Total N	Total P	Total K
----------------------	--------------------	------------------*kg ha*$^{-1}$	------------------	------------------	------------------	------------------
T_1 (0+0)	20	3	13	46	10	30
T_2 (0+26)	24	5	23	55	12	46
T_3 (0+39)	25	5	18	71	14	51
T_4 (0+52)	29	8	28	90	15	58
T_5 (10+0)	22	7	16	74	13	62
T_6 (10+26)	37	12	28	93	20	71
T_7 (10+39)	29	12	29	104	17	66
T_8 (10+52)	39	14	29	102	23	81
T_9 (20+0)	19	7	26	76	14	54
T_{10} (20+26)	46	11	29	88	20	70
T_{11} (20+39)	49	11	32	95	20	79
T_{12} (20+52)	41	11	32	93	21	64
T_{13} (30+0)	27	6	27	75	15	61
T_{14} (30+26)	68	12	34	107	15	79
T_{15} (30+39)	62	9	40	106	20	85
T_{16} (30+52)	40	10	44	93	17	86
LSD	10	4	12	15	5	13
SE	4	0.81	2	4.5	0.93	3.8
P value	**	**	**	**	**	**

Note: **indicate significance at ≤0.1% probability levels.

amount of N fertilizer (92 kg N ha^{-1}) applied in this growing season as well as to the high rainfall in 2013 than during the 2012 growing season. Results obtained during long-term experiments revealed a direct relationship between yield and the amount of rainfall during the vegetative period of wheat (López-Bellido *et al.*, 1996).

Table 8. Total N, P and K uptake (kg ha^{-1}) of wheat as affected by application of P and K at Cheffe Donsa during 2012 (S1) and 2013 (S2).

Treatment	Cheffe Donsa					
	S1			S2		
P + K	Total N	Total P	Total K	Total N	Total P	Total K
	----------------	----------------	----*kg ha^{-1}*----	----------------	----------------	----------------
T_1 (0+0)	48	10	14	69	12	31
T_2 (0+26)	48	10	20	93	15	50
T_3 (0+39)	53	10	27	84	15	61
T_4 (0+52)	74	12	22	90	9	61
T_5 (10+0)	62	14	9	78	16	44
T_6 (10+26)	85	17	61	117	20	8
T_7 (10+39)	80	18	46	95	16	69
T_8 (10+52)	84	15	55	106	18	84
T_9 (20+0)	72	13	21	85	14	58
T_{10} (20+26)	92	16	70	116	17	83
T_{11} (20+39)	76	22	34	101	17	71
T_{12} (20+52)	81	17	54	104	23	64
T_{13} (30+0)	55	10	19	95	9	63
T_{14} (30+26)	92	19	37	112	3	87
T_{15} (30+39)	83	21	62	109	19	73
T_{16} (30+52)	79	21	70	115	20	69
LSD	15	4	24	18	6	17
SE	3.7	1.1	5.2	3.6	1.2	5.1
P value	**	**	**	**	**	**

Note: **indicate significance at ≤0.1% probability levels.

Table 9. Total N, P and K uptake as influenced by P alone, K alone and P and K application at Akaki and Cheffe Donsa (means of 2012 and 2013).

Treatment	Akaki			Cheffe Donsa		
P + K	Total N	Total P	Total K	Total N	Total P	Total K
			kg ha^{-1}			
P alone						
T_1: (0+0)	33	7	22	59	11	23
T_5: (10+0)	48	10	39	70	15	27
T_9: (20+0)	48	11	40	79	14	40
T_{13}: (30+0)	51	11	44	75	10	41
K alone						
T_1: (0+0)	33	7	22	59	11	23
T_2: (0+26)	40	9	35	71	13	35
T_3: (0+39)	48	10	35	69	13	44
T_4: (0+52)	60	12	43	82	11	42
P + K						
T_6: (10+26)	65	16	50	101	19	35
T_7: (10+39)	67	15	48	88	17	58
T_8: (10+52)	71	19	55	95	17	70
T_{10}: (20+26)	67	16	50	104	17	77
T_{11}: (20+39)	72	16	56	89	20	53
T_{12}: (20+52)	67	16	48	93	20	59
T_{14}: (30+26)	88	14	57	102	11	62
T_{15}: (30+39)	84	15	63	96	20	68
T_{16}: (30+52)	67	14	65	97	21	70

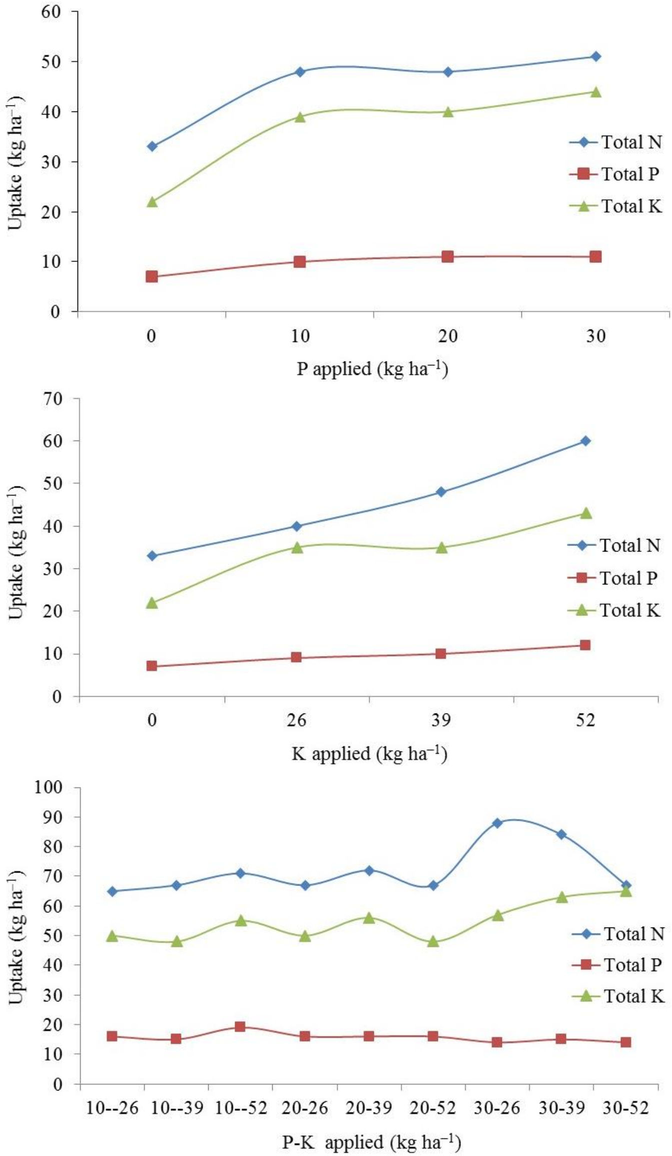

Fig. 2. Total nitrogen, phosphorus and potassium uptake as influenced by P alone, K alone and P and K application at Akaki, respectively (means of 2012 and 2013).

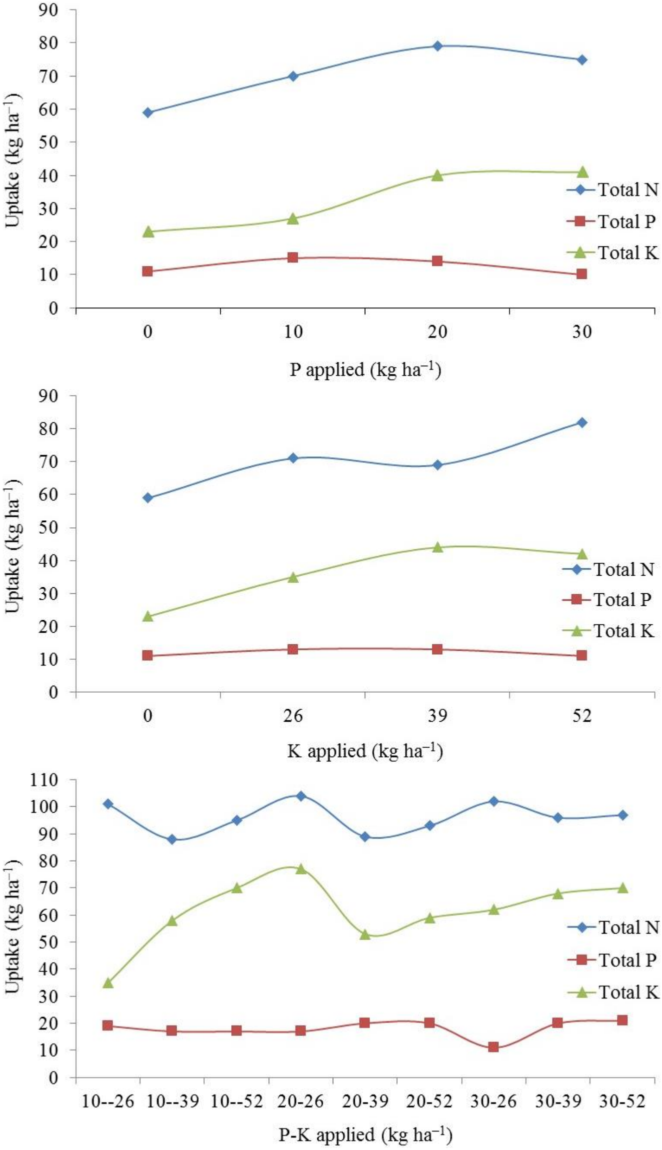

Fig. 3. Total nitrogen, phosphorus and potassium uptake as influenced by P alone, K alone and P and K application at Cheffe Donsa, respectively (means of 2012 and 2013).

In Ethiopia, farmers do not apply K fertilizers because researchers and development agents believe that the soil can supply the required K. This practice might hold true with the low yield levels of traditional cultivars. However, the introduction of modern high yielding varieties has increased both cropping intensity and yields, which results in larger removal of K and other nutrients from soil. Data presented in this paper do not fully support the perception that the soil of the central highlands of the country can supply adequate K for achieving high yields of modern varieties. The results of this investigation indicated that integrated application of P and K fertilizers enhanced yields and nutrient uptake of wheat at both sites over the two cropping seasons. These results are supported by the findings of Abiye *et al.* (2004) who stated that there was appreciable yield response upon K fertilization at Cheffe Donsa. They further verified that potassium application enhanced N uptake of wheat. Overall, the benefits of K fertilization should be evaluated after long term experimentation.

Conclusion

Wheat yield showed significant response to P and K application. Yield increase was observed at both locations over the two cropping seasons by the combined use of P with K. Thus, it can be concluded that the combined use of P with K could be beneficial to enhance productivity and nutrient uptake of wheat in central highland Vertisols of Ethiopia.

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Chapter 8

The Status of Plant Available Potassium (K) at Three Sites in Ethiopia

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Abstract

The role of potassium (K) in a balanced plant nutrition is an important soil fertility parameter to ensure better plant growth, increase yield and enhance food security. Assessment of plant available K was required to know the need for K fertilization and understand soil K distribution along profile under different land use types (LUTs). The objective of this study was to describe variation and availability of K in various soil types from three sites (Gununo, Anjeni and Maybar) in Ethiopia. The study was based on 239 soil samples taken at different depths (0-10, 10-30, 30-50, 50-100 cm) from three LUTs in three sites. Plant available K was determined using the Ammonium Acetate method. Shapiro-Wilk tests showed non-normal distribution ($p=0.002$, $\alpha=0.05$) for K data. Potassium values ($n=239$) varied from a minimum value of 0.07 to a maximum value of 90.2 $cmol_{(+)}\ kg^{-1}$ with 0.5 median value. Very low K level (<2 $cmol_{(+)}\ kg^{-1}$) was observed in 60% of the samples (mostly in Anjeni and Maybar sites).Variability was highest in Gununo among the sites and in forest land use (FLU) among the LUTs. Sixty-five percent of the tillage depth samples (0-30 cm, $n=128$) had a very low median value of 1.8 with 6.8 $cmol_{(+)}\ kg^{-1}$ variance. Median values were 0.53, 0.52 and 13.9 for crop land use (CLU), grass land use (GLU) and FLU respectively. Non parametric tests showed that K median values and distribution are significantly different ($\alpha=0.05$, $p<0.05$) across the three sites and LUTs. However, it is not significant for the soil profiles and the results agreed with Kruskal-Wallis and Chi-square tests. The paper also discussed plant available K in relation to other

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important soil properties. The study showed that very low levels of plant available K in most of the soils in the three sites which highlights the necessity to supplement K through fertilization.

Keywords: Plant available potassium, K, Ethiopia, potassium, soils.

Introduction

With a rapidly increasing population, Ethiopia needs to increase food production, in grain equivalent, by at least 1 million metric tons (Gameda, 2013). Currently, 12 million small holder farmers depend on 12 million hectares of land, but crop productivity level is low. Among other reasons, the low crop productivity (cereals <2 t ha^{-1} and pulses <0.8 t ha^{-1}) in Ethiopia is due to high soil nutrient depletion, land degradation, low soil inputs and poor land management practices (Zeleke *et al.*, 2010) which results in deficiency of key nutrients including K.

Nutrient balance studies have already proved that soil fertility depletion rates are high in Ethiopia. Recent studies have reflected the problem of K depletion (Haileslassie *et al.*, 2005; Haile and Mamo, 2013). Previous studies among smallholder farmers in Ethiopia at a national level have revealed a K depletion rate of 82 kg^{-1} ha^{-1} yr^{-1} (Haileslassie *et al.*, 2005), with erosion contributing to 63 percent of the loss. Digital soil fertility survey being conducted by Ethiopian Agricultural Transformation Agency (ATA) (Gameda, 2013) reveals deficiencies of six to seven nutrients, but only DAP and Urea (supply only two nutrients) were used by farmers for more than four decades.

The role of K in plant nutrition and in increasing productivity is important. Potassium is an essential nutrient for crops and is responsible for the roles 50 enzymes play in energy transfer and formation of sugar, starch and protein (Al-Zubaidi *et al.*, 2008). In most farming systems, including in Ethiopia, although K is an essential nutrient, priority has often been given to nitrogen (N) and phosphorus (P).

There are various approaches and methods which are used to determine plant available K in soils. Al-Zubaidi *et al.* (2008) have revealed that ionic strength and activity, activity coefficient and ratio, buffering capacity and free energy replacement are thermodynamic concepts that could be used to evaluate K availability. The UN Food and Agriculture Organization (FAO) states that there is no single method which might be considered the best for determination of nutrient status of a soil (FAO, 1980). This is backed up by Darunsontaya *et al.* (2010): "For a particular soil-plant interaction, selecting a suitable extraction to predict K supply depends how closely extracted K indicates the actual plant uptake by plants."

The four major forms of soil K are mineral, non-exchangeable (fixed or unavailable), exchangeable and solution (Al-Zubaidi *et al.*, 2008). Based on availability, K is classified as unavailable, slowly available or available. There are also studies which indicate that seasonal variation in available K is low (Tillman and Officer, 2000).

The most popular and standard method of determining K availability is cation displacement with neutral ammonium acetate (Cox *et al.*, 1999; Carter and Gregorich, 2006; Al-Zubaidi *et al.*, 2008). Several studies have confirmed that the ammonium acetate method is a highly predictive indicator of K availability for plants (Carter and Gregorich, 2006; Darunsontaya *et al.*, 2010). This method measures plant available K (exchangeable and solution forms). In a comparative study of K determination methodologies in Ethiopia, the amonium acetate method was found as one of the most suitable measurements for exchangeable K (Mamo *et al.*, 1996).

The belief in the past that Ethiopian soils are rich in K had undermined the importance of K fertilizations (Ayalew and Beyene, 2011; Ayele, 2013; Haile and Mamo, 2013).Examining trends in chemical fertilizer use in Ethiopia since the late 1960s also shows that K fertilizers have seldom been used.

Having realized the role of K in balanced plant nutrition and soil nutrient depletion associated with K, the demonstration of K containing fertilizers is being promoted in Ethiopia (Wanzala and Groot, 2013). The effort is being supported through nationwide digital soil fertility mapping conducted by the Ethiopia Soil Information System (ETHOSIS). Although the Democratic Republic of Congo (DRC) and Ethiopia are the only countries in sub-Saharan Africa with commercially viable deposits of potash, currently there is no commercial production of K in Africa (Wanzala and Groot, 2013). However, efforts are being made by big fertilizer companies to mine potash in Ethiopia and avail it for both local and export markets.

Studies on fertilizer market problems in Ethiopia highlighted opportunities to diversify the ranges of available fertilizers from Urea and DAP to more appropriate fertilizers (Wanzala and Groot, 2013). Expanding availability of relevant fertilizers will result in more sustainable use of soil resources, leading to increased production and productivity. However, current efforts in Ethiopia to map soil fertility, distribute custom-made fertilizers, mine fertilizer raw materials such as potash, etc., need further research.

Previous studies conducted on exchangeable K in Ethiopia have shown the need for varied K fertilization. Ayele (2013) revealed that there are low levels of K in watersheds in Lake Abaya. A recent study on the role of K fertilization on potato (Solanum tuberosum) at Kembata in southern Ethiopia did not significantly change yield (Ayalew and Beyene, 2011). Yet, an increase in Wheat grain and straw yield of about 1Mt per ha was reported due to K fertilizer application on Vertisols of Ethiopian Central Highlands (Astatke *et al.*, 2004). Meanwhile, a review by Haile and Mamo (2013) showed that K is a limiting factor in acidic soils in southern Ethiopia for better plant growth and increased yield. The authors reported that in acidic soil in southern Ethiopia, K fertilization had increased Potato and Wheat yield.

Using K fertilizers can improve plant nutrition, quality and yield, which in turn would increase the welfare of smallholder farmers in Ethiopia. But until recently, there has been reports reflecting the ability of Ethiopian soils to make K available to plants. Assessment of soils' ability to release K for plant uptake is an important step (Darunsontaya *et al.*, 2010). In Ethiopia, the extent of K deficiency and adequacy still needs additional evidence. There is limited evidence which shows the status of K under different land uses along cross-section of profiles.

Research on K in Ethiopia has focued usually on the role of K for various crops biomass and yield on different soils. For increased productity and better plant growth, it is also important to study the vertical distribution of K on different LUTs. Review of available literature in Ethiopia shows that past studies have not showed the variation and distribution of soil K along profiles. Vertical distribution of nutrient in soil shows how limiting a nutrient would be (Jobbagy and Jackson, 2001). Vertical distribution of soil nutrients provides insights on nutrient inputs (high inputs or accumulation), outputs (high outputs or depletion) and cycling process (Jobbagy and Jackson, 2001; Saini and Grewal, 2014). Knowledge of vertical distribution of K therefore forms a sound base for fertilizer recommendations (Saini and Grewal, 2014). This study examined variation and distribution of soil K in 64 soil profiles (on different land use types [LUTs]), determined status of exchangeable K which reflected the importance of K fertilizers in Ethiopia.

Materials and methods

The study area

The study sites are located in southern, north-western and north-eastern Ethiopia. The sites were previously research stations for the Ethio-Swiss funded Soil Conservation Research Program (SCRP). Gununo is located in Wolayta Zone, 16 km WNW of Sod town, at 37°38'E/6°56'N (Weigel, 1986b; SCRP, 2000b) in Damote-Sore district. Maybar is located in South Wollo Zone, 14 km SSE of Dessie town, at 39°40'E/11°00'N (Weigel, 1986a; SCRP, 2000d) in Albulko District. Anjeni is located in West Gojjam Zone, Dembecha District, 15 km north of Dembecha town at 37°31'E/10°40'N (Kejela, 1995; SCRP, 2000c) (Fig. 1).

The altitude of the sites varies from 1,982 meters above sea level (m.a.s.l) in Gununo to 2,858 m.a.s.l in Maybar. Two of the sites have a sub-humid climate except Gununo which has a humid climate (Thornthwaite classification).

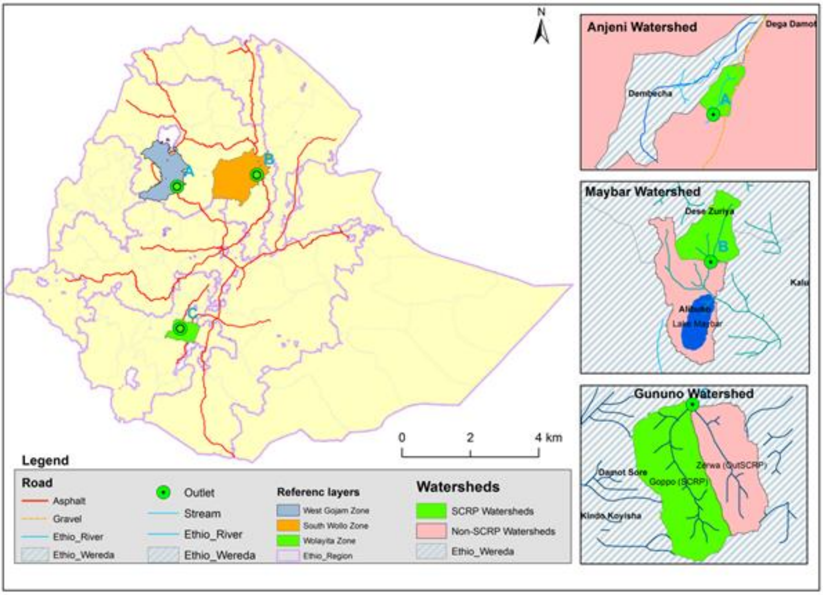
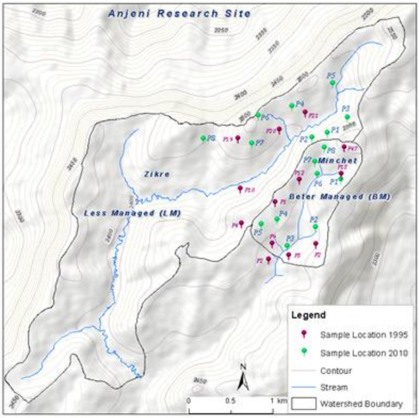


Fig. 1. Location map of the study area.

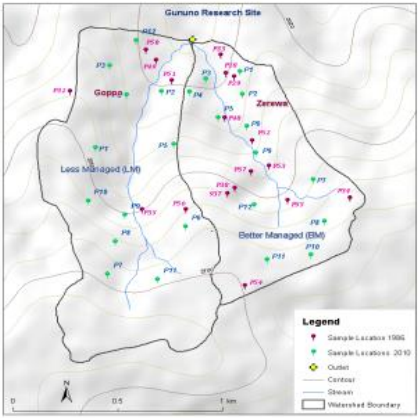
Soil sampling

Soils were sampled from three sites in adjacent or 'twin' watersheds grouped as less manged and better managed watersheds. Before samples were taken, land use history was recorded from land owners to ensure that LUTs have been maintained on each plot for the past 30 years. In the 1980s, the soils of the study sites were described and classified using FAO-UNESCO classifications. Profile (pit) description involves recording location, slope, position along the landscape, land use type and history (Edmonds, 1997).Within each watershed, plots were identified as major types of LUTs. Three LUTs were identified as cropland (CLU), forestland (FLU) and grazing land (GLU). A total of 64 profiles (four profiles per LUT) were dug in three sites. The number of profiles and soil sample densities recorded were much higher than recommended by Hazelton and Murphy (2007) (Table 1).

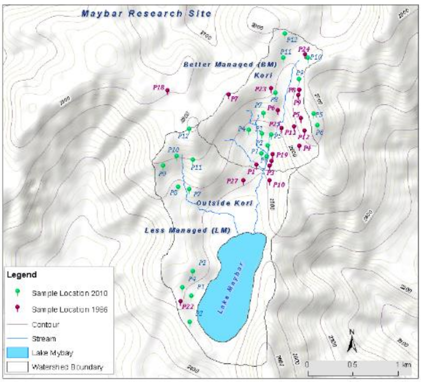
Purposive sampling was used (Carter and Gregorich, 2006) to ensure representation of major LUTs. Stratified random samples of four profiles were taken for each LUT in each watershed. Stratified depth samples were taken for each profile to a depth of 1 meter (Jobbagy and Jackson, 2001). Samples were taken from 0-10, 10-30, 30-50 and 50-100 cm depth. Fixed depth interval was used to study the vertical distribution of nutrients because soil horizons vary in thickness (Jobbagy and Jackson, 2001). The total number of soil samples for LUTs in each site is tabulated (Fig. 2; Table 1).



Anjeni



Gununo



Maybar

Fig. 2. Relative location of soil profiles in the study area.

Table 1. Soil types, samples, LUTs and profiles in three sites.

Study sites	Gununo (GUN)		Maybar (MAY)		Anjeni(ANJ)	
Major soil types (FAO-UNESCO) ++	Nitisols, Acrisols, Phaeozems, Fluvisols		Phaeozems, Lithosols, Gleysols		Alisols, Nitisols, Cambisols	
Watersheds name	Zerwa	Goppo	Inside Kori	Outside Kori	Minchet	Zikere
Watershed size (ha)	72.8	94	112.8	406.9	113.4	805
Number of LUT	3	3	3	3	2	2
Number of profile/watershed	12	12	12	12	8	8
Number of soil sample	24	24	24	24	16	16
Number of sample/site	96		81		62	

Note: +BM=better-managed or (SCRP sites) LM=less managed or (Outside SCRP).

++Classification (Weigel, 1986b; Kejela, 1995; SCRP, 2000a; SCRP, 2000b; SCRP, 2000c; SCRP, 2000d).

Soil and statistical analysis

Conventional soil analytical methods were used to determine soil physical and chemical properties. Air dried soil was grounded and sieved through 2 mm mesh. Core-samplers were used for soil bulk density determination. Soil texture was determined using the Bouyoucos hydrometer method. Soil moisture was determined using the oven dry method (for 24 hours at105oC). pH (water and CaCl2) was determined using a pH meter at a ratio of 1:2.5 (soil: water/chemical). Electrical conductivity (EC) was measured with a conductivity meter using distilled water. Soil organic carbon (SOC) (g kg^{-1}) was determined using the Walkely and Black method (FAO, 1970). A conversion factor of 1.72 was used to calculate the percentage of organic matter (OM).

Total N was determined using the Kejealdahal digestion method (Page, 1982). Available P was determined using the Olsen method. Cation exchange capacity (CEC) and exchangeable cations (Na, K, Ca, and Mg) were determined using the (neutral) Ammonium Acetate method, using an atomic absorption spectrometer (AAS)) (FAO, 1970).

Potassium was determined by saturating the exchangeable sites with an index cation (NH4+) using 1M (NH4OAc) at pH 7 (FAO, 1970; Darunsontaya *et al.*, 2010). The use of Ammonium Acetate (NH4OAc) solution as an extractant was based on the justification that results are closely related to plant uptake (Cox *et al.*, 1999; Al-Zubaidi *et al.*, 2008; Darunsontaya *et al.*, 2010).

Non-parametric tests were used to analyze the data as recommended for non-normally distributed data (Landu and Everitt, 2004; Strimbu *et al.*, 2009). Spearman rank correlation coefficient was used to compare K concentration in various depths (Jobbagy and Jackson, 2001). The effect of soil profile depth and land use on soil K were tested for significance level at $P<0.05$ and $\alpha=0.05$ level. The statistical analyses was used using SPSS Version 20.0 (IBM SPSS statistics, Armonk, NY, US).

Results and discussion

Result of normality test

Normality test of soil nutrient data is essential (Strimbu *et al.*, 2009) because distribution governs the type of statistical test to be selected. Such tests are essential when dealing with soil variability in connection with soil nutrients among LUTs. In a study of vertical distribution, soil nutrient data which are not normally distributed (as in Fig. 3) non-parametric tests were used (Jobbagy and Jackson, 2001; Strimbu *et al.*, 2009).

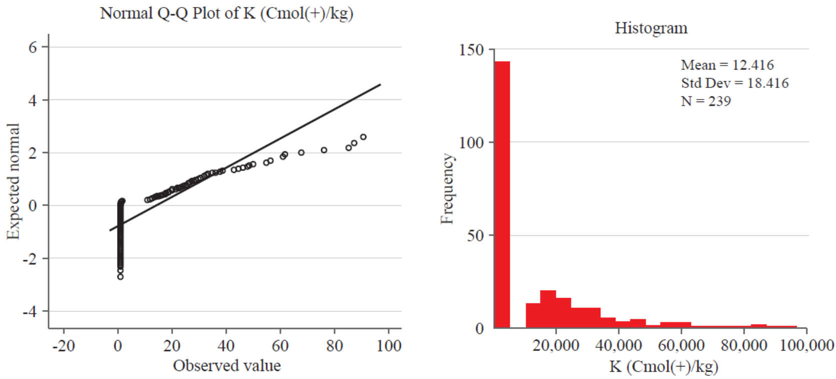


Fig. 3. Distribution pattern (Q-Q plot (a) Histogram (b)) of soil K data.

Summary of soils 'and K properties

The major types of soils in the study area were previously classified using FAO-UNESCO classification system (Weigel, 1986a; Weigel, 1986b; Kejela, 1995; SCRP, 2000a; SCRP 2000b; SCRP 2000c; SCRP 2000d) (Table 1). Nitisols and Phaeozems appear to be the most common type of soils in the study areas. Soils in the study area are slightly acidic. A small standard deviation for soils TN, BD and pH of the soils are noted while lower values are noted for exchangeable K, CEC, base saturation and EC (Table 2).

Soil pH values (5.1) show strong acidity (Hazelton and Murphy 2007; Soil Survey Staff, 2011). CEC ranged from moderate to high with very high base saturation (Hazelton and Murphy, 2007). Maybar soil pH values with water ranged from 5.9 to 7.0 and with CaCl2 values ranged from 5.7 to 6.5 (Weigel, 1986a). Gununo soil pH (water) values ranged from a value of 4.6 to 7.5 and with $CaCl_2$ values ranged from 4.3 to 5.9 (Weigel, 1986b).Anjeni soil pH (water) values ranged from a value of 4.0 to 7.3 (Kejela, 1995). The relation between soil pH and K availability showed that low levels of pH value (acidity) in the soil in general reduce K availability.

Table 2. Soil descriptive statistics in three sites under three LUTs (n=239).

Soil properties	Minimum	Maximum	Mean	Std. Deviation	Range	Variance	Median
% Sand*$^{+,}$**	0	60	25.20	10.2	60	105.6	26
% Silt*$^{+,}$**	2	74	29.68	11.5	72	132.8	28
% Clay*$^{+,}$**	16	80	45.14	15.4	64	239.9	44
pH water**	4.0	7.0	5.6	0.6	3.0	0.4	5.6
pH $CaCl_2$*$^{+,}$**	4.0	6.2	5.1	0.5	2.2	0.3	5.1
EC (µS)*,**	1.1	89.0	20.9	11.6	87.9	136.6	18.2
CEC (meq 100 gm^{-1})$^{+,}$**	12.62	58.34	34.6	12.3	45.7	153.4	33.7
Base sat.,**	10.5	299.7	95.4	54.5	289.1	2975.8	79.3
TN %*$^{+}$	0.01	0.57	0.16	0.08	0.5	0.007	0.15
Av P (ppm)*$^{+,}$**	0.40	23.2	2.5	2.2	22.8	5.1	2
K ($cmol_{(+)}$ kg^{-1})$^{+,}$*,**	0.07	90.9	12.4	18.4	90.8	339.1	0.58
Ca ($mol_{(+)}$ kg^{-1})**	0.7	46.3	16.2	13.6	45.6	186.7	9.5
Mg ($cmol_{(+)}$ kg^{-1})**	0.5	11.3	4.1	2.9	10.8	8.5	3.4
Na ($cmol_{(+)}$ kg^{-1})$^{+,}$**	0.05	0.9	0.2	0.1	0.9	0.01	0.2
% OM$^{+,}$**	0.08	11.5	3.5	2.2	11.4	5.0	3.4
BD (gm/cm^3)*$^{+,}$**	0.9	2.0	1.2	0.14	1.0	0.02	1.2

Note: *Non parameteric Independent Samples Median Test and Kruskal-Wallis test^{+}($p<0.05$, $\alpha=0.05$) across categories of LUTs. **Non parameteric Independent Samples Median Test ($p<0.05$, $\alpha=0.05$) across three sites.

The tillage layer's (0-30 cm, n=128) median soil K value is 0.63 $cmol_{(+)}\ kg^{-1}$) while the deeper profiles have a lower median value of 0.58 $cmol_{(+)}\ kg^{-1}$. Sixty percent of the samples (n=143) have value ≤2 $cmol_{(+)}\ kg^{-1}$ which shows very low levels of K availability. A nutrient classification adopted by Weigel (1986ab) gives the interpretation that there was low levels of K in the tillage layer. Median values were used to describe K data which is non-normally distributed (Tillman and Officer, 2000). Interpretation of soil K status was based on FAO's (1980) which shows that none of the soils in this study lies in very high K status level class.

Exchangeable K distribution along the soil profiles

There is little contrast in soil exchangeable K values along the soil profile. The tillage layer (0-30 cm) has a median value of 0.63 $cmol_{(+)}\ kg^{-1}$ while the deeper profiles (30-100 cm) have a median value of 0.58 $cmol_{(+)}\ kg^{-1}$. The minimum value recorded for 0-10 cm was the highest along the profiles which may also reflect role of soil organic carbon in making soil K more available. The lowest values for 0-10 cm ranged from 0.1 to 0.2 $cmol_{(+)}\ kg^{-1}$. The lowest values for the other profiles (10-30, 30-50 and 50-100 cm) were from 0.07 to 0.1 (Fig. 4).

Table 3. Descriptive statistics of soil exchangeable K ($cmol_{(+)}\ kg^{-1}$) along soil profile.

Depth (cm)	0-10	10-30	30-50	50-100
Sample (n)	64	64	60	51
Mean	12.0	11.0	12.0	14.9
Median	0.70	0.56	0.49	0.67
Variance	397	312	324	331
Stand. dev.	19.8	17.6	18.0	18.2
Minimum	0.13	0.07	0.07	0.09
Maximum	87.3	76.3	90.0	56

The dispersion of exchangeable K along the profile is highest in deepest profiles and lowest in surface soil. The median and minimum value of exchangeable K along the soil profiles seems to be similar. The maximum values are recorded in the deepest depths (50-100 cm) but the pattern along the profile is variable.

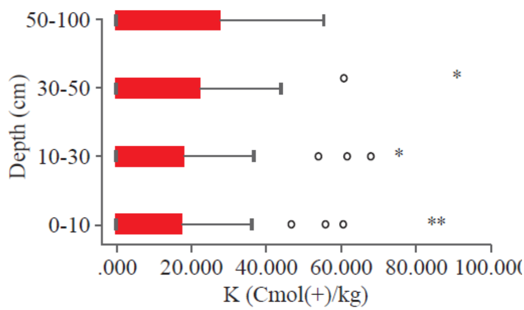


Fig. 4. Transposed box plot for soil exchangeable K ($cmol_{(+)}$ kg^{-1}) along profiles.

Potassium is one of the strongly cycled nutrients and it is more concentrated in the upper 20 cm (Jobbagy and Jackson, 2001). However, results from this study does not agree with this hypothesis and it seems that leaching and weathering had significantly affected exchangeable K along the profiles. The Spearman rank correlation coefficient (rs) (two tailed) result is not significant (α=0.05, rs=0.03, p=0.6) for median K concentration for various depths. Kruskal-Wallis test results are not significant (α=0.05, p=0.6) for median values and distribution of exchangeable K across four soil profiles. Results agree with Chi-square test (χ2 test) which did not show any significant difference in the median values of exchangeable K across the four soil layers (3, n=239, p=0.6).

A previous study by Weigel (1986a) on Maybar soil exchangeable K along the profile showed that 84 percent of variable depths of surface profiles had higher values of K compared to the sub-surface profiles. Fifty percent of Gununo soils had higher K values in surface layers while 15 percent had the opposite pattern. The rest (35%) have shown irregular distribution (Weigel, 1986b).Sixty percent of Anjeni soil profiles had higher K values in surface layers while 20 percent had the opposite pattern and the rest (20%) have shown irregular distribution (Kejela,1995).

Of the four major processes (weathering, atmospheric deposition, leaching and biological cycling) described by Jobbagy and Jackson (2001) that shape vertical distribution of soil nutrients, the effect of weathering dissolution seems to be a major factor governing K distribution in soil profiles. The effect of leaching, moving K downward to sub profiles, increasing K concentrations at depths (30-50 cm) is not visible for profiles in this study.

Variability of exchangeable K among LUTs

Comparison was made for exchangeable K variability among the three major categories of LUT (Fig. 5).

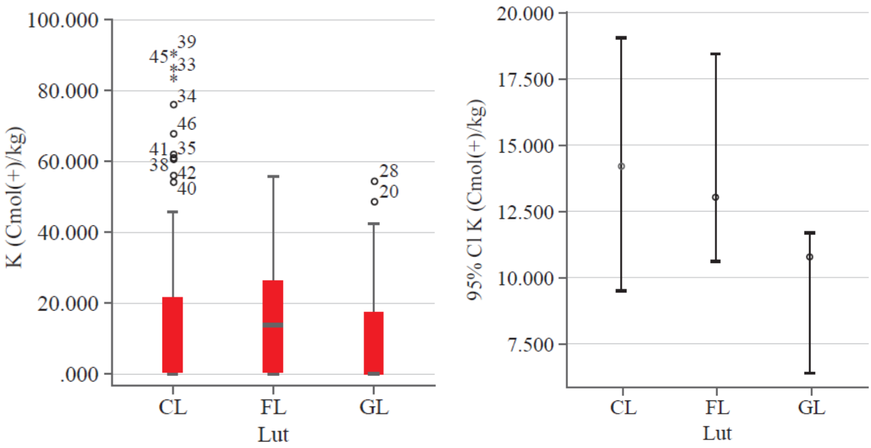


Fig. 5. Box plot (a) and error bar (b) for soil K ($cmol_{(+)}\ kg^{-1}$) under different LUTs.

Box plots show that CLU has the highest variability while GLU has least variability. CLU has the highest number of outliers and most of the samples were from Gununo while the minimum values of K among the LUTs seem to be similar, the box plot shows that FLU has a higher median (set as horizontal line of the box) value (13.9) compared to CLU and GLU which have similar median values (0.5 $cmol_{(+)}\ kg^{-1}$). Reduced land management on grazing land and lack of K fertilizer application on crop lands might have contributed to depletion of K on CLU and GLU, resulting in low exchangeable K median values. The FLU has the highest standard deviation (1.7) followed by GLU (1.2) and CLU (0.8).

Exchangeable K was highly variable under FLU, followed by CLU and then GLU. The high variability of K on forestland could be, firstly, due to variation in forest cover type (i.e. eucalyptus to junipers). Secondly, the topographic variability of the forest lands (hilly, valleys and depressions) which influences soil movement. Third, the forests are the result of an afforestation program and the extent and type of land degradation varies on the sites (Weigel, 1986a; SCRP, 2000d). Unlike the FLU, similarity in GLU topographic location and land cover might have reduced variability.

Ranges of extreme values of exchangeable K ($cmol_{(+)}$ kg^{-1}) between the LUTs among the three sites were 0.09-90.9 for CLU, 0.07-55.0 for GLU and 0.1-56.5 for FLU. The box plot (Fig. 5) shows the difference between LUTs. The values of K vary from a minimum value of 0.09 to a maximum value of 90.0 on CLU. The values range from 0.1 to 56.5 on FLU and 0.07 to 55.0 for GLU.

Non-parametric tests were conducted (n=239) to compare median K values and K distribution across categories of LUTs, showing a significant difference (p=0.01, α 0.05). Kruskal-Wallis test results were significant (α=0.05, p=0.02) for median values and distribution of soil K across LUTs (α=0.05, p=0.02). Results also agree with the Chi-square test, showing a significant difference in the medians of soil K across the three LUTs (2, n=239, p=0.02).

Variability of exchangeable K among the three sites

Non-parametric tests (Kruskal-Wallis and Chi-square) were conducted (n=239) to compare the median values of exchangeable K and its distribution across the three sites. Kruskal-Wallis test results were significant (α=0.05, p=0.02) for the median values and distribution of exchangeable K across three sites. Results agree with the Chi-square test, which showed a significant difference in the median values of exchangeable K across the three sites (2, n=239, p=0.00).

The median value of Gununo site is the highest (n=96, 24 $cmol_{(+)}$ kg^{-1}) while values for Anjeni and Maybar sites are (n=62) 0.2 and (n=81) 0.3 respectively. Gununo has the largest dispersion of exchangeable K (309 variance and 17 standard deviation) while the other two sites have a variance of 0.05 and 0.2 standard deviation. The minimum values of K in Gununo are much higher than the maximum values obtained at Anjeni and Maybar.

The box plot (Fig. 6) also shows variability of exchangeable K. Gununo has a variance of 309 while Anjeni and Maybar have a variance of 0.05 and 0.06. Standard deviation for Gununo is higher (17) than Anjeni and Maybar (0.2).

Exchangeable K values in Maybar range from 0.29 to 1.66 $cmol_{(+)}$ kg^{-1} of soil (Weigel, 1986a). Gununo exchangeable K values ranged from 0.06 to 5.57 $cmol_{(+)}$ kg^{-1} of soil (Weigel, 1986b). Anjeni soil K values range from 0.1 to 13 $cmol_{(+)}$ kg^{-1} of soil (Kejella, 1995). Although the laboratory methods used are identical, sample location, number and profile variability might hinder comparison of results obtained from the studies in the 1980s and with this study, not undermining changes in exchangeable K status over time.

Study on soil K variability (Tillman and Officer, 2000) has found that there are several factors which interact to affect soil K variation. While the current sampling method can show the status of exchangeable K, it is difficult to predict the general pattern of K variation within various LUTs. In previous studies, partial soil K data in LUTs have not shown a uniform pattern (Kejella, 1995; Weigel, 1986ab).

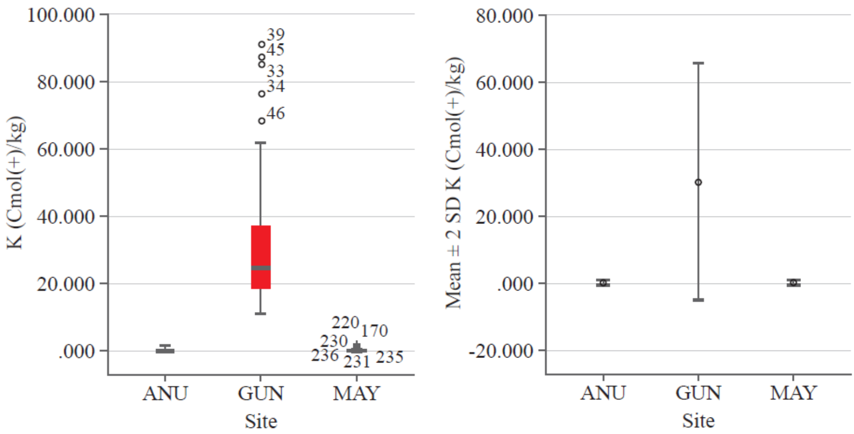


Fig. 6. Box plot (a) and error bar (b) for soil K ($cmol_{(+)}$ kg^{-1}) in three sites.

Recent review on vertical distribution of available K (Saini and Grewal, 2014) did not find any definite pattern in various soils. Similary, Saini and Grewal (2014) result on vertical distrubtuion ofhe soil K did show any pattern as also found in this study (Fig. 7 a-f).

Correlation of exchangeable K with basic soil properties

Correlation (Spearman's rho, r_s) of exchangeable K with other properties was examined for 239 samples.Non-parametric correlations (Spearman's rho, $r_s$two tailed test, at α=0.05 level) was run to determine the relationship between exchangeable K and the soil texture-(clay, sand and silt). Results showed a very weak positive significant correlation with the percentage of clay and sand (r_s=0.04, p=0.02) and avery weak negative correlation withthe percentage of silt (r_s=-0.02, p=0.00). Results agree with Saini and Grewal (2014) in that K had positive correlation with clay, silt and CEC and a negative correlation with sand. But the degree of correlation is very weak.Results also indicate that higher values of K occured due to higher clay contents (Darunsontaya*et al.*, 2010).This study also confirms that exchangeable K is mostly contributed by the finer fractions of the soils.

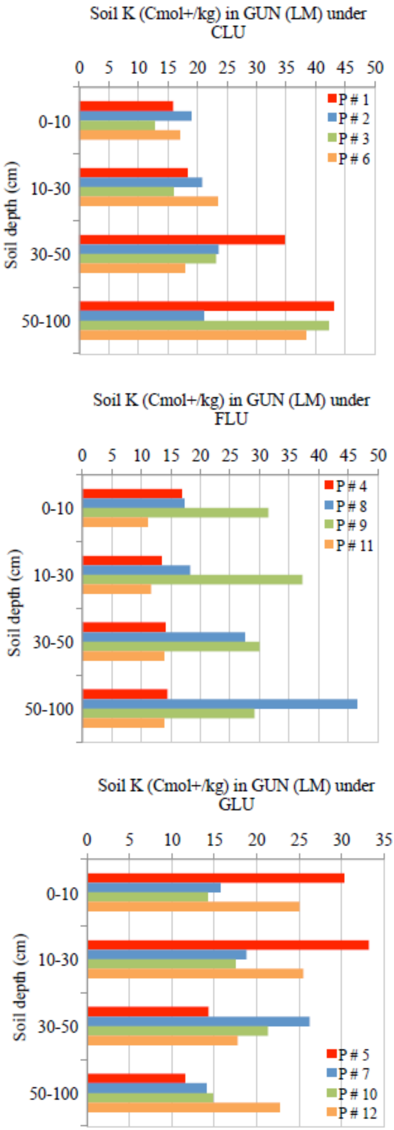


Fig. 7a. Exchangeable K (cmol$_{(+)}$ kg^{-1}) vertical distribution at Gununo under LUTs (less managed watersheds).

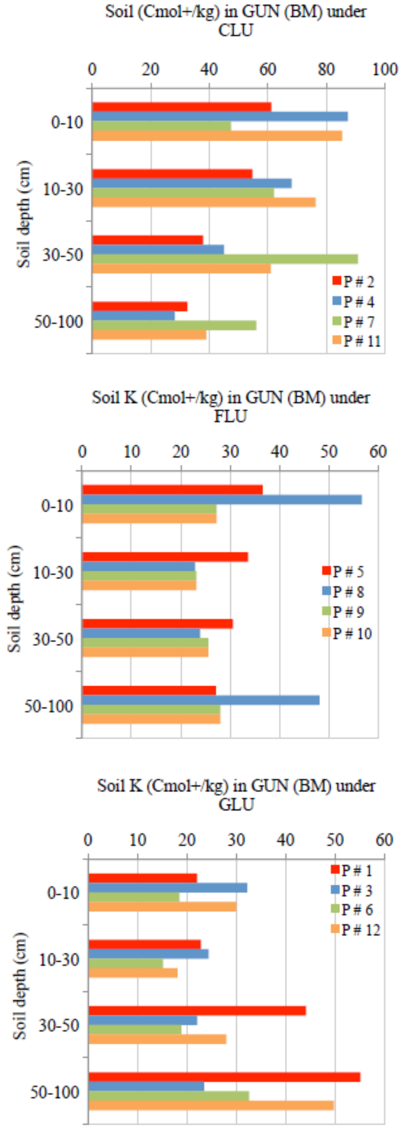


Fig. 7b. Exchangeable K (cmol$_{(+)}$ kg^{-1}) vertical distribution at Gununo under LUTs (better manged watersheds).

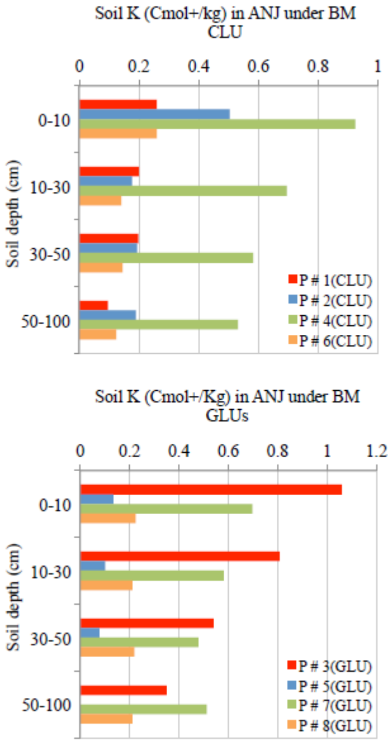


Fig. 7c. Exchangeable K (cmol$_{(+)}$ kg^{-1}) vertical distribution at Anjeni under LUTs (better manged watersheds).

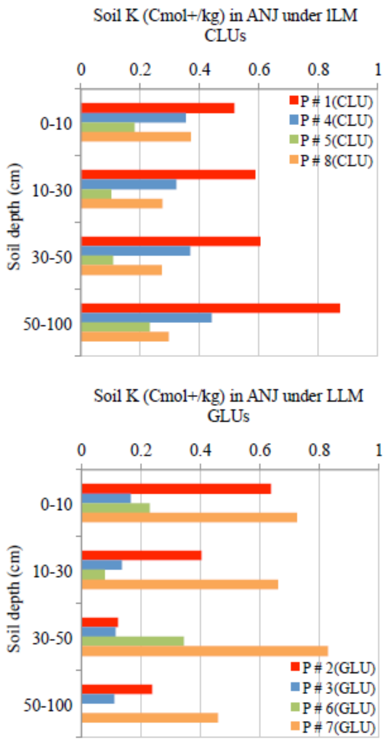


Fig. 7d. Exchangeable K (cmol$_{(+)}$ kg^{-1}) vertical distribution at Anjeni under LUTs (less managed watersheds).

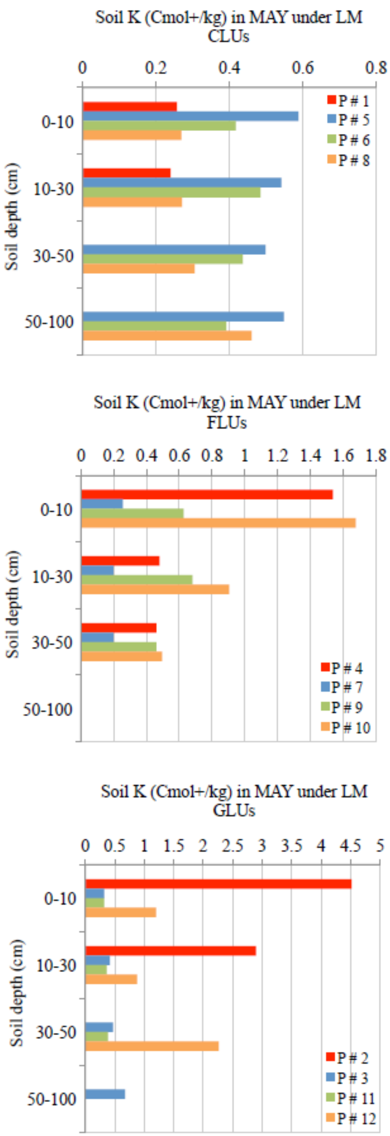


Fig. 7e. Exchangeable K (cmol$_{(+)}$ kg^{-1}) vertical distribution at Maybar under LUTs (less managed watersheds).

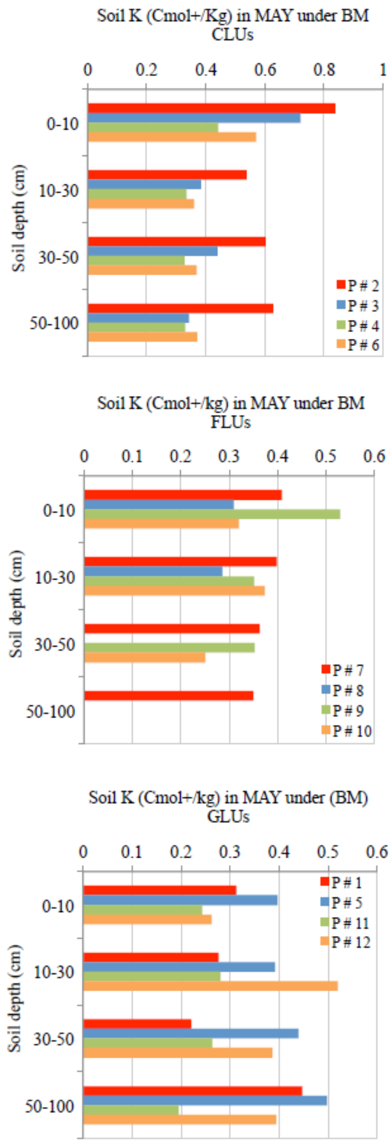


Fig. 7f. Exchangeable K (cmol$_{(+)}$ kg^{-1}) vertical distribution at Maybar under LUTs (better manged watersheds).

Spearman's rho (r_s) two tailed test at α=0.05 level correlation between exchangeable K and soil pH was detrmind. Results showed anegativebut significant correlation with soil pH (measured by water and $CaCl_2$). As soil pH is reduced (becomes acidic), K availability was reduced. Results agree with Saini and Grewal (2014) in that K had negative correlation with pH but the degree of correlation is very low. In acidic soils, the colloidal surfaces are held by H^+ and Al^+ and K+ can be leached, resulting in low soil K levels.

Table 4. Correlation coefficient (r_s) of exchangeableK ($cmol_{(+)}\ kg^{-1}$) with soil properties.

Soil properties	Correlation coefficient (r_s) with K
Soil pH(H_20)	-.305**
Soil pH($CaCl_2$)	-.150*
Av P	.431**
% TN	0.07
% Sand	0.130*
% Clay	0.13*
% Silt	-0.25**
BD	0.44
CEC	0.11
EC	0.26**
Na	-.43**
Ca	-.119

*Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

Conclusions

This study showed the need for K fertilizer application because most of the soils sampled in the three sites had very low levels of exchangeable K. Soil exchangeable K varied considerably in Gununo compared with the other two sites (Anjeni and Maybar). Variability in Gunno suggests the need for specific soil and plant tests before using K supplementation. Soil K variability rank order among the LUTs were: FLU>CLU>GLU.

Non-normal distribution of K data values (n=239) varied from a minimum value of 0.07 to a maximum value of 90.2 $cmol_{(+)}\ kg^{-1}$ with a median value of 0.5. The tillage depth samples (n=128) also had a very low median value (1.8 $cmol_{(+)}$

kg^{-1}) reflecting the need to supplement K for a balanced nutrition. Profile distribution patterns for K were not unform but sub-soil profiles were better than surface, suggesting that the role of plant cycling is small compared to effect of leaching and weathering.

Non-parameteric statistical tests showed that median values of K and its distribution was significantly different ($\alpha = 0.05$, $p < 0.05$) across the three sites and LUTs. However, the Kruskal-Wallis and Chi-square test both reveal that it is not significant for the soil profiles. Correlation of individual cations (Na, Ca, Mg) with K is negative while weak positive correlation was obtained with sand, clay, and CEC.

This study also recommends that additional study be conducted to examine the availability of K in the study areas. Combining this study with K mapping, plant uptake, nutrient interaction, critical levels and yield respond trials would be a useful step to develop accurate K recommendation rates.

Acknowledgement

Financial support for this study was obtained from the U.S. National Science Foundation (NSF) (grant number GEO-0627893) through the International START Secretariat in 2010 as START Grants for GEC Research in Africa. We are grateful to Bosena Bizuneh and Nigussu Bekele (Ethiopian Institute of Agricultural Research staff at Debe Zeit Research Center, Ethiopia) for their assistance during field sampling and laboratory analysis.

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Chapter 9

K Research Needs in Crops in sub-Saharan Africa

John Wendt[1]

Abstract

Potassium (K) is one in a suite of nutrients required for balanced crop nutrition. Formulating crop- and soil-specific fertilizers that incorporate K requires knowledge of soil nutrient deficiencies and specific crop requirements. One of the greatest constraints in many African countries is the availability of very few fertilizer nutrients to smallholder farmers (often only nitrogen (N), phosphorus (P), and K), and even these macronutrients are often not supplied in balance to specific crop demands, resulting in inefficient nutrient use. Other deficiencies that may limit N, P, and K uptake are often not considered, and data on these deficiencies not available. However, with appreciation developing of the importance of secondary nutrients and micronutrients – required for balanced nutrition and necessary for profitable returns on fertilizer investment – a blending industry is emerging to meet these demands. Using examples from Burundi and Rwanda, we show how soil nutrient assessments and specific fertilizer experiments can be used to rapidly develop crop-specific fertilizers that offer a substantial return on investment. The necessity of proper K supply in relation to specific crop demand is highlighted, as are circumstances where potassium sulfate may be preferred to potassium chloride.

Introduction

Fertilizer consumption in sub-Saharan Africa is extremely low, on the order of 13 kg of nitrogen (N), phosphorus pentoxide (P_2O_5) and potassium oxide (K_2O) (Minot and Benson, 2009). High fertilizer costs and poor agronomic efficiency of applied fertilizers (defined as the kg of produce per kg of applied nutrient) render returns on fertilizer investments low for many African farmers. Poor agronomic efficiency is due to multiple factors, including inconsistent rainfall, poor

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agronomic practices, and lack of either labor or mechanization for timely land preparation and weeding.

But what if the fertilizer itself is contributing to poor fertilizer use efficiency, and in particular, poor potassium (K) use efficiency? Optimal plant growth and yields require that a suite of nutrients be made available in balanced proportions, according to specific crop requirements. Fertilizers must supply nutrients not adequately available in the soil. The long-held assumption is that N, phosphorus (P), and K, being required in the largest quantities, will be the most deficient, and that other nutrients are adequately supplied by the soil. In sub-Saharan Africa, N, P, and K are the nutrients most widely supplied. The secondary nutrients calcium (Ca), magnesium (Mg), and sulfur (S), or the micronutrients zinc (Zn), copper (Cu), manganese (Mn), iron (Fe), boron (B), or molybdenum (Mo) are for the most part not available to smallholder farmers, and are often difficult to find outside of the commercial farming sector.

The necessity of balanced crop nutrition

Table 1 shows the amounts of nutrients extracted by various crops at different yield levels. The data were extracted from various internet sources, and may vary considerably based on soil and climatic conditions. Little data were available for Mo, whose deficiency is generally corrected with an application of 70-80 g ha^{-1}.

Yet, secondary micronutrient (SMN) deficiencies can have major impacts disproportionate to the small quantities required. Liebig's law of the minimum states that states that growth is controlled not by the total amount of resource available, but by the scarcest resource, or limiting factor. If severely deficient, SMNs can limit response to N, P, and K. Research has for decades shown instances of SMN deficiencies in various locations in sub-Saharan Africa (Schutte, 1954; Agboola *et al.*, 1970; Osiname *et al.*, 1973; Kang and Osiname, 1976; Sillanpää, 1982; Kang and Osiname, 1985; Ojeniyil and Kayode, 1993; Wendt and Rijpma, 1997; Weil and Mughogho, 2000; Abunyewa and Mercer-Quarshie, 2004; Lisuma *et al.*, 2006; Manzeke, 2013). Much of the SMN research has been done when only one or two nutrients are deficient. When multiple SMNs are deficient, full response to N, P, and K will not be realized until all are applied. Soil acidity constraints must also be addressed through liming.

In this manuscript, we examine data collected on SMN response since 2012 in Burundi, Ethiopia, Mozambique, Rwanda, and Uganda. The data show that SMNs are severely limiting NPK response. In some cases, we are able to disaggregate the K response, and show that when multiple SMN deficiencies are addressed, K use efficiency increases dramatically.

Table 1. Nutrients removed at various yield targets in harvested products and crop residue.

Crop	Maize	Rice	Wheat	Beans	Potato	Cassava	Soybeans
Yield target	5 Mt ha^{-1}	7 Mt ha^{-1}	5 Mt ha^{-1}	3 Mt ha^{-1}	30 Mt ha^{-1}	30 Mt ha^{-1}	3 Mt ha^{-1}
	Total nutrient removal (harvested product + crop residue) kg ha^{-1}						
Nitrogen (N)	100	150	155	144	129	103	88
Phosphorus (P)	20	20	23	41	18	15	20
Potassium (K)	100	180	103	120	144	77	44
Calcium (Ca)	13	30	8	94	5	57	19
Magnesium (Mg)	21	30	23	22	9	22	10
Sulfur (S)	13	7	20	10	13	12	7
Zinc (Zn)	0.230	0.280	0.431	0.150	0.105	0.452	0.127
Boron (B)	0.240	0.210	0.124	0.150	0.045	0.159	0.142
Copper (Cu)	0.070	0.200	0.073	0.020	0.060	0.050	0.034
Manganese (Mn)	0.733	4.725	0.566	0.234	0.672	0.720	0.202
Iron (Fe)	0.357	1.050	0.923	0.109	1.340	0.830	0.607

Note: P and K are expressed as kg of element, not as P_2O_5 and K_2O. Actual quantities extracted may vary considerably.

Figure 1 shows unpublished data from various countries on various crops. In the control plots, no fertilizers have been added. Either NP or NPK were applied in the treatments labeled NP(K). The NP(K)+SMN treatment represents the same NP(K) application, with an added suite of nutrients including S, Zn, B, Cu and/or dolomitic limestone, which in addition to partially neutralizing soil acidity, adds Ca and Mg. In most cases, the SMN addition dramatically improves overall fertilizer response, in some cases more than doubling the response realized by NP(K) alone.

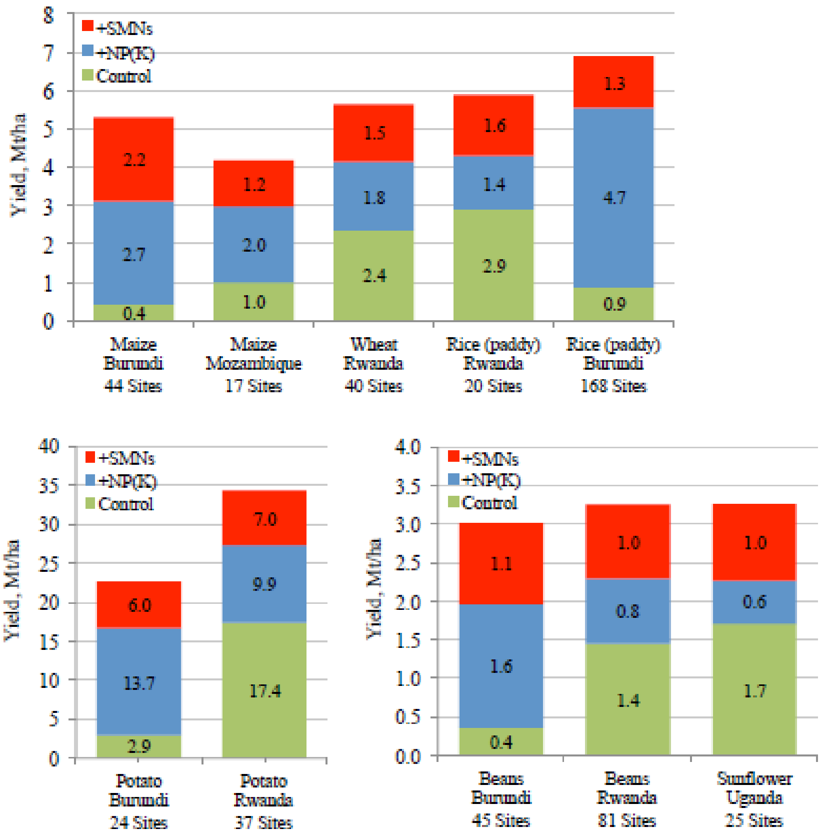

Fig. 1. NP(K) and SMN response realized in various crops in several countries in East and Southern Africa on smallholder farms.

How representative are these responses of sub-Saharan African smallholder farms in general? These experiments were carried out at multiple dispersed sites on various commodities, and we believe broadly represent responses obtainable in these countries. Similar results have been obtained in Ethiopia.

Soil availability of SMNs in sub-Saharan Africa

Soil maps give an indication of the extent of SMN deficiencies and acidity constraints. Ethiopia has launched a wide-scale soil analysis program, which has found multiple SMN deficiencies in the majority of the country. Similar maps of Burundi and Rwanda are shown in Figs. 2ab. The International Fertilizer Development Center (IFDC) has also mapped considerable regions of Uganda and lesser regions of Mozambique and Zambia. In all cases, multiple soil SMN deficiencies are the norm rather than the exception.

Why have extensive SMN deficiencies gone unrecognized? This may be due to the fact that many laboratories in Africa do not have capabilities to analyze SMNs, and the general lack of availability of SMN fertilizers for experimentation. While researchers have long recognized SMN deficiencies, almost all research has been done on individual nutrients; thus, when multiple SMN deficiencies exist (which appears to be the norm), response to individual SMNs is suppressed by the deficiencies of other SMNs. Omission trials (discussed below) allow one to address multiple SMN deficiencies simultaneously.

In addition, African soils are distinct from those in Europe, Asia, and North America, where NPK needs predominate. Africa has not benefited from acid rain, a by-product of industrialization that deposits large amounts of sulfate. In addition, Africa has a relatively stable geology and has not experienced many recent (in geological terms) soil-formative events such as uplifting, glaciation, and volcanic activity; thus, soils in general tend to be older and more weathered (Kang and Osiname, 1985).

Diagnosing specific nutrient response

Using an omission trial design, it is possible isolate the effects of individual nutrients including K, and to calculate the agronomic efficiency of K. In an omission trial, one treatment includes all nutrients, and is described as the “All” treatment. Each subsequent treatment omits only one nutrient. The yield loss due to the omission of a nutrient, in the presence of all other essential nutrients, gives one the opportunity to realize the maximum response to each nutrient. Because all other nutrients are in sufficient supply, the efficiency of any nutrient omitted is not affected by the lack of other nutrients.

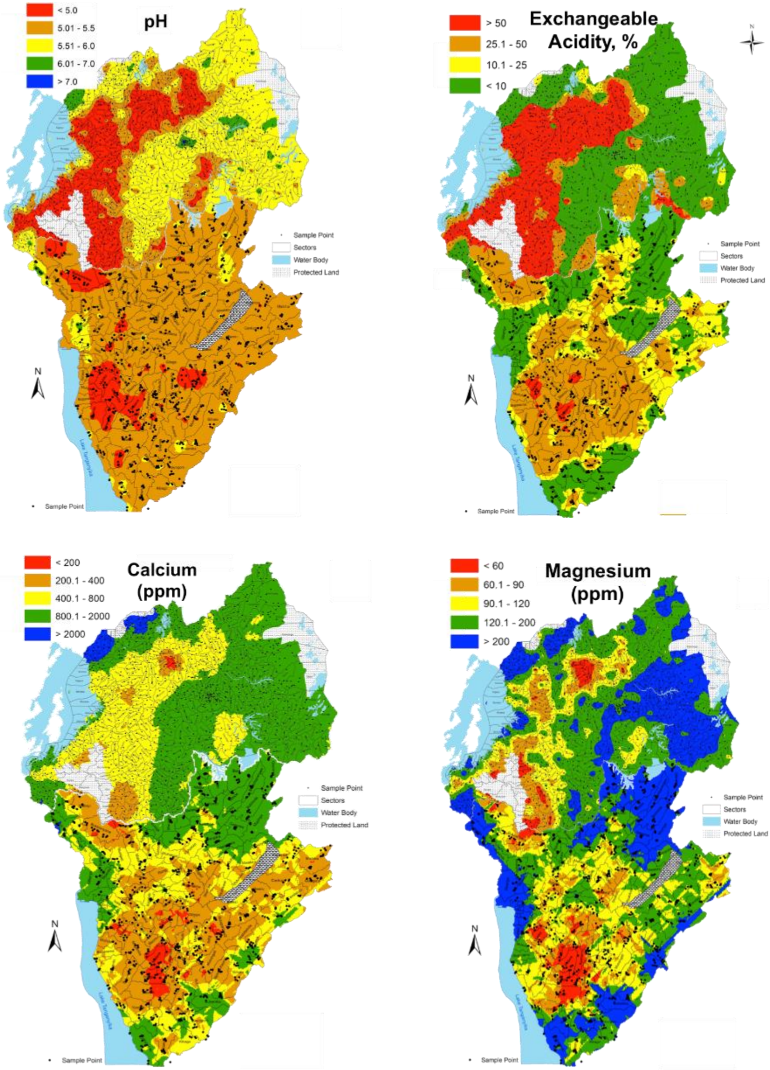

Fig. 2a. Soil acidity and SMN constraints in Burundi and Rwanda. Crop sensitivities to deficiencies vary. Green and blue areas are considered sufficient for many crops. Source: http://www.ifdc.org/documents/burundi-soil-maps/ and http://www.ifdc.org/documents/rwanda-soil-maps/.

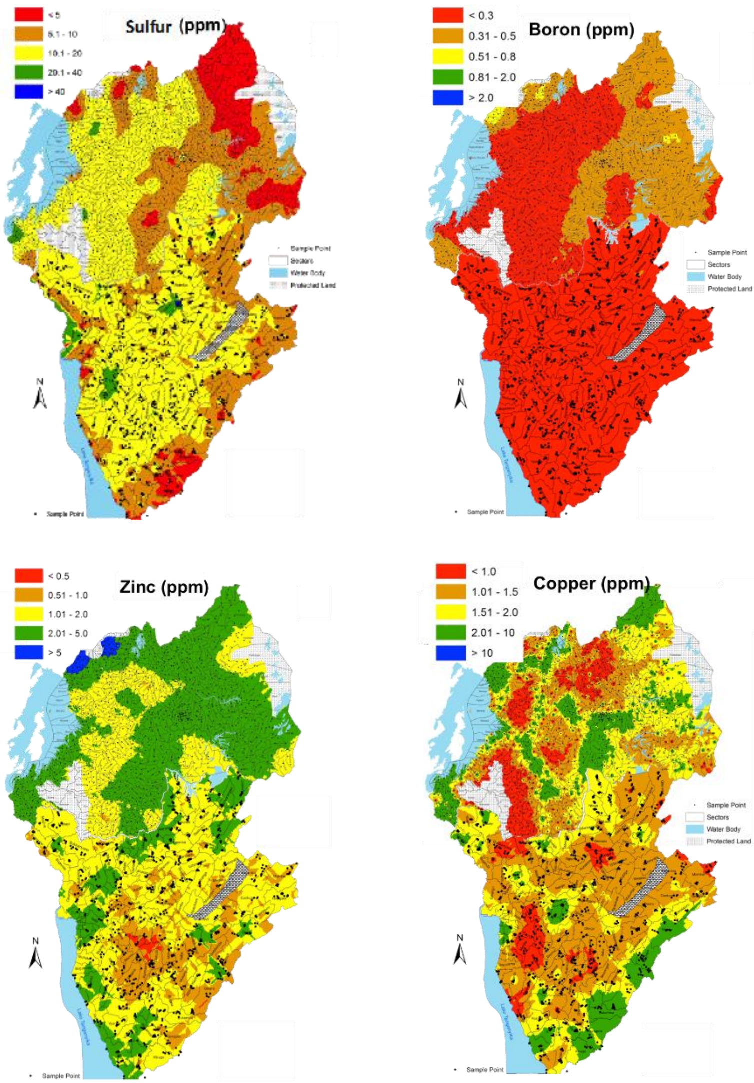

Fig. 2b. Soil acidity and SMN constraints in Burundi and Rwanda. Crop sensitivities to deficiencies vary. Green and blue areas are considered sufficient for many crops. Source: http://www.ifdc.org/documents/burundi-soil-maps/ and http://www.ifdc.org/documents/rwanda-soil-maps/.

Table 2 summarizes omission trial results in Burundi and Rwanda where K was included as an omitted nutrient. The agronomic use efficiency of K is very high in all trials, with the exception of maize, which will be discussed later. K use efficiency was particularly high for rice in Rwanda. The 66 kg of paddy rice per unit K_2O applied would be roughly equivalent to 43 kg of grain after cleaning. This high efficiency is due to the fact that Rwandan rice has been cultivated for up to 20 cropping cycles over the past decade using a K application rate of 34 kg K_2O ha^{-1}. This has resulted in severe K depletion because the rice stover is commonly removed and fed to livestock. A 4 Mt ha^{-1} rice harvest, the Rwandan average, will remove some 125 kg of K_2O ha^{-1} so severe K deficiency has been induced, resulting in a very large response to applied K. Generally speaking, an agronomic use efficiency for K of 20 would be very profitable for cereals, indicating that additional K could be applied to all cereals.

Also noteworthy is the yield reductions (compared to the "All" treatment) of S, Zn, B, and Cu. For most crops, omission of these elements resulted in significant yield decreases. The combined effect of omitting all of these nutrients together is shown in Fig. 1. This can have a dramatic effect on K use efficiency. For example, omission of any of S, Zn, B, and Cu in Rwandan rice reduces the maximum response by over 1 Mt ha^{-1}, even in the presence of K, and the combined effect of omitting all four reduces yields by an average of 1.6 Mt ha^{-1} (Table 1), which will dramatically reduce response to K. This shows the importance of addressing multiple nutrient deficiencies together, and the importance of SMNs in realizing efficient K use.

In spite of the presence of multiple nutrients and dolomitic lime in the maize treatment, K response was below that of other crops in Burundi. The critical soil K level for maize is generally considered to be 80 ppm, whereas the average K concentration of the 16 maize sites was 56 ppm, with only two of the sites above the critical value. In maize, fertilizers are placed near the maize planting station, whereas in other crops (except for beans), K is either banded (potatoes) or broadcast (rice and wheat). The local placement of potassium chloride (KCl) may have the effect of inducing aluminium (Al) toxicity in these very acid soils, in which pH averaged 4.7. The positive K^+ ion may be displacing Al^{3+} into the soil solution, inducing localized Al toxicity. This effect was not observed in beans, which could be due to the fact that potassium sulfate (K_2SO_4) was used as the K source in beans in all treatments except the "All-S" treatment. In the "All-S" treatment, yields were severely reduced. The sulfate may have the effect of reducing Al toxicity, as sulfate reacts with Al to form the non-toxic cation $Al(SO_4)^+$ (Kinraide and Parker, 1987). The use of potassium sulfate may be more efficient on acid soils under some circumstances, and merits research attention.

Table 2. Omission trial results where K was included as an omitted nutrient. This allows K use efficiency to be calculated

Country	Crop	Season	No. of sites	Control	All	All K	All S	All Zn	All B	All Cu	Agroninomic efficiency K	Nutrients in "All" application
					---------------*Yield, Mt ha*$^{-1}$---------------						*kg harvest kg*$^{-1}$ *K*$_2$*O*	--------*kg ha*$^{-1}$--------
Rwanda	Wheat	2014a	40	2.35	5.6	4.8	5.0	5.2	4.7	4.8	29	64N 46P_2O_5 30K_2O 10S 3Zn 1B+0.25Cu (foliar) + 0.6Mg (foliar)
Rwanda	Rice paddy	2013b	20	2.22	6.0	4.1	4.9	4.9	4.8	4.8	66	81N 34P_2O_5 30K_2O 12S 3Zn 2B 0.25Cu (foliar)
Rwanda	Potato	2014a	37	17.4	34.3	31.3	30.2	30.9	30.8	31.1	122*	75N 75P_2O_5 50K_2O 10S 2Zn 1B+0.25Cu (foliar) + 0.6Mg (foliar)
Burundi	Maize	2014a	16	0.43	5.2	4.9	5.0	4.2	3.7	3.7	12	71N 46P_2O_5 30K_2O 13S 3Zn 1B+0.25Cu (foliar) + 750 kg dolomite

Table 2. Omission trial results where K was included as an omitted nutrient. This allows K use efficiency to be calculated

Country	Crop	Season	No. of sites	Control	All	All K	All S	All Zn	All B	All Cu	Agroninomic efficiency K	Nutrients in "All" application
					---------------*Yield, Mt ha*$^{-1}$---------------						*kg harvest kg*$^{-1}$ *K_2O*	--------*kg ha*$^{-1}$--------
Burundi	Beans	2014a	16	0.36	3.0	2.2	2.1	2.9	2.9	N/A	26	41N 46P_2O_5 30K_2O 13S 3Zn 1B + 750 kg dolomite
Burundi	Wheat	2014b	10	0.52	3.3	2.5	2.9	2.6	2.7	2.9	25	58N 40P_2O_5 30K_2O 10S 3Zn 1B 0.25Cu (foliar)
Burundi	Rice paddy	2014b	45	0.88	6.8	6.0	6.6	6.1	6.5	6.3	27	71N 30P_2O_5 30K_2O 10S 3Zn 2B 0.25Cu (foliar)

Note: *In the Rwanda potato trial, K was not eliminated in the "All-K" treatment, but reduced from 50 kg ha^{-1} to 25 kg ha^{-1}. Therefore, the agronomic efficiency is based on 25 kg K_2O. Burundian wheat was severely affected by drought.

Potassium demands of various crops, and implications for fertilizer supply

As is clear from Table 1, crops differ in their K requirements. In order to meet these requirements, smallholder farmers currently rely on a very few compound (NPK) fertilizers for K supply (often one compound per country), and rarely have access to straight K fertilizers. The result is that the likelihood of supplying K at an optimal rate is low; thus, some crops may be over-supplied, while others under-supplied. The example of Rwandan rice has already been mentioned. The only K fertilizer generally available to smallholder farmers is 17:17:17. At an application rate of 200-300 kg ha^{-1}, this fertilizer can meet P requirements for rice and potato, but this rate results in severely sub-optimal K application. If farmers were to increase the rate, they would be effectively applying P unnecessarily, which is wasteful and gives poor returns to the fertilizer investment, thus discouraging use.

Obtaining high nutrient use efficiency is key to getting farmers to invest in fertilizers. Not only should SMNs be included as required, but K application must be balanced to crop demands. Efficient returns on fertilizer investments demands a diversification of fertilizer products, which can be met by fertilizer compounds and blends. Fortunately, a blending industry is becoming increasingly established in Africa, but is producing primarily for commercial clients. The research community must link to the fertilizer industry to supply a diversity of efficient fertilizer products to smallholders.

Conclusions

Once N and P are supplied, K is often not the most limiting nutrient. In many cases, SMN deficienciesand soil acidity constraints must be addressed to realize optimal K response. Potassium fertilizers need to contain adequate quantities of K to meet crop-specific demands. This will require research on K rates in the presence of adequate amounts of SMNs, both to determine optimal K response and crop-specific soil critical K values, as these differ from crop to crop. The research community must link with the emerging blending industry to develop and evaluate crop-specific fertilizer blends.

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Chapter 10

Improving Smallholder Soil Health and Agricultural Productivity in Africa: AGR's Approach and Outcomes

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Abstract

Improving soil health is essential to reversing the low productivity that has plagued Africa's smallholder agriculture over the past 40 years. During this period, the yield of maize, a staple food crop in sub-Saharan Africa (hereafter referred to as Africa), stagnated at about 1.0 t ha^{-1}. To address the situation, there is consensus among the research and development community that the best approach is that of integrated soil fertility management (ISFM) which integrates organic and inorganic sources of nutrients to replenish soil nutrients. To promote the broad uptake of ISFM technologies, AGRA has supported mass awareness through large and small on-farm demonstrations in 13 countries since 2008. Besides maize, the demonstrations included other staple African food crops: sorghum, millet, cassava, rice, teff and several grain legumes (beans, soybeans, cowpeas, pigeon pea, chickpea, and groundnuts). The demonstrations were designed through close participation with the communities: farmers, extension staff, input suppliers (seeds and fertilizers), and agro-dealers, among others. Access to input and output markets were enhanced through a value chain approach. This enhanced uptake. Generally, the use of ISFM technologies increased increase yields of grain legumes by over 100% and that of cereals by over 200% when compared to the control plots where ISFM technologies were not used. This is against baseline yields of 1.0 to 2.0 t ha^{-1} for cereals and under 0.5 t ha^{-1} for grain legumes. In areas with less rainfall, where sorghum and millet are the predominant crops, fertilizer microdosing is the most promising ISFM technology. This entails applying about a third of the recommended fertilizer rate in the planting holes as opposed to broadcasting it. For maize, fertilizer use is generally attractive when grain yields exceed 2.0 t ha^{-1} in many regions. However, taking these impacts to scale and sustaining them requires improving access to

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affordable credit to purchase fertilizers that are expensive in Africa, access to markets, and extension and advisory services to smallholder farmers.

Introduction

Several studies show that African soils are the poorest in the world (NEPAD, 2009; Sanchez, 2015). Declining soil fertility in most African countries has been caused by a number of factors, the main one being soil nutrient mining through continuous cropping with little or no use of fertilizers to replenish lost nutrients (Duflo *et al.*, 2011; Duflo *et al.*, 2008; Bvenura and Afolayan, 2013; Kiage, 2013; Sanchez, 2015). The deteriorating soil fertility has seen per capita food production in sub-Saharan Africa, decline since the 1960s (Ahlers *et al.*, 2013; McIntire, 2014). At the same time, Africa's population has grown to about one billion, placing increased pressure on food security (Sanchez, 2015).

While organic inputs improve soil fertility by increasing soil organic matter, they have limited ability to replenish certain essential macronutrients such as soil phosphorus (P), without which plants are unable to complete their vegetative life cycle (Mukuralinda *et al.*, 2010; Nash *et al.*, 2014). The use of inorganic fertilizers is a proven way to reverse the trend of declining soil fertility and food production in many parts of the world (Duflo *et al.*, 2008, 2011; Beaman *et al.*, 2013; Kiage, 2013; Sanchez, 2015). Despite the enormous agronomic and financial benefits of using fertilizers to grow crops, their rate of usage in Africa has remained low for many decades. This is estimated 10 kg of nutrients ha^{-1} compared to 110 kg of nutrients ha^{-1} in Latin America and over 130 kg ha^{-1} in Asia (Ahlers *et al.*, 2013; Beaman *et al.*, 2013; Islam *et al.*, 2013; Jayne *et al.*, 2013).

The need to improve soil health is, therefore, of paramount importance. There is, indeed, consensus among the scientific and development community that soil fertility and land degradation that is associated is the fundamental cause of low and declining productivity, especially under small smallholder agriculture in Africa (Mukuralinda *et al.*, 2010; Kiage, 2013; Nash *et al.*, 2014). This means that, unless this problem is addressed, not much can be gained from other efforts such as the use of improved seeds and good agronomic practices, including water management. To overcome declining soil health in Africa, researchers and development agencies have been advocating for the use of medium application rates of fertilizers (about 50 kg ha^{-1}) (NEPAD, 2009) that could be combined with organic inputs such as compost manure, green cover crops, and cattle manure for sustainable management of the soil base (Mukuralinda *et al.*, 2010).

Although there are positive trends of improvement recently in the productivity of smallholder agriculture, much more needs to be done to accelerate and sustain the gains made (Sanchez, 2015). This requires enhancing access to fertilizers within the framework of ISFM practices, and promoting associated good agronomic practices that, by necessity, involves the use of improved seeds (Vanlauwe *et al.*, 2011). ISFM, which commonly refers to the addition of inorganic fertilizers in combination with organic inputs, ensures a healthy soil capable of sustaining high crop yields, subsequently leading to improved food security and income generation for farmers (Mukuralinda *et al.*, 2010). Unfortunately, the high cost of fertilizers and lack of awareness among African smallholder farmers on the benefits of using inorganic fertilizers are some of the factors responsible for low usage of fertilizers in Africa (Duflo *et al.*, 2008, 2011; Sanchez, 2015).

It is against this background that AGRA was set up in 2006 as a pan-African center to catalyze a transformation in Africa's smallholder agriculture. The focus is on raising the productivity and incomes of some 20 million smallholders by 2020. In this paper, we report on a comprehensive approach used to scale up and improve soil health, and highlight some key outcomes and lessons learnt from some of 13 initial focal countries of the program.

Our approach

AGRA's transformative approach centers on using value chains, starting with the staple food crops of Africa (AGRA, 2011; 2012), which include maize, sorghum, millet, cassava, rice, teff (in Ethiopia). They also include several grain legumes (beans, soybeans, cowpeas, pigeon pea, chickpea, and groundnuts. As an alliance, AGRA forged a strong partnership with the public and private sector to bring the key interventions needed to raise crop yields and incomes to farmers and associated agribusinesses. Increasing yields sustainably requires improving access to improved seeds, affordable finance, soil health interventions, and remunerative markets (AGRA, 2011; 2012).

On soil health, which is the focus of this paper, the key thrust was scaling up the use of ISFM practices that involve the use of mineral fertilizers with organic sources of nutrients, including farmyard and compost manure. It also involved the use of grain legumes that, if well managed, can fix considerable amounts of nitrogen biologically from the atmosphere (Mutoko *et al.*, 2014). This requires the application of small amounts of P in general, and the use of specific rhizobium inoculum on some grain legumes such as soybeans that are not native to Africa. This also applies to other legumes that are native to African but do not fix much nitrogen through the indigenous rhizobia bacteria (Sheahan *et al.*, 2013; Nash *et al.*, 2014).

To create broad awareness and knowledge of the 'best-fit' ISFM options, thousands of demonstrations (both large and small) were established on farms, roadsides and on public institutions. The demonstrations were designed with the close participation of the communities: farmers, extension staff, input suppliers (seeds and fertilizers), and agrodealers, among others.

Typically, the demonstrations used three treatments involving maize: a) farmer's practice control with no use of fertilizers or farmyard manure; b) fertilizer rate recommended by local agricultural research institutes using nitrogen as the basis given its widespread limitation in most soils in Africa; and c) half the recommended rate. The logic for the last treatment was this could achieve equal or close to the full rates that are often too high and costly for most smallholder farmers to use.

Nitrogen (N) rates applied to the demonstration plots at the ‘full’ recommended rate for maize for the specific agro-ecology ranged from 60 to 125 N kg ha^{-1}. Phosphorus and potassium (K) were applied at sufficient levels to overcome their limitations in all plots.

Different yields are observed under different agro-ecological zones that vary from site to site. This is shown in Table 1 that provides key biophysical and soil characteristics of some of the locations where the large demonstrations were conducted.

Creating awareness is essential but not sufficient to bring about large scale uptake of ISFM technologies. For this to happen, the program undertook a complementary initiative dubbed ‘going beyond demonstrations’ that aimed to address access to financing for farmers to buy inputs, especially fertilizers that are expensive in Africa. The ‘going beyond demonstrations’ initiative also involved bringing on board produce buyers, including local small and medium enterprises that often act as off takers for the large buyers. It also required strengthening farmers’ organizations so that they can benefit from economies of scale by reducing high transaction costs associated with separate individual actions.

Table 1. Soils and agro-ecological characteristics of different demo sites

Country	District/site	Dominant soils	pH	Average rainfall	Organic carbon (%)
Kenya	Kakamega	Haplic Acrisols; Haplic Lixisols	5.1	1,320	1.9
	Busia	Acrisols	5.1	1,110	1.3
Rwanda	Gatsibo	Acrisols	4.9	545	3.2
	Kayonza	Acrisols	5.4	613	3.9
	Kirehe	Acrisols	5.6	656	3.1
Tanzania	Arumeru	Eutric Leptosols; Andosols	7.3	264	2.4
	Hai	Nitisols	7.1	318	2.5
	Moshi	Nitisols	7.3	260	1.7
Uganda	Busia	Plinthic Lixisols; Haplic Ferralsols	5.6	951	2.2
	Namutumba	Plinthosols	5.7	639	2.0
	Tororo	Haplic Ferralsols; Plinthosols	5.6	722	1.6

Note: Intra and inter country variation in terms of soils and agro-ecological characteristics is huge. These variations would, to a large extent, explain the variations in fertilizer use rates u across countries and locations within them.

Key outcomes

Maize yields – demonstrations and farmers' own field

Maize yield under the demonstrations was more than doubled in most cases, compared to farmers' practice, even with half the application recommended fertilizer rates (Table 2). Nitrogen use efficiency (NUE) associated with these yields ranged between 9 and 38 kg of grain per kg of N applied. These rates are generally comparable to those in developed countries. The result indicates crop yields under rain-fed Africa's conditions with generally poor soils can be productive.

Table 2. Grain yield under different fertilizer rates across countries (*Source:* AGRA, unpublished data).

Region	Treatment	Grain yield
		------------$t\ ha^{-1}$------------
Average	Control	1.6
	Half	2.8
	Full	4.0
Mozambique	Control	1.8
	Half*	3.1
	Full	3.7
Tanzania	Control	2.2
	Half	2.6
	Full	5.0
Malawi	Control	1.3
	Half	3.3
	Full	4.2
Zambia	Control	1.6
	Half*	2.5
	Full	3.5

Note: *In some cases, half rate fertilizer application is as good as full rate. Therefore financial benefits to farmers should be taken into account before recommending certain fertilizers rates.

Under a range of conditions and smallholder management practices, NUE varied from region to region (Table 3). In some cases, NUE declines as the application rate increases beyond a certain application rate. In different agro-ecological zones, NUE as low as 12.5 is observed and as high as 45.6 in some cases.

These agronomic use efficiencies are good because the addition of a small quantity of N led to huge increases in maize grain yield as the soils had been highly deficient in N. Under farmer's conditions, yield levels were several folds lower, even when they applied the recommended fertilizer rates. This is demonstrated by the maize yields of farmers in several districts in northern Ghana (Fig. 1).

Table 3. NUE of maize in different countries and locations within them

Country	Fertilizer N rate	Maize grain increase
	-------*kg ha*$^{-1}$------	-------*per kg N applied*-------
Mozambique	40	31.6 (27.3-36.0)
	80	26.3 (23.9-28.7)
Tanzania	30	36.8 (34.2-39.5)
	60	42.9 (40.8-45.0)
Malawi	40	45.6 (40.8-50.5)
	80	36.3 (34.5-38.1)
Zambia	46	12.5 (10.0-14.9)
	92	25.0 (22.1-27.9)
Rwanda	33	20.9 (18.6-23.1)
	66	29.2 (25.9-32.5)
Kenya	30	10.2 (8.1-12.3)
	60	16.9 (14.5-19.4)
Uganda	40	21.5 (18.2-24.7)
	80	38.8 (33.3-44.3)

Note: *Figures in parentheses are 95% confidence intervals.

Some of the factors responsible for this are that farmers spread the recommended fertilizer rates over larger areas than advised by the research and extension staff, their plant populations are often not adequate, and their weeding and pest and disease management are sub-optimal. Unfortunately, the national agricultural extension and advisory services, as well as the national agricultural research and training programs, are often inadequate and poorly resourced to train farmers. The number of soil scientists and agronomists are also very few in nearly all African countries to conduct research relevant to farmers conditions. This is particularly important for ISFM technologies that are knowledge intensive and that require adapting solutions to the specific socio-economic conditions of farmers in different agro-ecological zones.

The need to fine tune fertilizer rates and ISFM technologies is essential. This is demonstrated by the results from various locations (Fig. 2) that show maize yield

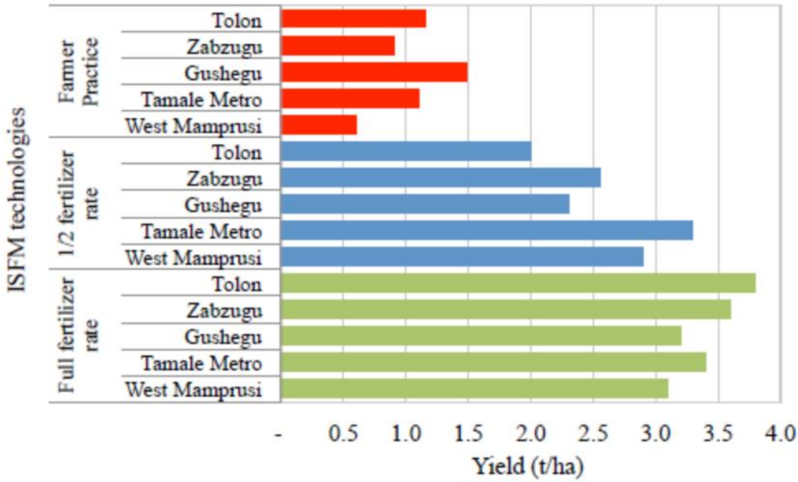

Fig. 1. Maize yield under farmer management conditions in Ghana. *Source:* AGRA, unpublished data.

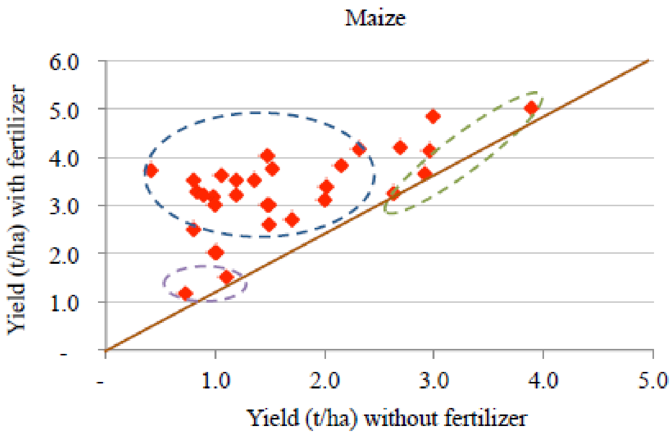

Fig. 2. Responsiveness of maize yields with and without fertilizer across 30 locations in six agro-ecological zones in Africa. *Source:* AGRA, unpublished data.

can be as high as 3 t ha^{-1} in some fertile soils, even without fertilizer. Yet with fertilizer in some soils, yields may be as low as 1 t ha^{-1}. Getting higher yields in the latter is constrained by various factore, including: high soil acidity or alkalinity; limitations of nutrients (both macro and micronutrients); low soil organic matter; abiotic factors such as moisture stress; among others.

The yields of grain legumes can also be increased considerably through the application of fertilizers. For instance, with small application of P nutrients and rhizobium inoculum, legume yields increased significantly across several countries and locations within them (Fig. 3).

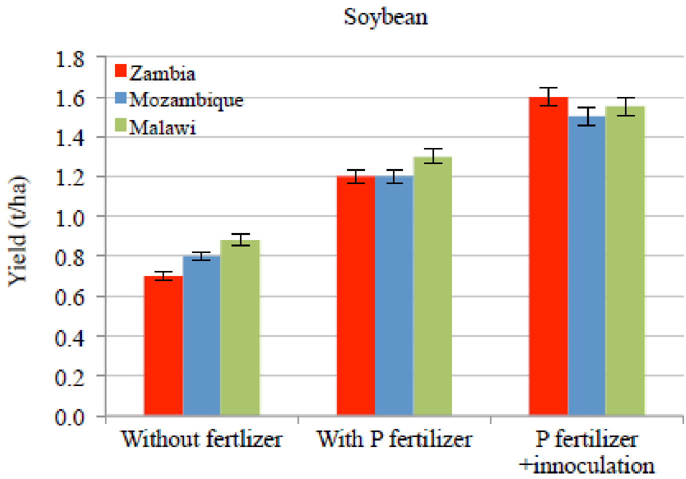

Fig. 3. Soybean yield with P fertilization and rhizobium inoculation across three countries. *Source:* AGRA, unpublished data.

The benefits of fertilizer use can also be extended to farmers in more marginal rainfall areas. In the drier sorghum and millet belts of three Sahelian countries (Burkina Faso, Mali, and Niger), the demonstrations involved the use of fertilizer microdosing. This involves the application of small amounts of fertilizer (which could be split between planting time and 4-5 weeks later) - about one-third the recommended broadcast rate - into planting holes (Camara *et al.*, 2013). Where possible, farmyard manure should be applied along with the fertilizer in order to increase its use efficiency. Microdosing increased sorghum yields by 2-3 times compared to the control fields (Fig. 4). Across regions and seasons, microdosing gave consistently higher yields.

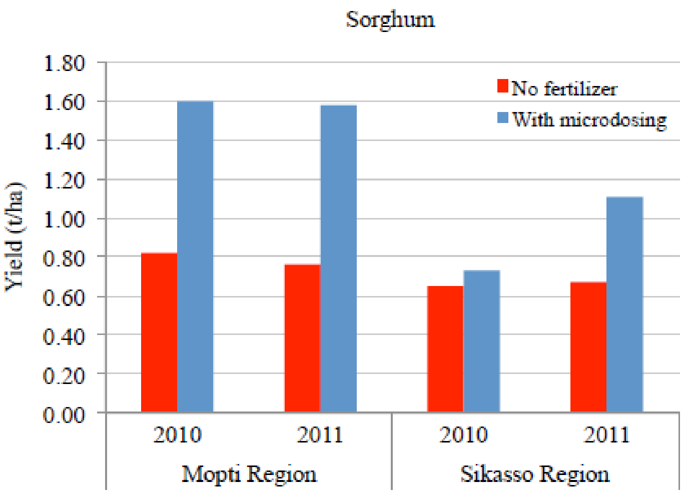

Fig. 4. Sorghum yields with and without fertilizer microdosing in two regions of Mali. *Source:* AGRA, unpublished data.

Financial benefits

Economic analysis of the yield from the demonstration plots indicates that it is financially attractive to use fertilizers along with improved seeds. Microdosing proved to be an equally profitable technology. For instance in Mali, sorghum farmers practising microdosing recorded almost five times as much profit compared with farmers applying no fertilizer (Table 4).

Table 4. Economic returns on sorghum with fertilizer microdosing technology in Mali.

	Labor	Inputs	Total costs	Crop income	Net income	Marginal rate of return*
No fertilizer	180.9	3.5	184.4	216.5	32.1	-
With fertilizer microdosing	208.5	32.4	240.9	392.7	151.8	2.1

Note: *Marginal net benefit divided by marginal cost (net benefits between two treatments divided by change in costs). Microdosing fertilizer was applied at 6.1 kg N ha^{-1} & 15.6 P ha^{-1}. Economic returns are in US$.

Going to scale

The ‘going beyond initiative’ demonstrated that yields can be raised considerably when farmers receive production inputs along with advice on good agronomic practices. This is evident from a project in Tanzania that targeted 20,000 farmers in two districts (Mbeya and Mbozi) in the southern highlands of Tanzania. Maize yields increased three-fold compared to the baseline year, as well as when compared to farmers in the same region that did not receive inputs (Fig. 5). In both districts, farmers were facilitated to acquire credit to buy improved seeds and fertilizers for the season. This may explain the higher yields recorded in the two districts. However, only 8% of the target farmers managed to secure credit in time.

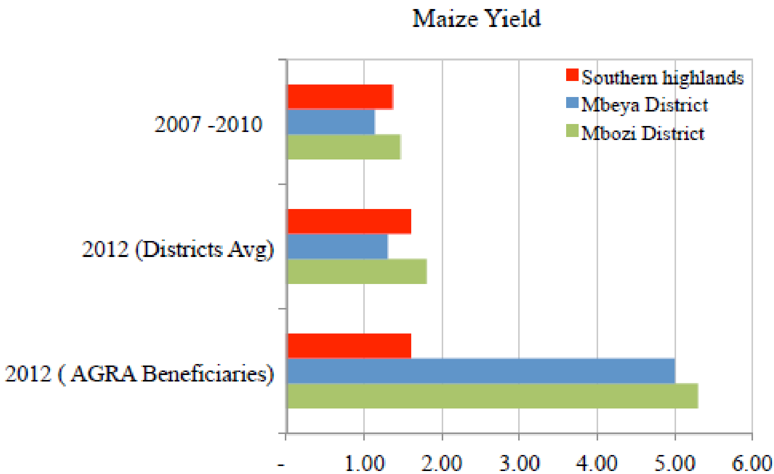

Fig. 5. On farm maize yields in the southern highlands of Tanzania. *Source:* AGRA, unpublished data.

Lessons learnt

Five key lessons stand out from our efforts to improve soil health under smallholder farmers at scale:

- Demonstrations are essential to create awareness but are not sufficient to bring about large scale uptake of ISFM that, by necessity, involve the use of fertilizers that are expensive in Africa. This requires taking a comprehensive approach that address the systemic challenges associated with lack of affordable credit to buy inputs. The cost of borrowing credit from financial institutions in Africa is high, well over 20% p.a. in most countries.

- Taking a value chain approach in which the private sector is involved can help address the financial constraints of smallholder farmers in accessing inputs. This, however, requires additional support activities that lower their risks, which includes credit guarantee facilities with financial institutions and strengthening farmers associations in ways that enhance their skills to aggregate produce and respect contracts.
- The integration of cereals with legumes is essential for improvement of soil fertility. The legume crops contribute significantly to soil organic matter and NUE in ISFM systems. However, scaling out legume-based systems is seriously constrained by the availability of improved legume seeds and availability of rhizobium inoculum, especially in rural areas. This is because seed companies do not aggressively market legume seeds in the same way as cereals, especially hybrid maize. This requires exploring alternative approaches (e.g., farmer groups, public institutions, CGIAR centers, etc.), at least until demand grows to a point where the private sector can engage effectively.
- There is a shortage of skilled manpower to carry out good agronomic and soil fertility research nd extension work. Hence there is a need to invest in the capacity of young talents to pursue higher learning at diploma, degree, masters and doctorate levels.
- Scaling out ISFM technologies are knowledge intensive. Therefore, there is a need to create and adopt new ways of teaching and learning, especially in higher education, research and innovation in the agricultural sciences. This will produce graduates with the necessary mix of scientific knowledge and skill sets: communications and writing, managerial and entrepreneurial skills and societal adaptability to operate in a changing environment.

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Chapter 11

Soil Fertility Status and NPK Blends at Planting for Maize Growing in the Western Kenyan Counties Uasin Gishu and Busia*

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Abstract

Crop production on smallholder agricultural land must increase considerably if the growing world population is to be fed. To achieve this, affordable soil testing methods, fertilizer recommendations and the accessibility of optimal fertilizers containing the required nutrients are required. The SoilCares mobile laboratory offers affordable soil testing using infrared spectroscopy and slightly modified Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) for fertilizer recommendations (through the use of blends) to smallholders. SoilCares soil testing results from 2,107 samples from Uasin Gishu and Busia counties in Kenya were analyzed using archetype analysis and QUEFTS to derive: i) more accurate soil fertility classification; and ii) to optimize the formulation of NPK planting blends for maize. The study showed that eight soil archetypes could be distinguished of which four were dominant. Additionally, four fertilizer-blend archetypes were distinguishable for all counties which comply reasonably well with the NPK fertilization at planting necessary for 5 t ha^{-1} maize production. These blends are 12:25:0, 6:22:14, 0:40:0, and 13:33:0 (N-P_2O_5-K_2O). Median relative difference between the advised and optimally needed N, P_2O_5 and K_2O application rates at planting were 36, -10 and 0 %, respectively. The method described, including mapping, may be useful in assisting decision-making by the fertilizer industry, traders and policymakers on the production and availability of crop or region specific NPK blends.

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Introduction

In order to feed a fast-growing world population ways must be found to increase crop yields, particularly for smallholder farmers in developing countries (FAO, 2009). Many of these smallholders are confronted with an enormous yield gap in crop production, i.e. a difference between potential yield and actual yield. The key factors in determining this potential yield difference are soil nutrient management and soil fertility status (Licker *et al.*, 2010). Nitrogen (N), phosphorus (P) and potassium (K) are macronutrients that play a major role in plant growth and crop yields (Marschner, 2012). In smallholder farming systems, export of N, P and K from fields and farms often exceeds input via e.g. fertilizers. Such negative N, P, K balance sheets lead to a gradual and unsurmountable decrease in N, P and K soil fertility status (Roy, 2003; Smaling, 1993). Restoration of soil fertility status and the provision of crop specific N, P and K recommendations are prerequisites to increase crop yields. Closing the yield gap must therefore begin with precise and affordable soil testing, followed up with the development of fertilizer recommendations, and making such fertilizers accessible to farmers. Shepherd *et al.* (2007) have shown that infrared technology can be used for soil testing. It is an indirect method that requires calibration and validation studies. However, when this is achieved, the method gives precise results and it then becomes a promising and cheap tool for routine soil testing for smallholders.

The QUEFTS fertilization model (Quantitative Evaluation of the Fertility of Tropical Soils, Janssen *et al.*, 1990) has been developed for N, P and K fertilization of maize in Kenya. It calculates the optimal nutrient rates taking into account the measured fertility status of the soil, interactions between soil pH and N-, P-, K-supply, fertilizer nutrient efficiency, and the (desired) yield level. The QUEFTS model has also been applied and tested for the other main staple crops throughout the world (Sattari *et al.*, 2014).

The accessibility of organic and mineral fertilizers to smallholders is often limited even though long-term fertilizer subsidy programmes have been set up in many African countries to promote fertilizer use. Additionally, the repeated use of e.g. urea and (ammonium) N and P containing fertilizers has led to soil acidification, decrease of K status and low use efficiency of N or P, or both of these nutrients. The major reason for these side-effects is that nutrient application is not tuned to the specifically measured soil nutrient status and crop nutrient demand for optimal production.

Negative side effects of blanket fertilizer recommendations are well known, and prescribed blends cannot be applied before: i) the actual and specific soil nutrient status in different regions/countries has been identified; ii) the recommended N, P and K rates for optimal crop production are calculated; and iii) techniques have been established to optimize a limited number of appropriate NPK blends. In this context, ‘appropriate’ implies that deviations from actual demand are acceptable.

Archetypal analysis is an empirical, data-driven classification algorithm yielding a few typical and representative combinations of the underlying multivariate data set (Cutler and Breiman, 1994). These typical combinations are called archetypes. Once archetypes are established, any new instance represented by the underlying data set can be classified to one archetype. Archetypal analysis has been used in economics (Porzio *et al.*, 2008) and can also be used to classify soil or fertilizer blend archetypes. This is the basis for optimizing appropriate NPK fertilizer blends.

During the first three months of 2014, SoilCares analyzed 2,107 soil samples from agricultural land from the two Western Kenyan counties, Uasin Gishu and Busia (Fig. 1). The goal of the work reported in this paper was to determine for these counties:

- archetypes of soil fertility status
- archetypes of NPK blends to apply at planting for maize

Fig. 1. Location of the two Western Kenyan counties, Uasin Gishu and Busia.

Materials and methods

The field study was carried out in the two Western Kenyan counties, Uasin Gishu and Busia (Fig. 1).

Soil sampling was carried out by the smallholders themselves. They were provided with an auger, sample bag, registration form, and top soil (0-20 cm) sampling protocol. Mandatory information was inter alia the spatial origin of the soil sample and crop type to be planted. Spatial origin of a sample was defined by sub-location (level 5 of Kenya from the Global Administrative Areas version 2 database). There were 117 sub-locations in total in the Uasin Gishu and Busia counties.

In total, 2,107 soil samples were collected and handed over to the SoilCares Mobile soil testing laboratory (Fig. 2). After receipt, the (moist) soil samples were crushed and sub-sampled using a combined grinder/sub-sampler device. The sub-sample was dried with a forced air flow for about 1 hour at 40˚C until dry. Subsequently, the dried samples were crushed, sieved to 2mm, and subdivided to obtain a representative 15 ml sub-sample. This sub-sample was finely ground using a ball-mill followed by determination of the diffuse reflection mid-infrared spectrum. Spectra were analyzed and soil testing data were derived using the SoilCares calibration set for Kenyan soils. Data flows in the system were continuously checked to internal quality standards, and soil testing data were only released when checks were passed. Data presented are Organic Carbon (Org C), Total Nitrogen (Tot N), acidity (pH-$CaCl_2$), phosphorus stock (P stock), exchangeable calcium (exch. Ca), magnesium (exch. Mg) and potassium (exch. K), and contents of clay and sand (Table 1).

Fig. 2. SoilCares mobile soil testing laboratory.

The QUEFTS model (Janssen *et al.*, 1990), including modifications (Sattari *et al.*, 2014) was used to carry out scenario studies to calculate: i) the potential N, P and K supply from soil; ii) the N, P and K demand of different yield levels; and iii) the remaining fertilizer nutrient demand.

Scenario calculations were made for two maize yield levels (2 and 5 t ha^{-1}) and two levels of nutrient recovery fractions of applied fertilizer (normal and high). It was assumed that 22 kg N, 3.7 kg P, and 14.6 kg K need to be taken up by maize plants to produce 1 t of maize grains. If the necessary nutrients could not be supplied by the soil, the remaining nutrients were assumed to be applied by fertilizer (expressed as kg ha^{-1}). Calculated amounts of fertilizer nutrients were converted to N, P_2O_5 and K_2O for ease of comparison to blend compositions. For the two yield levels, at the normal level, it was assumed that fertilizer nutrient recovery by the crop was 50% of applied N, 10% of applied P, and 50% of applied K, whereas at the higher level it was 50% of applied N, 20% of applied P, and 75% of applied K. For fertilizer advice, calculations of soil pH values below 4.9 were set to 4.9 - assuming that lime was applied by the farmer prior to fertilization. This was done in order to exclude the effects of strongly acidic soils on nutrient supply and fertilizer use efficiency. In relation to calculations of potential soil nutrient supply, soil pH values determined in water were increased by 0.3 pH units above the original 0.01M $CaCl_2$ pH values.

Archetypal analysis was done using the archetype-package (Eugster & Leisch, 2009) within the R statistical environment (R core team, 2013). Input data were scaled (mean centred and divided by their standard deviation) before use. All named soil property data were taken as input for soil archetypal analysis. After the model building phase, each of the 2,107 soil samples was classified to one of the soil archetypes. Blend archetypes were calculated for the basal fertilizer application of 5 t yield aim and normal recovery fraction of applied fertilizer only; 30% of the total N rate was subtracted for the top-dressing application. Prior to blend archetypal analysis, the calculated amounts of N, P_2O_5 and K_2O (kg ha^{-1}) were converted to the blend ratios used for the blended products (e.g. NPK 16:23:7) subject to the assumption that the sum of N, P_2O_5 and K_2O should not exceed 46% in the blend (when urea is the leading N product with the highest nutrient content, any addition of other fertilizer will dilute the total nutrient content in the blend). After the model building phase, each of the 2,107 soil samples was classified to one of the blend archetypes. To assess the impact of not using the optimal nutrient rate but the selected archetype blend, for N, P_2O_5 and K_2O we calculated: i) the absolute nutrient residuals (fertilizer - plant need at planting); and ii) the relative nutrient residuals (absolute residuals $plant^{-1}$ need at planting*100). Fertilizer nutrient recovery fraction was also taken into account. Knowing the N, P and K plant demand to provide 5 t of maize yield, the application rate (kg ha^{-1}) of the NPK blend was optimized. This was achieved by minimizing the sum of the N, P_2O_5 and K_2O absolute residuals over the range of possible nutrient application rates.

Geographical representations of the results were obtained using ArcGIS software.

Results

Soil

In total, 1,139 and 968 samples originated from Busia and Ushia Gishu counties, respectively. Table 1 provides a summary of the soil test values obtained.

The range within the soil characteristics measured was huge but seemed to be comparable for the sub-locations of Busia and Uasin Gishu counties. Nevertheless, soils in Uasin Gishu seemed to be more fertile, because median values for contents of Org C, Tot N, clay and exch. Ca, Mg and K were higher at a comparable pH value.

When archetypal analysis was applied to the whole soil data set, 8 different soil archetypes could be distinguished. Table 2 shows the soil characteristics per archetype. In most cases, 2 to 6 soil characteristics are decisive in differentiating between 2 archetypes. For example, archetype 5 has a lower Org C content, Tot N and exch. Ca, Mg and K as compared to archetype 7. The pH of these archetypes are the same.

When the 2,107 soil samples were classified according to the archetypes, fewer than 100 samples were classified to each of the soil archetypes 1, 2 and 6. Between 200 and 400 samples were classified to each of the soil archetypes 3, 4 and 8, and more than 400 samples to each of the soil archetypes 5 and 7.

The maps in Fig. 3 illustrate that in the sub-locations of the two counties, soil archetypes 3, 4, 6 and 7 were mainly present in Busia, whereas soil archetypes 5 and 8 were predominant in Uasin Gishu. Only 12% of the 117 sub-locations had only one soil archetype. In the other sub-locations, 2-7 archetypes were present. The distribution was as follows: 23% had 2 archetypes, 26% had 3 archetypes, 20% had 4 archetypes, 14% had 5 archetypes, 4% had 6 archetypes and 1% of sub-locations had 7 soil archetypes.

QUEFTS scenario studies

Fig. 4 and Table 3 present the result of the QUEFTS scenario studies in which the effect of maize yield level and P and K fertilizer efficiency on total N, P_2O_5 and K_2O fertilizer application rate were simulated for each of the 8 soil archetypes.

It is clearly visible that samples belonging to one soil archetype are restricted to a specific location in the three dimensional representation of the nutrient application rates. Nevertheless, there is an overlap between different soil archetypes. Yield levels and rates of nutrient recovery have a strong influence on

Table 1. Soil characteristics (median and range) of the total dataset and for Uasin Gishu and Busia counties separately.

Soil characteristic	Unit	Total (n=2,107)		Busia (n=1,139)		Uasin-Gishu (n=968)	
		Median	Range	Median	Range	Median	Range
Organic C	g kg^{-1}	17	4-87	13	4-87	21	5-68
Total N	g kg^{-1}	1.5	0.3-4.9	1.2	0.3-4.5	1.9	0.5-4.9
Exch. Ca	mmol+ kg^{-1}	27	0-269	17	0-269	28	0-269
Exch. Mg	mmol+ kg^{-1}	13	0-63	12	0-63	15	2-63
Exch. K	mmol+ kg^{-1}	3.4	0-9.2	2.5	0-9.2	4.5	0.7-9.2
pH		4.9	4.0-6.6	4.9	4.0-6.6	4.8	4.1-6.0
Clay	g kg^{-1}	510	10-820	420	10-780	580	40-820
Sand	g kg^{-1}	300	70-840	340	70-840	270	70-820
P stocks	mmol P kg^{-1}	5	1-23	5	1-23	6	1-20

Table 2. Soil characteristics of each of 8 archetypes distinguished in the Uasin Gishu and Busia data set (n=2,107), division of soil samples over the 8 soil archetypes, and the number of sub-locations where a specific soil archetype is most common.

Soil characteristic	Archetypes							
	1	2	3	4	5	6	7	8
Organic C	8	73	11	6	22	28	7	27
Total N	0.7	4.3	0.8	0.5	2.1	1.3	1.0	2.6
Exch. Ca	34	157	0	12	26	231	18	8
Exch. Mg	14	36	4	6	18	56	5	8
Exch. K	1.7	8.7	0.5	2.0	5.1	5.9	1.0	5.1
pH $CaCl_2$	5.3	5.3	4.2	5.7	5.0	5.8	5.0	4.2
Clay	280	530	110	50	670	460	560	680
Sand	370	280	720	820	240	190	140	170
P stock	14	19	1	3	2	13	4	10
Number of soil samples classified to archetype	64	39	264	312	557	95	411	365
Number of sub-locations classified mainly to soil archetype	3	1	6	15	29	6	32	25

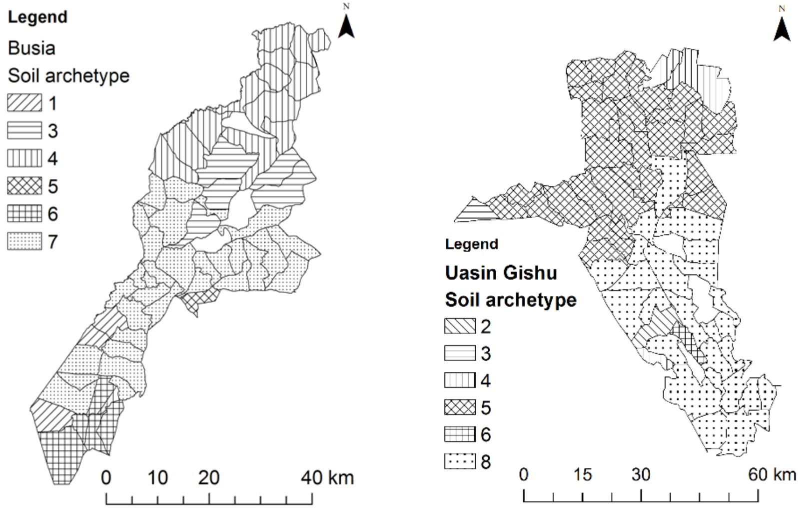

Fig. 3. Main soil archetypes represented in each of the counties of Uasin Gishu and Busia (defined by Global Administrative Areas (GADM); http://www.gadm.org/).

recommended amounts of nutrients. For example, high nutrient use efficiency at yield level 5 t ha^{-1} (Fig. 4d) showed reduced total P_2O_5 and K_2O nutrient needs compared to normal nutrient use efficiency at the same yield level (Fig. 4c).

Further analysis was restricted to the 5 t of maize per ha yield scenario with normal nutrient recovery rates (Table 3). The study showed that total N, P_2O_5 and K_2O application rates ranged from 78-159, 90-411 and 0-176 kg N, P_2O_5 and K_2O ha^{-1} respectively. Distinct differences existed between the soil archetypes, again with overlap occurring between soil archetypes.

Four NPK blend archetypes could be distinguished for fertilization at planting (Table 4). Archetype 3 is a pure P fertilizer. Archetypes 1 and 4 are NP blends and archetype 2 is an NPK blend. 49% of soil samples were classified as archetype 1; 38% as archetype 4; 8% as archetype 3; and 6% as archetype 2. Blend archetype 1 was the major blend in 59% of the sub-location areas. Nevertheless, in one sub-location more than one blend archetype was advised (Fig. 5). Only in 6% of the sub-locations did all soil samples from this sub-location have the same blend archetype. All the other sub-locations had two to four blend archetypes; 38% of sub-locations had two blend archetypes; 33% of sub-locations had three blend archetypes; and all four blend archetypes were present in 22% of the sub-locations.

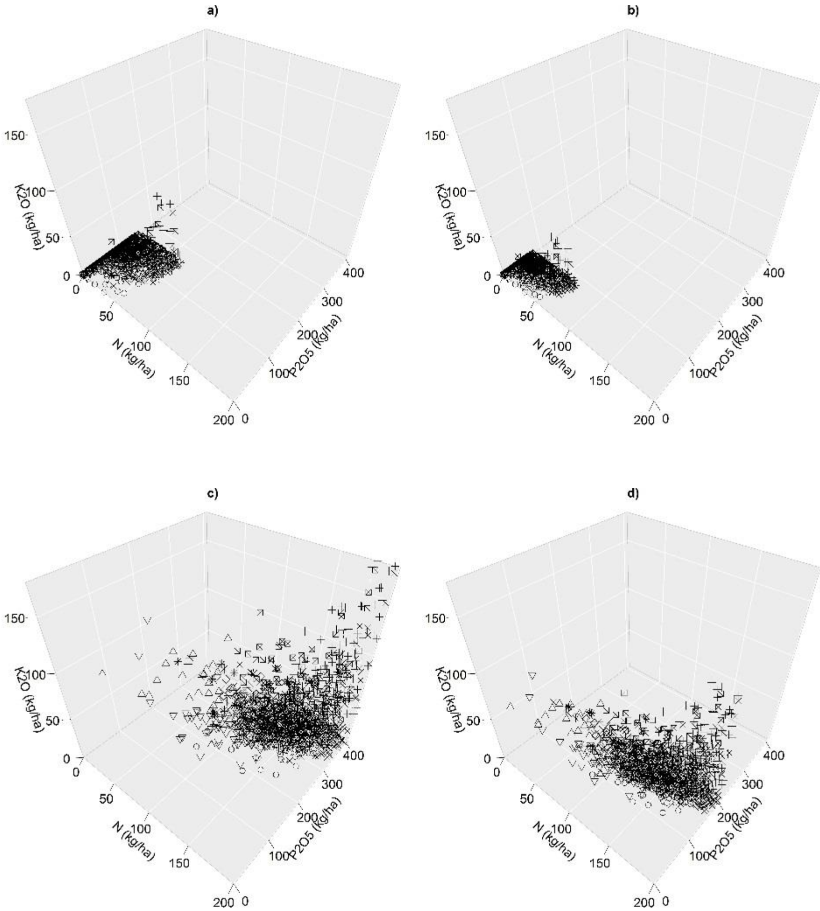

Fig. 4. 3D total fertilizer nutrient application rates for: i) 2 t maize yield (graph a and b); ii) 5 t maize yield (graph c and d); iii) normal nutrient recovery fraction (graph a and c); and iv) high nutrient recovery fraction (graph b and d). Different symbols refer to soil archetypes as mentioned in Table 2 and Fig, 3.

Table 3. Total maize fertilizer nutrient needs per soil archetype with a projected 5 t ha^{-1} maize yield per ha and normal nutrient recovery fraction of applied fertilizer (50% of N, 10% of P and 50% of K taken up by the plant). Median, minimum and maximum nutrient needs for all soil samples belonging to one soil archetype are presented.

Soil archetype	Total fertilizer N			Total fertilizer P_2O_5			Total fertilizer K_2O		
	Median	Min	Max	Median	Min	Max	Median	Min	Max
	---*kg ha^{-1}*---								
1	159	97	186	306	144	359	0	0	81
2	78	0	111	255	90	320	36	0	97
3	172	88	200	398	307	411	40	0	176
4	170	71	199	377	276	411	0	0	172
5	146	5	178	366	276	411	0	0	31
6	106	0	158	273	121	339	0	0	103
7	139	69	193	368	290	411	7	0	172
8	135	0	166	334	253	388	0	0	98

Table 4. Description of blend archetypes at planting for 5 t maize yield per ha and normal nutrient recovery fraction.

Fertilizer	Blend archetype			
	1	2	3	4
N	12	6	0	13
P_2O_5	25	22	40	33
K_2O	0	14	0	0
Number of samples classified to blend archetype	1,032	130	153	792
Number sub-locations classified mainly to blend archetype	67	2	7	41

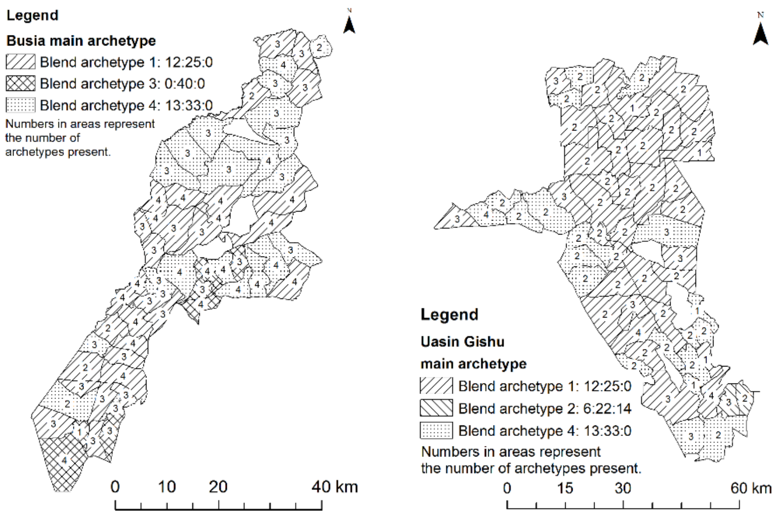

Fig. 5. Distribution of main planting blend archetypes in the sub-locations of Busia and Uasin Gishu.

When the classified blend archetype at planting is applied in a per sample optimized amount to the field, a shortage or excess amount of N, P_2O_5 or K_2O may occur because the blend composition does not fit perfectly to the specific NPK fertilizer demand of maize on that field. For all samples, the excess/shortage of N, P_2O_5 and K_2O was calculated. Table 5 gives the summary statistics of the calculated absolute nutrient residuals at planting in kg N, P_2O_5 and K_2O ha^{-1} for the soil samples leaving out the 10% lowest and 10% highest residues (10-90% percentiles). In addition, the relative nutrient residuals at planting (residuals/plant need at planting*100%) are presented for this 10-90% percentile.

Table 5. Summary statistics on absolute and relative nutrient fertilizer residuals at planting.

Type of residual	Population characteristic	N	P_2O_5	K_2O
Absolute nutrient residuals: fertilizer - plant needs (kg ha^{-1})	10% percentile	-30	-57	-36
	Median	37	-37	0
	Mean	35	-29	-4
	90% percentile	59	0	0
Relative nutrient residuals: absolute residuals/plant needs (%)	10% percentile	-27	-16	-100
	Median	36	-10	0
	Mean	34	-8	-26
	90% percentile	63	0	0

When the recommended blend archetype was applied in an optimized amount, the analysis showed the median residual N, P_2O_5 and K_2O was 37, -37 and 0 kg ha^{-1} respectively. Eighty percent of the soil samples (10-90% percentile) had deviations from the recommended N application rate between -30 and 59 kg ha^{-1}. For P_2O_5 and K_2O, this ranged between -57 and 0, and -36 to 0 kg ha^{-1}, respectively. This translated into median relative residuals of 36%, -10% and 0% for N, P_2O_5 and K_2O.

Discussion

Routine soil testing using infrared technology in combination with the SoilCares mobile laboratory is a promising first step to decreasing the crop yield gap experienced by smallholders. In this Uasin Gishu - Busia project, more than 2,100 samples provided by smallholder farmers were analyzed by one bus run by a team of three people within eight weeks. All smallholders received a field and crop specific fertilizer recommendation within about three hours of presenting their samples.

The data plotted at the sub-location level of Uasin Gishu and Busia are useful to obtain recent, detailed information on actual soil fertility status. Soil test data of soil samples, in combination with the calculated optimal NPK application rate according to the QUEFTS fertilization model, provide a data set which can be used to derive optimal fertilizer blend compositions using the archetype approach.

The soil samples from Uasin Gishu and Busia could be classified to eight soil archetypes with unique soil property combinations. Mainly different soil archetypes were found in the two counties. Nevertheless, huge soil variability was encountered even at sub-location level. There appeared to be no direct relationship between the soil archetypes and the well-known soil types on soil maps. The reason for this is probably that on common soil maps only general static soil characteristics are included. When dynamic soil characteristics are incorporated, more detailed and precise soil fertility maps can be produced. These changes in the dynamic soil characteristics are probably the outcome of recent farm, fertilizer or crop residue management, but this statement needs further investigation.

Soil archetypes, as derived in this study, provide a very useful starting point for assessing soil fertility status and advising on fertilizers and their rates of application. However, this is only possible when the soil archetypes remain constant for a long period. If this is not the case, communication and knowledge transfer on soil fertility status and fertilizer application rates becomes more challenging. Future research should also address this point.

Fig. 4 and Table 4 (exemplary for the maize yield of 5 t ha^{-1} assuming normal nutrient recovery fraction) showed the huge variation that can be expected in the optimal N, P_2O_5 and K_2O application rates because of differences in soil archetype. However, when the archetype approach is used for the calculated N, P_2O_5 and K_2O rates of all samples. An optimization step needs to be included to derive the optimal amount of blend that should be applied to a single field. Each of the 2,107 soil samples was classified to one blend archetype. Calculations showed that, although N, P_2O_5 and K_2O residuals existed, the magnitude (absolute and relative) was acceptable.

This study showed that the SoilCares mobile soil testing concept is a good starting point for minimizing the yield gap. The infrared technology is an affordable soil testing method for smallholders and the QUEFTS calculation model has a good scientific basis for deriving field and crop specific N, P_2O_5 and K_2O recommendations. Results are returned within three hours. As described in this paper, data can also be analyzed in more detail to define soil advice and blend archetypes. This new information is a good basis for knowledge transfer to smallholders, as well as for the economic production of NPK blends potentially of use for large areas of agricultural land and crops.

Acknowledgement

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