Research Findings

Response of bread wheat to KCl fertilizer application in Jihur Kebele, Moretina Jiru woreda, Amhara region, Ethiopia (2014). Left: Plot receiving blended fertilizer and urea only. Right: Plot receiving the same treatment with 100 kg/ha KCl. *Source:* Obtained from ATA and MoANR collections, courtesy of Prof. T. Mamo.

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

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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

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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 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.

One of the soil K depletion factors in Ethiopia. *Source:* Istockphoto.

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 (14 kg ha^{-1}), as well Morocco and Nigeria (FAOSTAT 7-2011). Currently, some 13% of the world's cultivated area is in SSA, yet the region accounts for less than 1% 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.

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

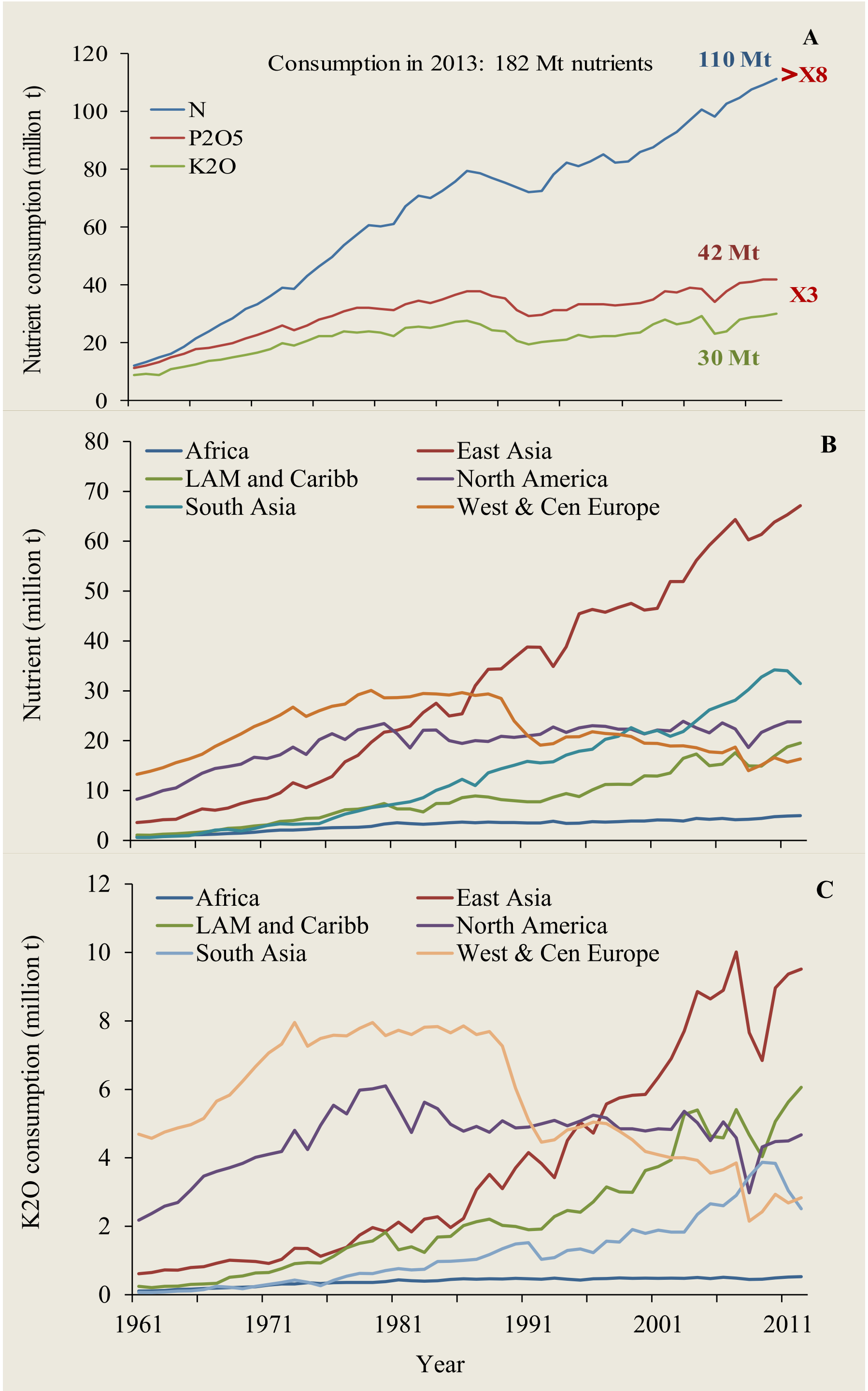

Fig. 1. A: Global N, P_2O_5 and K_2O consumption 1961-2013 (growth is interrupted only by global crisis). B: Growth in nutrient consumption (almost all regions). C: Potash consumption in regions 1960-2012.

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 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).

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.

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.

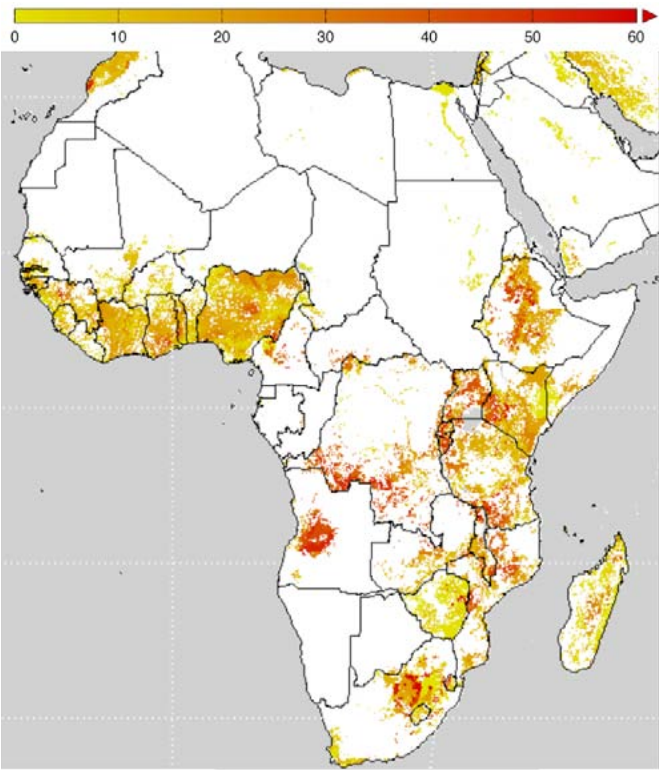

Fig. 2. Rate of potash application to major cereals from 0 to 60 K_2O kg ha^{-1} throughout Africa. *Source:* Mueller *et al.*, 2012.

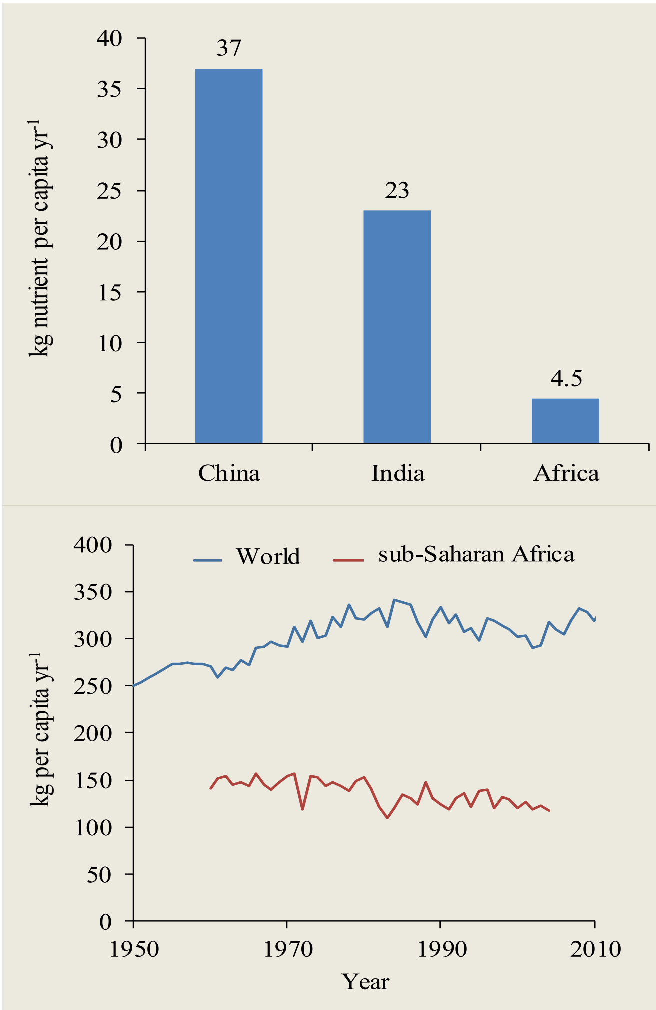

Fig. 3. Nutrient consumption per capita per year and kg of grain produced per capita. *Source:* Nutrient consumption per capita calculated from FAOSTAT and IFA; nutrient consumption per kg of grain produced per capita grain from Worldwatch, USDA and UNPOP.

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

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.

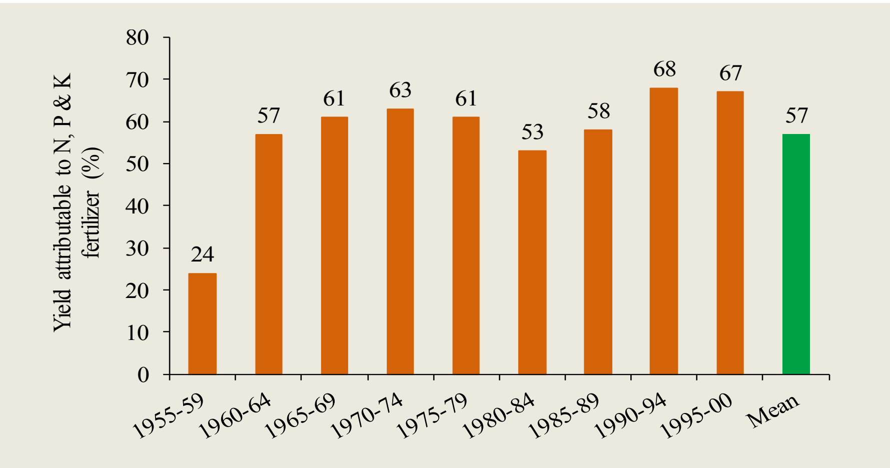

Fig. 4. Continuous maize yield attributable to N, P and K fertilizer and lime over 46 years in the University of Illinois Morrow plots. *Source:* Stewart *et al.*, 2015.

Evidence 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 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

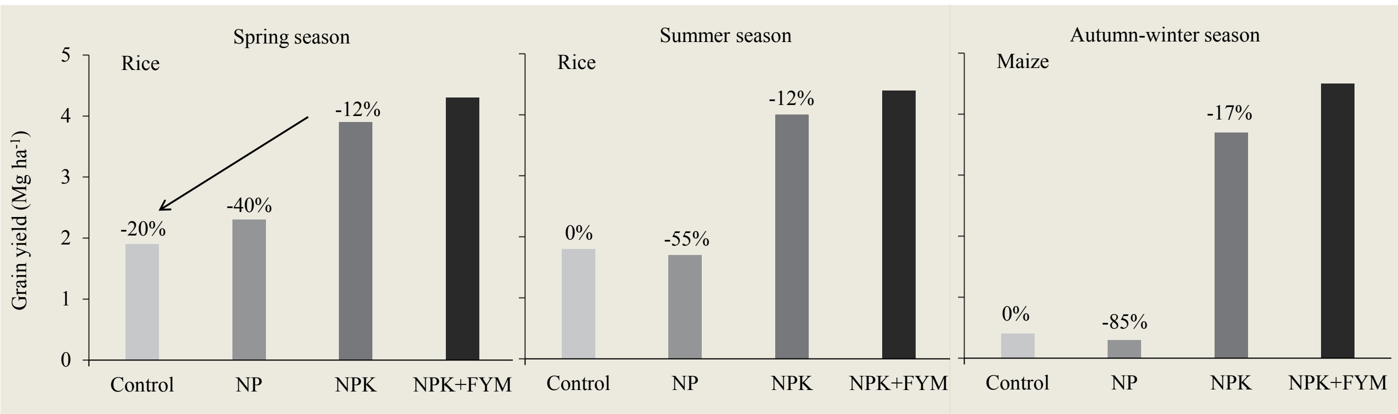

Fig. 5. Average yields (mean of five years) in a long-term cropping system experiment in the Red River Delta, Vietnam. Percentages indicate cumulative yield gaps. *Source*: Mussgnug *et al.*, 2006.

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.

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

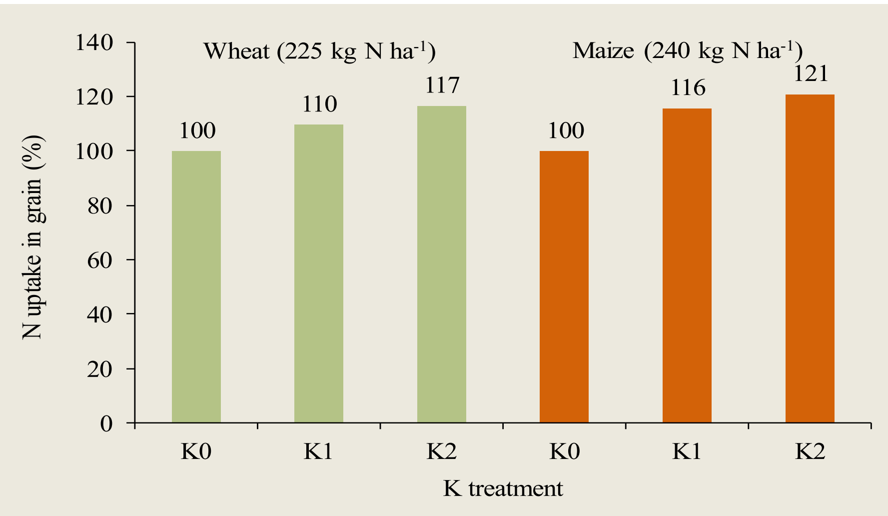

Fig. 6. Improving nitrogen use efficiency by better K application. Data calculated from: Niu *et al.*, 2013 (wheat) and Niu *et al.*, 2011 (maize).

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

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.

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.

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.

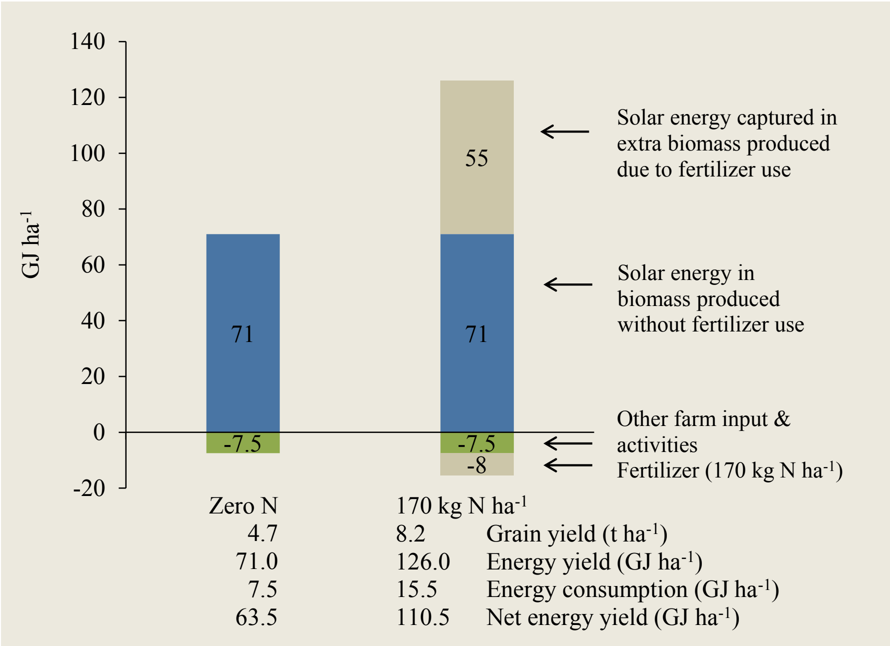

Fig. 6. Illustration of the solar energy captured by a hectare of wheat (8.2 t ha^{-1}) and the energy invested in its production (after EFMA, 2006).

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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