Nutrient shortages and agricultural recycling options worldwide, with special reference to China

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Abstract.
Mineral nutrients such as Phosphorus and Zinc are getting scarcer worldwide. Unlike fossil fuels, for which over time substitutes can be developed, these nutrients cannot be substituted as they are essential for life on earth. For instance, in both plants and animals Phosphorus is a component of DNA, RNA, ATP and of phospholipids which form all cell membranes. Phosphorus is thus essential for the replication of cells and consequently growth and ultimately reproduction. Further, phosphorus in humans is mostly concentrated in bones giving shape to the human body, which largely consists of water. A significant fraction of these minerals is disposed of in the form of manure and considered a pollutant to be disposed of often via surface water eventually to the ocean or fixated in the soil which amounts to an almost irreversible loss. Another fraction is lost in industrial transformation. According to the US Geological Survey, the easily and economically mineable reserves of phosphate rock are sufficient for some 120 years of current consumption levels. In the case of Zinc this is 22 years. Moreover, phosphate rock resources are very unevenly distributed. For example, 65 per cent of Phosphate rocks are located in China, Morocco and Western Sahara. These conditions may affect Phosphorus availability elsewhere. This paper provides a first quantification for some essential mineral nutrients as they occur in different sections of the geosphere and explores possible solutions to ensure sustainable fertilizer options. For Phosphorus these include the mining of P on P-intoxicated land, abstaining from high and inefficient doses of P, and P recovery from urban human and animal waste as well as waste products from biofuel production. Further waste product recycling will be easier and less costly when production and consumption areas are geographically close. Saving options for micro-nutrients such as Zinc are largely similar to those for Phosphorus, but in addition can consist of the reduction of non-agricultural applications. The second part of the paper provides an application for China. We analyze net nutrient use in Chinese agriculture and address the question to which extent China can reduce this net demand in the coming decades, while meeting its requirements for food, feed and biofuel. For this, we use the Chinagro welfare model that comprehensively depicts China's farm sector in 2433 counties while connecting these through trade and transportation flows to each other, to rural and urban consumers and to abroad. The model computes net surpluses from application of N, P and K fertilizer in crop fields. The paper presents scenario simulations suggesting excessive use of N and P, while K application is insufficient and actually mined from the soil. The findings thus indicate that more balanced fertilizer mixes will be required to sustain high crop yields, which simultaneously would reduce currently experienced environmental problems.

1. Introduction

Quite a few mineral nutrients are essential for growth, functioning and health of plants, animals and human beings. In humans, nutrient deficiency generally causes retardation of growth and development and particular disease symptoms may develop, including in some cases even mental retardation. Overdoses of essential mineral nutrients are toxic and also affect growth and health. Generally, humans need a balanced supply of essential mineral nutrients and the same applies to plants. Imbalances lead to nutrient-specific diseases. Since most human food directly or indirectly derives from plants grown in soils, human nutrient deficiencies and toxicities are essentially attributable to soil nutrient deficiencies and toxicities.

Being essential to all life, these mineral nutrients possess the distinct feature that no technological progress will ever make it possible to dispense of them, unlike fossil fuels, and nitrogen fertilizer, which can eventually be replaced by substitutes such as solar, tidal, and wind energy.

These mineral nutrients are like fossil fuels non-renewable but unlike fossil fuels they are to a large extent recoverable after use, particularly if they are used by living organisms. Indeed, they belong to the most basic reproductive cycles on Earth.

In fact, every element of the F6 complex of rising demand worldwide for food, feed, fuel, fibres, forestry, fisheries directly as well as indirectly points to F7 as F6 plus rising demand for fertilizer, and among these, essential mineral nutrients PK and micronutrients require particular importance, because unlike N they cannot be collected from the atmosphere.

Overview

Around 1500, Leonardo da Vinci wrote that ‘We know more about the movement of the celestial bodies than about the soil under our feet’. Our paper reviews some of the insights that were gained since, but cannot escape the conclusion that the statement holds true today much as it did at the time. The paper proceeds as follows.

First, we briefly describe the role of essential mineral nutrients, and the application levels required, and calculate for how long soils could supply them in sufficient quantities to sustain annual cropping. Second, we turn to the supply side of mineral nutrients and draw an inventory of the levels present in the soil and the resources available for fertilizer production and indicate under specified assumptions how long these would last. Third, we review some options for increased efficiency in fertilizer use and discuss the impact of residual fertilizers on essential mineral nutrients that are not applied with them. Next, we describe several options to use scarce resources more adequately and to recycle nutrients after use. Finally, we use outcomes from a simulation model of Chinese agriculture to project nutrient balances for N, P and K, looking for ways to enhance nutrient use efficiency, while sustaining high productivity levels.

2. Rising demand for biomass

According to the UN’s mean projection, world population is still to increase by about fifty percent, to peak at about 9.5 billion around 2050. At the same time, rising incomes in developing countries will lead to higher demand for livestock products, and, consequently for animal feeds as well (Tilman et al., 2002). To meet this demand agricultural production will have to be stepped up, including a doubling of global grain supply by 2050. Further adding to this demand pressure is the growing demand for renewable energy, particularly liquid fuels that triggered production of bioethanol and biodiesel, albeit so fat only with lavish subsidies, which competes for land, labor and inputs with food and feed crops. While these drivers are well documented by now, far less is known about the demand for and relative scarcity of various inputs.

Naturally agricultural production can be increased through area expansion as well as through improved yields per hectare. Advocates of energy from biomass argue tend to concede that current generation biofuels compete with food but they expect technological change to allow for cultivation on land where no crops can grow, ranging from bushes in the desert, to high grasses and tropical forests. Whether this is possible largely depends on soil conditions, temperature and rainfall. Overriding limitations may result from low temperatures, insufficient rainfall, steepness, shallow soils, stoniness and rockiness and chemical constraints such as severe salinity. In between these unsuitable areas and the land currently cultivated there are still large surfaces that are not intensively used. Agronomists tend to agree that these lands are of a lower inherent quality as compared to those lands already used for cultivation (e.g. Young, 1999).

Expanding cultivation on these lands will have to account for environmental considerations, such as biodiversity preservation, besides significant losses as a result of continued urbanization, erosion and salinization. Climate change will also cause losses in some regions but these might be compensated by gains elsewhere.

Hence it will be necessary to raise yields per hectare. For this, better irrigation, improved seeds and intensified nutrient application will be needed. As nutrient deficits tend to be multiple and to show complex interactions, with higher dosage of one chemical often lowering the effectiveness of another, it often proves quite difficult to eliminate them.

Ample use of N and P fertilizer has in the past been the key to crop yield improvements in many parts of the world but their uptake efficiency has become very low while the accumulation of P in surface waters has frequently led to eutrophication. With respect to N, it has now become clear that N_2O emissions deriving from fertilizer use in the past have been seriously underestimated. (Crutzen et al., 2007). Increased use of N fertilizer through area expansion and higher doses thus could result in a much stronger climate forcing causing a chain of reactions with unpredictable effects on agricultural production (e.g. increased methane emissions from the arctic tundra).

At the same time, nutrient mining, in the sense of harvesting more nutrients than are being applied that may have to be compensated for in the future. In many parts of Africa the extreme situation prevails that land is frequently cultivated, the harvested crop removed from the land and no fertilizers are being applied whatsoever (Stoorvogel et al., 1993). In fact, the fertilizers that are being applied usually consist of N, P and K only. The other essential plant nutrients they may contain are often considered ‘impurities’ and as fertilizers become more sophisticated, these tend to disappear from the package, and crops have to acquire them from soil, which will have to be replenished in the future.

This holds in particular for agro-fuels to be grown on marginal soils, especially because of the need to concentrate cultivation around large, energy effective agro-fuel factories as is already the case for ethanol production from sugarcane in Brazil.

In short, whatever the purpose crops are being grown for, they require essential plant nutrients. These needs are far from modest, and while Nitrogen can be retrieved from the air, all others are of mineral origin and hence non-renewable (e.g. Tilman et al.,2002), making it all the more important to save on their use, and to recycle as much as possible of the quantities applied.

3. Role of essential mineral nutrients

We focus on soil nutrient deficiencies since those in crops, animals and humans derive from these. Table 1 presents an overview of essential mineral nutrients for plants, animals and humans. To illustrate how essential mineral nutrients may affect growth we discuss the case of the macro-nutrient P and the micro-nutrient Zn.

Phosphorus

Phosphorus is a component of DNA, RNA, ATP, and also the phospholipids which form all cell membranes. It is thus an essential element for all living cells. The function of phosphorus as a constituent in macromolecular structures is most prominent in nucleic acids which, as units of the DNA molecule, are the carriers of genetic information i.e. fundamental to life: division of cells, growth and reproduction. In humans most P is located in bone tissue, thus providing the structure of the human body, which largely consists of water. P is also a constituent of Adenosine triphosphate (ATP) a carrier of energy, for instance captured during photosynthesis in plants and which is required for the synthesis of starch (human food). Furthermore, inorganic P strongly affects photosynthesis and carbon partitioning in leaves and photosynthesis is almost totally inhibited if inorganic P in the chloroplasts falls below certain levels (Marschner, 1995). All this confirms that the purity of the P may be critical for human health.

Zinc

Zinc plays a role in neurotransmission and has a catalytic and structural role in enzyme reactions (various sources quoted in Alloway, 2009). Zn further plays a role in protein molecules involved in DNA replication. Zinc deficient plants have low rates of protein synthesis and consequently low protein content (Marschner, 1995). Zinc is an essential mineral of exceptional biologic and public health importance. Zinc deficiency affects about 2 billion people in the developing world and is associated with many diseases. In children it causes growth retardation, delayed sexual maturation, infection susceptibility, and diarrhea, contributing to the death of about 800,000 children worldwide per year (Black, 2003). Soil Zn deficiency is very widespread indeed. In Turkey, Pakistan, India and China together 148 million hectares or about 50% of the arable land are considered deficient (various sources quoted in Alloway, 2009).

Copper

Cereal crops grown on organic soils (greater than 30% organic matter to a depth of 30 cm) often respond to copper fertilization. Copper deficient soils tend to be either sandy or light loam soils with relatively high levels of organic matter (6-10%). High levels of soil phosphorus or heavy applications of manure are often associated with a copper deficiency on these soils. Wheat, barley and oats are the most sensitive to it and show e most obvious disease symptoms.

The other essential mineral nutrients in Table 1 perform many functions that of equally vital importance for plants and animals. Essential mineral nutrients have no substitute.

4. Available stocks of essential mineral nutrients: cultivable soils versus mineable reserve base

The levels of essential plant nutrients in the soil vary with the content in the original soil parent material, soil formation processes and history, the level of past removals with the crop product and the fertilizer history of a particular piece of land. Thus, even without any cultivation history and past fertilizer use, soils can be deficient in some elements, simply because its concentration in the soil parent material was low. Yet, removals are obviously larger when crop yields are high, and have to be compensated eventually.

Table 3 lists the average prevalence of elements in the earth's crust. The figures are crude estimates but their magnitude and variability seems in agreement with other estimates in the literature. From the last column of this table makes we can calculate for selected elements, the average nutrient presence in the soil, for an average bulk density of 1.2. On this basis, the 20 cm topsoil of 1 hectare of land will contain 2,520 kg of phosphorus. Inclusion of the subsoil up to 50 cm results in 6,300 kg of P per hectare. Assuming that per ton of cereal 3.5 kg of P is removed from the land, never to return, a 5 ton crop removes 17.5 kg and theoretically the P in the soil could last for 360 years, and obviously, for double-cropping the figure drops to 180 years. Similar calculations for Zn show that the first 50 cm of soil contain 420 kg of Zinc, on average. Removal per ton is estimated at 0.03 kg only and theoretically the quantities present could sustain 2800 years a 5 ton crop for single-cropping. Next, we can compare the quantities of mineral nutrients in the upper 50 cm of presumably cultivable soils with the quantities in the mineable reserve base. It appears that soil P is almost equal to the quantity of possibly mineable phosphate rock and soil Zn is about 8 times the potentially mineable Zn.

However, the absolute total level of essential mineral nutrients present in soils would seem to be optimistic since most cannot be accessed by plants. These mineral nutrients have different forms (chemical bonds) as well as different pools (e.g. in soil water, organically bound, or adsorbed to clay particle). Soil chemistry analysis can establish total and available nutrient levels. Not surprisingly, crop yields tend to respond most to addition of a scarce input and the effect gradually vanishes with rising application. Table 4 shows 'available' values for P, Cu, Zn and Fe in topsoils and subsoils of the Angonia district in Mozambique, a region with very large variations in soil parent materials, resulting in entirely different soils. Moreover, the soil samples were taken in 1978 when there was little industrial activity in the neighborhood and fertilizers had not been used yet. The data thus represent a large variation of natural fertility levels, and their means and ranges seem in accordance with observations made elsewhere. It appears that of 1,000 ppm total P only about 20 are available in the topsoil and about 10 in the subsoil. With respect to micronutrients almost all observations are below 5 ppm and average levels are in the order of 1 to 2 ppm. Hence the top 50 cm of one hectare contains only 93, 4.5 and 8 kg of available P, Zn and Cu, respectively, sufficient for a 5 ton cereal removal for 5, 30 and 276 years, respectively, illustrating that in the absence of fertilizer application, continuous cropping and removal of high yields in the case of P and Zn can only be sustained for a short period of time.

Two sources of readily available micronutrients exist in soils: nutrients that are absorbed onto soil colloids (very small soil particles) and nutrients that are in the form of salts dissolved in the soil solution. Organic matter is an important secondary source of some microelements. Most elements are held tightly in complex organic compounds and may not be readily available to plants. However, they can be an important source of micronutrients when they are slowly released into a plant available as organic matter decomposes. The chemical behavior of metals is primarily governed by retention and release reactions with the soil matrix. The soluble behavior of Zn, Cu, and many other microelements varies from soil to soil and is influenced by soil properties, such as Ph, organic matter content, clay and iron oxide content. Of these, soil Ph is often found to have the largest influence, due to its strong effect of solubility and speciation of metals. Sanders et al. (1986) found that each unit decrease in Ph results in approximately 2-fold increase in the concentrations of metals such as Zn, Ni and Cd in soil solution. The specification process thus affects metal availability to plants and leach ability to ground and surface waters.

Besides absolute levels of essential mineral nutrients in the soil, relative proportions matter as well, and in a complex way in some cases synergetic, in others antagonistic. A well-known antagonism is that high P levels in the soil induce Zn deficiency, and vice-versa.

While bilateral relationships have been depicted, much less seems to be known about the substitution between multiple essential nutrients present in the soil but in qualitative sense some interrelationships are well established, such as the fact that both manganese and molybdenum are needed for the assimilation of nitrates by plants. There are mutually beneficial effects of phosphorus and molybdenum. For some plants, zinc and phosphorus are needed for optimum utilization of manganese. Copper utilization is favored by adequate manganese which in some plants is assimilated only if zinc is present in sufficient amounts. Excess copper may adversely affect the utilization of molybdenum. Iron deficiency is encouraged by an excess zinc, manganese, and copper. Excess phosphate may encourage a deficiency of zinc, iron and copper. Heavy nitrogen fertilization intensifies copper deficiency. Excess sodium or potassium may adversely affect manganese uptake. Iron, copper, and zinc may reduce the absorption of manganese, and so on.

The interrelationships also depend on the presence of resource pools. For instance, it may be suspected that compensating transfers will occur between the different pools but the documented evidence on the topic is scarce and inconclusive (Ma, 2009). Furthermore, crops can obtain scarce nutrients through a mutualistic relationship with mycorrhizeae (soil fungi) whereby the plant feeds and links to the fungus with assimilates in return. Such fungi have access to a larger volume of soil than plant roots and can also access nutrients from pools that are unavailable to higher plants.

In sum, the total amounts of essential mineral nutrients present in soils vary with the type of parent material in which they have developed, the soil formation history and land use in the past. Of the available stocks, little is available to the root zone of plants. Persistent cultivation with high yields inevitably leads to soil nutrient deficiencies including micro-nutrients, even though requirements are minor. Hence, maximal recycling of crop residuals is necessary, and fertilizer application eventually has to fill the gap, which takes us back to the availability of mineral deposits.

5. Scarcity of essential mineral nutrients for fertilizer production

The present section reviews the reserves and possible scarcity of minable resources, which is of deposits of much higher concentration than ordinary soils. Table 2 presents for a number of essential plant nutrients the reserves, the reserve base, annual production/consumption and the years left of reserves at current consumption levels (please note that quantities are expressed in different units; Source USGS, 2006). Reserves are identified and considered economically exploitable with current technologies and price levels. The reserve base consists of projected resources and those identified but not economically exploitable with current technologies and price levels. Nitrogen is not included in Table 2, since it is not mined and derives from atmospheric sources in which it is amply available. Future availability depends on stocks of natural gas which are large, but energy scarcity may result in considerable price hikes in the cost of production. Reserves of mineable Ca and S not given, but these are very large. Reserves and reserve base of Phosphate rock include large quantities (25-30 percent in Table 2) in China that are suspected to be low grade ore (i.e. have a low percentage of P_2O_5). Cobalt is included in Table 2. While not considered as an essential plant nutrient, it is essential in animal nutrition and is also required for biological nitrogen fixation by legumes. Table 2 relies on the US Geological Survey, the only comprehensive source of information. We note that the underlying data are supplied by countries that supply a particular mineral nutrient and might, therefore, be less reliable as the information may be price sensitive and hence strategic. Here also we focus on P and Zn.

Phosphorus

Table 2 shows that the largest quantity of a mined essential mineral nutrient produced refers to phosphate rock. Phosphate rock is almost entirely (95%) used for the production of fertilizers. Other uses include detergents, food additives and industrial applications. At current production levels, the reserve available would last over 100 years. If no new easily and cheaply mineable reserves can be identified, this reserve will at current prices be depleted within 50 and 100 years from now, since demand is rising. Higher prices would reduce the pace of expansion but as was mentioned in the introduction, drivers such as biofuel would have the opposite effect.

For a significant part of this reserve base, mining is expensive with current technology if not impossible. In addition, outside the oceans the ore mostly is of lower grade, and often contains high concentrations of for instance Cadmium and Uranium that would contaminate the food chain. Removal of these toxic elements is possible but at high cost. Regarding oceans, large phosphate reserves have been identified on continental shelves and sea mounts but they cannot be disclosed economically, with current technology, and mining would presumably have significant impact on marine ecology.

Another issue of concern would be that spatial distribution of present, land-based mines is highly uneven, with about 60 percent concentrated in Morocco and Western Sahara, and China. This has geo-political as well as economic implications; witness the fact that China already levies a 135 percent export tax on phosphate rock (Cordell et al., 2009) thus virtually banning exports.

Zinc

Major uses of Zinc are outside agriculture. For instance, in the USA, about 75 percent is by steel companies. Besides agriculture, the chemical, paint and rubber industries are significant users. Agriculture is special because as for other essential nutrients, substitution to other substances is not an option, as it is essential in plant, animal and human nutrition. There is some recycling but in all including the non-recycled disposal only 30 percent of Zinc is kept in a form that might be reused (Gordon et al., 2006) as the remainder undergoes effectively irreversible transformation, say for galvanizing iron.

Zinc, unlike phosphate rock, has widely spread deposits worldwide. Here the concern is, however, that its global mineable reserve is currently estimated at only 220 million tons which, at current consumption levels, would be sufficient for 22 years only, against total identified zinc resources in the order of 1.9 billion tons, which again seems problematic particularly in view of the 70 percent loss in industrial processes.

Other essential mineral nutrients

Table 2 also shows that for micronutrients reserves are particularly low. This is worrying because these mineral nutrients have applications other than agriculture e.g. Copper in electrical systems, with a fast rising demand particularly for solar cells. Moreover, it has become increasingly evident that micro-nutrient deficiency may put a major constraint on crop yields, and that soil nutrient deficiencies are often transferred to human deficiencies (e.g. Voortman et al.., 2003; Yang et al., 2007). These deficiencies may in part be attributable to high macro-nutrient applications to which we now turn.

6. Fertilizer practice and consequences for the availability of essential nutrients

The Asian Green Revolution that enables crop yields of rice, wheat and maize to rise spectacularly primarily relies the application of large dosages of N, P and K fertilizer jointly with the introduction of improved varieties that are responsive to these inputs. However, evidence is mounting that currently available technologies will not be able to sustain high yield levels in the long run.

For instance, Ladha et al. (2003) report for 33 long-term experiments (mostly in India but also from Bangladesh and China) that rice yields stagnate in 72 % of the locations and actually decline in 22%. For wheat these figures are 85% and 6%, respectively. Aggarwal et al. (2004) also observe declining productivity trends in the Indo-Gangetic plains even with application of N, and k fertilizers and modern farm management. Furthermore, Biswas and Benbi (1997) show for the Punjab in a 20-year experiment that yields of maize gradually decrease. Recently, it was calculated that average rice yields in the Indo-Gangetic plain decreased 41 kg $ha^{-1}yr^{-1}$ (Tirol-Padre and Ladha, 2006). At the same time, the use of mineral N and P is often highly inefficient. For instance, of the N applied in irrigated rice systems in Asia only 31 % is harvested with the crop (Cassman et al., 2002). The efficiency of P use is at similar or even as low as 10% (Baligar et al., 2001). Zhu and Chen (2002) further observe a positive relation between annual N use and food production, but also that the regression coefficient is rapidly decreasing, thus indicating that N becomes less efficient possibly due to decreasing marginal returns. The inefficiency of P is obviously of serious concern because the mineable reserves are finite.

Obviously, high use of N and P also has important environmental effects, such as high emissions of N_2O and NH_3 from farmlands, increased levels of N in groundwater, algal blooms in lakes and red tides in estuaries as reported on China (Zhu and Chen, 2002).

Another consequence of high dose fertilizer applications is the increase of P levels in agricultural soils. For instance in 20 year experiment with rice-wheat in the Indo-Gangetic plain a three-fold increase of available soil P was observed (Kumar and Yadav, 2001). A large scale sampling of soils in South Korea shows that in about 30 years Available P increased 2.5 times on lowland paddy soils and 5-fold on upland soils (Joh and Koh, 2004). One of the reasons for accumulation of applied P is the relative immobility of P in soils.

This is favorable because in this way a scarce resource is conserved in the soil and does not dissipate too much into oceans but at the same time P-accumulation has antagonistic effects on the micro-nutrient uptake by plants, as was mentioned earlier. There is for instance evidence of micro-nutrients becoming scarce in the Indo-Gangetic plains. Zinc deficiency is notably widespread (Aggarwal et al., 2004; Pingali and Shah, 2001). Biswas and Benbi (1997) also show in long-term experiments that high yields could be maintained only with the application of Zn or farmyard manure, which obviously contains micro-nutrients. Chaudury and Nawal (##) demonstrate that continuous application of farmyard manure increases available levels of Zn, Fe, Mn and Cu in the soil. Also in China micro-nutrient deficiencies are wide-spread. About 30-40 percent of the total land surface has micronutrient deficiencies of Zn, Fe, Se, Mo, Cu, Mn, B or separately or in combination, with 2 micronutrient deficiencies for all soils (Yang et al., 2007). These are particularly evident in densely inhabited areas due to a complex of factors, including natural conditions, a long history of intensive cultivation and P fertilizer induced deficiencies. At any rate, continued overdoses of P fertilizer are a certain recipe for yield decline.

Finally, increasing available soil P levels will also affect food quality. Application of P fertilizer generally increases the phytate content of a crop. Phytate is an anti-nutrient that plays an important role in seed germination but cannot be digested by mono-gastric animals such as pigs, chickens and humans. Consequently, most its P-content is excreted directly. Moreover, phytate inhibits the uptake of Zn and may cause Zn-deficiency even for food that contains sufficient Zn. People actually suffer from micronutrient deficiencies in many parts of China and their numbers seem to be increasing rapidly. Among the Chinese population sub-clinical Zn deficiency has reached 50-60 per cent (Yang et al., 2007). Continued overdosage of P fertilizer will reduce food quality and further increase zinc deficiencies in humans.

In sum, in many parts of the world, notably China, soils have become intoxicated with P. This causes environmental problems, it reduces crop yields, lowers food quality and raises human micro-nutrient deficiencies. Moreover, P is a finite resource that cannot be substituted away from as far as human nutrition is concerned, and may become scarce in the near future and its continued application will require the use of essential mineral nutrient which are even scarcer, run out earlier and which have applications outside agriculture.

7. Solutions

The above discussion already hints at the solutions. Supplies are scarce, demand is often excessive, and even where it is moderate significant technology improvements could be envisaged through precision agriculture, so as to fertilize the crop rather than the soil, and by recycling. Closing the cycle of essential mineral nutrients is essential, precisely because they are essential to all life on earth. This is not an easy task because spreading scarce nutrients on land may actually cause their dissipation in soils, groundwater and eventually to the sea, to the extent that they become irrecoverable.

Nonetheless with respect to P various suggestions can be made:

- Abstain from P application on P intoxicated land (actually P mining)
- Do not apply P on P fixing soils (additional benefit conservation of bio-diversity)
- Where P is not fixed and where it is deficient apply soil specific doses that account for the crop requirements and the quantities of P present in the soil.
- Use small and effective doses (timing in relation to crop development, micro-dosing, precision agriculture)
- Reduce losses in the chain from field to fork, which are in the order of 55% (Cordell et al., 2009)
- Recover P from urban human waste and animal waste or use waste directly
- Use ashes from biomass use in e.g. energy production
- Use by-products of agro-fuel production
- Change the geography of production and consumption to reduce the distances to transport waste (large cities on low productive land in the neighborhood of highly productive land)
- Use fertilizer in food and feed exporting areas and waste in importing areas.

In fact the above strategies would apply for all essential mineral plant nutrients, but for those elements that have other than agricultural applications such as Zinc the following points may be added:

- Replace scarce essential nutrients with less scarce elements in non-agricultural uses
- Avoid dissipative uses in non-agricultural applications (e.g. galvanizing iron in the case of Zn)

To become successful in reducing the use of essential mineral nutrients and to close the nutrient cyclus it further seems important to expand existing knowledge as to how soil chemical complexities affect crop yield and nutrient use efficiency:

- Nutrient interactions
- Effect of cation ratios on P and micro-nutrient uptake
- Ways and means to change non-available nutrients in the soil into available forms
- The role of mycorrhizeae
- Non-Rhizobia nitrogen fixation

8. Challenges in China

So far, reference was repeatedly made to China, for obvious reason. China not only is the most populated country in the world, with the largest agricultural supply and demand by far, it also has a very high population density of 10 persons per hectare of arable land. While its population growth has been slowing down significantly due to the one-child policy and numbers are even expected to drop by the middle of this century, also as a result of this fast transition, the fast urbanization and industrialization process is taking its toll of arable land. And if there is any country where demand for livestock products has been rising fast and is expected to continue doing so, then China. This rising pressure on agricultural land makes it, quite understandable that Chinese authorities have refraining on large expansion of agriculture-based biomass production of energy, beyond the inefficiency of available technologies themselves.

Closer to the subject of this paper, China has been able to achieve its impressive successes in feeding its people, and with some feed imports, its fast rising livestock as well, only thanks to high yielding technologies, and high fertilizer dosage, primarily NPK both organic and chemical, while micronutrients are primarily being recycled from organic matter consisting of manure, night soil, and crop residuals. We have seen that phosphorus application was particularly high, causing loss of micro-nutrient content and effectiveness, of zinc and copper in particular. We also noted that China is the world second largest producer of P, but that it keeps most of its production within its borders, by levying 135 per cent export tax. This in itself is illuminating as it foretells what may happen in the future in other parts of the world as major mineral deposits run out.

Chinagro simulations

We take a closer look at the nutrient imbalances of N, P and K by consulting the Chinagro welfare model, a geographically detailed general equilibrium model that comprehensively depicts China's farm sector in 2433 of its counties, while connecting these through trade and transportation flows to each other, to urban and rural consumers and to abroad (Keyzer and van Veen, 2005; Fischer et al, 2007). As indicated in Figures 1 and 2, simulation with this model shows excessive application of N and P while the balance for K is negative, implying that K is being mined. The findings on these nutrient balances are confirmed by the literature (## reference).

Frequently observed environmental problems corroborate these findings: ground water polluted with N and eutrophication of surface and coastal waters by P. The high level of 60% of Chinese children being sub-clinical Zn deficient may possibly in part be explained by the high doses of P applied causing Zn deficiency. The main challenge for China is therefore to develop optimal fertilizer mixes, which can sustain high crop yields of good quality food.

9. Conclusions

Emerging scarcity of essential mineral nutrients should be a major source of concern to policy makers worldwide, for various reasons.

1. Being essential to all life on Earth, these nutrients can not be substituted for.
2. Being mineral these resources are non-renewable, albeit that their recycling is farmers core business and has been since mankind engaged in agriculture.
3. The fraction that does not remain in arable topsoils and is not returned is virtually lost forever, since it no longer is accessible to the root zone of crops and present in concentrations that are too low to be economically recoverable.

4. For some of the nutrients the ratios of mineable deposits over present use have reached surprisingly low, plainly alarming levels.
5. This is all the more disturbing as mineral deposits are very unevenly distributed around the world, particularly for P, and are likely to become cause of international tensions.
6. In recent years, significant additional claims for these resources have been emerging from rising demand for energy from biomass, and the demand will only become stronger as because biomass production is to take place on lands of lesser quality.
7. In some parts of the world, notably China, current intensity of mineral nutrients application seems to have reached levels where it becomes counterproductive, often even toxic through its negative impacts on micro-nutrients, and its emissions ground and surface water (for N and indirectly, methane, also in the air).

Hence it would seem that priority should be given to reduced application, precisely targeted to the plant's root zone, and to maximal recycling.

The simulation exercise for the nutrient balances in China indicates that significant savings on N and P are possible, while K has application would have to be increased. More balanced fertilizer mixes are likely to sustain high yield level, while avoiding environmental problems.

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Table 1. Essential mineral nutrients in plant and human nutrition

Nutrient	Plants [1)]	Humans [2)]	Nutrient	Plants [1)]	Humans [2)]
Phosphorus	+	+	**Cobalt**	±	+
Potassium	+	+	**Chromium**	-	+
Sodium	±	+	**Boron**	+	-
Calcium	+	+	**Molybdenum**	+	+
Magnesium	+	+	**Nickel**	±	(+)
Sulphur	+	+	**Aluminium**	±	-
Manganese	+	+	**Chlorine**	±	+
Iron	+	+	**Iodine**	-	+
Zinc	+	+	**Silicon**	±	+
Copper	+	+	**Selenium**	±	+

[1)] ‘+’:essential; ‘-‘: not required; ‘±’ :essentiality not established, but considered beneficial
[2)] ‘+’:essential; ‘-‘: not required; ‘(+)’: essentiality not established, but possibly required
Source: Nubé and Voortman, 2006; based on Marschner 1995 ; Garrow et al, 2000; Wiseman, 2002.

Table 2. Presence of elements in the Earth's crust according to 5 sources

Oxygen	O	46.60%	47.40%	46%	46.71%	46.10%
Silicon	Si	27.72%	27.71%	27%	27.69%	28.20%
Aluminum	Al	8.13%	8.20%	8.20%	8.07%	8.23%
Iron	Fe	5.00%	4.10%	6.30%	5.05%	5.63%
Calcium	Ca	3.63%	4.10%	5.00%	3.65%	4.15%
Sodium	Na	2.83%	2.30%	2.30%	2.75%	2.36%
Potassium	K	2.59%	2.10%	1.50%	2.58%	2.09%
Magnesium	Mg	2.09%	2.30%	2.90%	2.08%	2.33%
Phosphorus	P	0.12%	1000 ppm	1000 ppm	1300 ppm	1050 ppm
Manganese	Mn	0.10%	950 ppm	1100 ppm	900 ppm	950 ppm
Sulfur	S	0.05%	260 ppm	420 ppm	520 ppm	350 ppm
Chlorine	Cl	0.05%	130 ppm	170 ppm	450 ppm	145 ppm
Chromium	Cr	0.01%	100 ppm	140 ppm	350 ppm	102 ppm
Nickel	Ni		80 ppm	90 ppm	190 ppm	84 ppm
Zinc	Zn	trace	75 ppm	79 ppm		70 ppm
Copper	Cu	0.01%	50 ppm	68 ppm		60 ppm
Nitrogen	N	0.01%	25 ppm	20 ppm		19 ppm
Cobalt	Co	trace	20 ppm	30 ppm		25 ppm
Boron	B	trace		8.7 ppm		10 ppm
Molybdenum	Mo	trace	1.5 ppm	1.1 ppm		1.2 ppm
Iodine	I	trace	0.14 ppm	0.490 ppm		0.450 ppm
Selenium	Se	trace	0.05 ppm	0.05 ppm		0.05 ppm

Table 3. Available P, Cu, Zn and Fe in the topsoil and subsoil of soils in Angonia district, Mozambique (values in ppm; tr = traces or practically 0).

Variable	N	Mean	Std Dev	Minimum	Maximum
P (topsoil)	115	21.7	23.7	tr	109.00
Cu (topsoil)	114	1.5	1.1	0.08	6.24
Zn (topsoil)	114	1.0	0.5	0.22	2.84
Fe (topsoil)	114	2.2	1.3	0.70	6.40
P (subsoil)	111	11.5	27.7	tr	192.00
Cu (subsoil)	111	1.3	1.3	0.04	7.96
Zn (subsoil)	111	0.6	0.3	0.16	2.00
Fe (subsoil)	111	1.1	1.1	0.30	9.00

Source: Unpublished basic data, Voortman.

Table 4. Mineral nutrient resources: reserves, consumption and years left at current consumption levels in 2006

Element	Formula	Unit	Reserve	Reserve base	Production 2006	Years left on reserve	Years left on reserve base
Macro-meso-nutrients							
Phosphate rock	variable	1000 tons	18,000,000	50,000,000	145,000	124	345
Potash	K_2O	1000 tons	8,300,000	17,000,000	30,000	277	567
Magnesium	Mg	1000 tons	2,200,000	3,600,000	4,050	543	889
Micro-nutrients							
Boron	B_2O_3	1000 tons	170,000	410,000	4,750	36	86
Cobalt	Co	1 ton	7,000,000	13,000,000	57,500	122	226
Copper	Cu	1000 tons	480,000	940,000	15,300	31	61
Iron	Fe	million tons	160,000	370,000	845	189	438
Manganese	Mn	1000 tons	440,000	5,200,000	11,000	40	473
Molybdenum	Mo	1 ton	8,600,000	19,000,000	179,000	48	106
Zinc	Zn	1000 tons	220,000	460,000	10,000	22	46
Possibly essential							
Nickel	Ni	1 ton	64,000,000	140,000,000	1,550,000	41	90

Observations:
-Reserves are identified and considered economically exploitable with current technologies and price levels
-Reserve bases are expected resources and those identified but not economically exploitable with current technologies and price levels
-Reserves of essential mineral nutrients Ca and S not given but these are very large
-Reserves and reserve base of Phosphate rock include large quantities (25-30 percent) in China that are suspected to be low grade ore i.e. have a low percentage of P_2O_5.
-Cobalt is not considered as an essential plant nutrient, but is essential in animal nutrition and is also required for biological nitrogen fixation by legumes.
Source USGS, 2006.

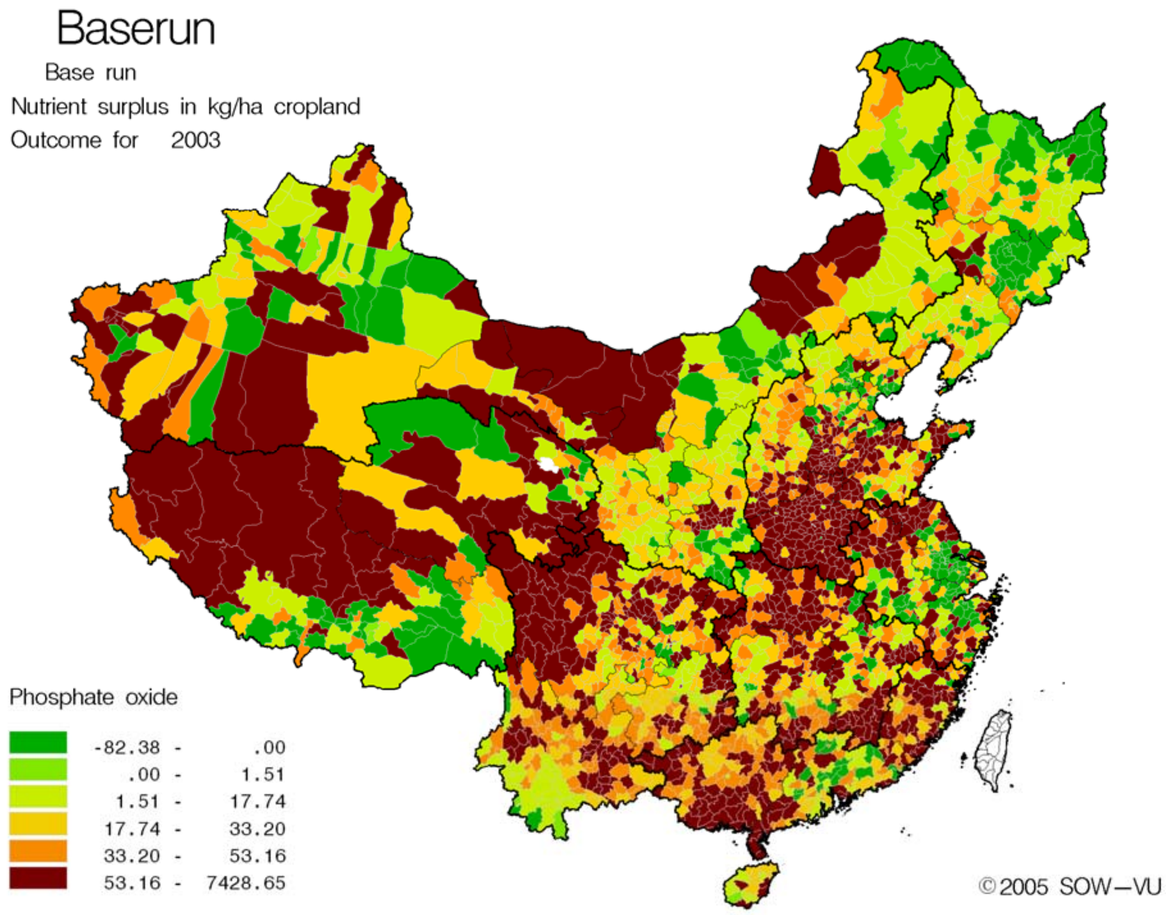

Figure 1. County level P balances in Chinese agriculture (the spatial patterns for N are similar)

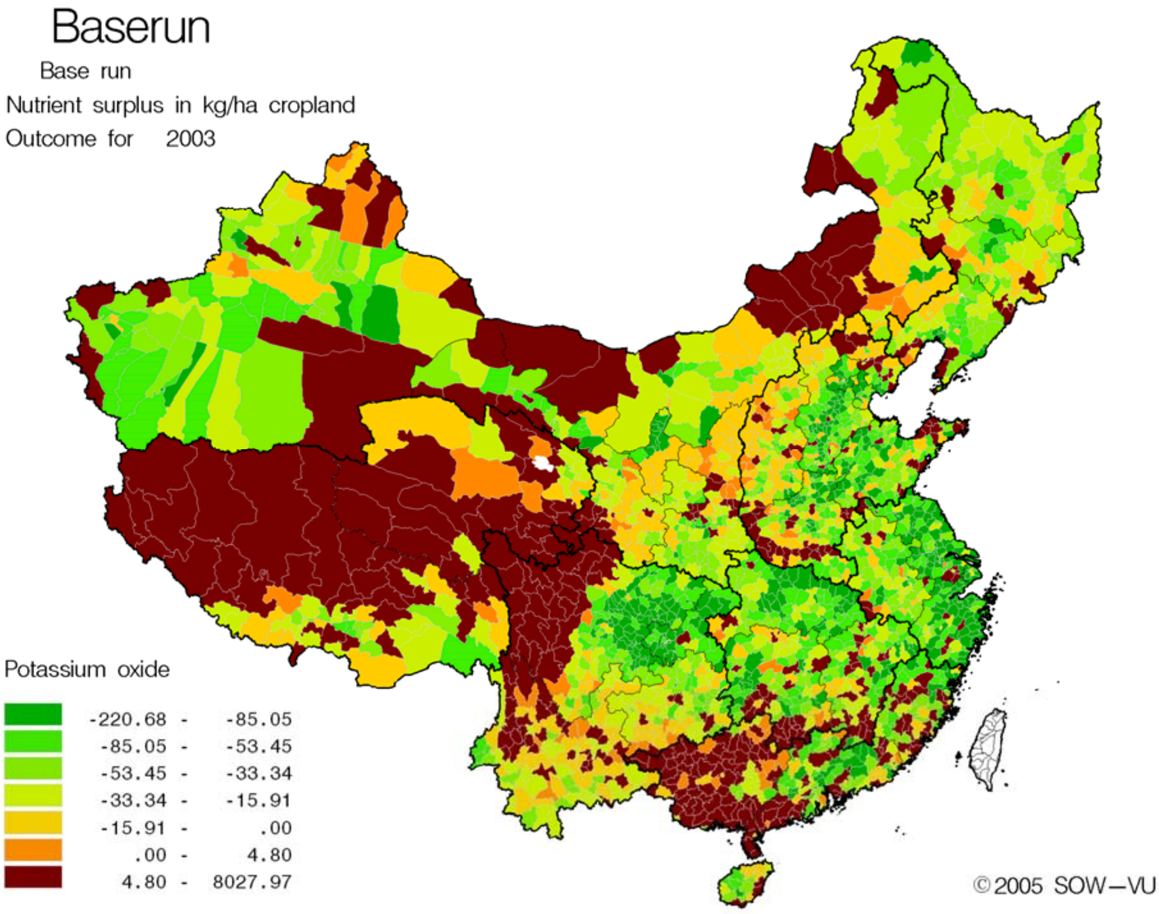

Figure 2. County level K balances in Chinese agriculture