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

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Abstract

'Life can multiply until all the phosphorus has gone and then there is an inexorable halt which nothing can prevent'

Isaac Asimov

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 balances 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 is insufficiently applied 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

Quit a number of mineral nutrients are essential for life on earth (Table 1). These nutrients affect growth, functioning and health of plants, animals and human beings. Generally the growth of living creatures is retarded and disease symptoms may develop, if uptake of these essential minerals falls short of requirements. Some nutrient deficiencies may even cause mental retardation in humans (Hetzel, 1983). The amounts of essential nutrients needed for life to function properly vary with the type of nutrient and the life form concerned. Some nutrients are usually needed in relative large amounts: e.g. Phosphorus (P), Potassium (K), Calcium (Ca). Others, the so-called micronutrients, are needed in very small amounts only, but are nonetheless essential: e.g. Zinc (Zn), Copper (Cu), Boron (B), Molybdenum (Mo). Because of the effect essential mineral nutrients can have on plant growth, some of them, such as Phosphorus, are already extensively used in agriculture as fertilizers so as to sustain high crop yields. Others, such as Zinc, are currently mainly used in non-agricultural applications, but increasingly also micronutrient deficiencies are expected and reported in agriculture (refsVoortman et al., 2003). Because of the size of the populations of the countries where such deficiencies have been observed, like China and India, a rise of demand for the agricultural use of micronutrients must be expected. However, the globally available resources of these essential mineral nutrients are limited and there are many competing uses other than food production. In fact, every element of the F6 complex of rising worldwide demand for food, feed, fuel, fibre, forestry, fisheries directly or indirectly points towards rising demand for fertilizer nutrients (adding the 7th F). Among these fertilizers, the essential mineral nutrients P, K and micronutrients require particular attention, because unlike Nitrogen, which can be obtained from the atmosphere, they have to be mined from finite reserves as present in the crust of the earth.

Two further contextual observations are in place here. On the negative side, mineral nutrients are essential to all life and, therefore, possess the distinct feature that no technological progress will ever make it possible to replace them. Unlike fossil fuels, which can eventually be replaced by substitutes such as solar, tidal, and wind energy, such opportunities will not exist. On the positive side, 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, mineral nutrient cycling is one of the most basic reproductive cycles on Earth.

The possibility of future mineral nutrient scarcities and their potential impacts on life on Earth has received very little attention in the literature, if compared, say, with the possible impacts of climate change. Most attention has been given to Phosphorus, a mineral nutrient which is almost exclusively used in agriculture (Asimov, 1974; refs). However, as will be shown in the following, for a number of micronutrients, with competing uses, the situation is far more precarious, while depletion of available resources can be expected in the very near future. This paper, therefore, intends to sketch a perspective on potential nutrient scarcities and the need to use and re-cycle them effectively.

Overview

In this paper we first sketch what the essentiality of mineral nutrients entails. This is followed by an assessment of the factors which will increase the demand for biomass, and, consequently, the increasing demand for mineral fertilizers to be expected. Next the level of essential mineral nutrients in soils and their availability for plant uptake is inventoried. On this basis we calculate how long soil supplies of essential mineral nutrients could possibly sustain annual cropping. We further highlight many uncertainties on these issues, which simply exist because of lack of knowledge on the functioning of soil ecosystems. Next we inventory the mineral resources available for fertilizer production and how long these will still be available under various assumptions. Thereafter we discuss current fertilizer practice with emphasis on the Green Revolution areas in Asia and present a case study on China. Particular emphasis is on the efficiency of fertilizers and the impact of residual fertilizers on essential mineral nutrients that are not applied with them. We end with discussing the various strategies available to deal with increasing scarcity of essential mineral nutrients.

2. The essentiality of mineral nutrients

Life on Earth requires minimal levels of essential mineral nutrients to function properly. Below such levels we speak of deficiency, which finds expression in various symptoms. At the same time, consumption of too high levels of essential mineral nutrients also affects growth and health (toxicity). In essence, to lead a healthy and productive life, humans need a balanced supply of essential mineral nutrients. The same applies to plants and when uptake of one or more nutrients from the soil is restricted their physiology is equally disturbed and nutrient-specific diseases develop. Ultimately the plant may die or reproduction may be affected, causing lower economically useful yields in the case of crops. Table 1 presents an overview of essential mineral nutrients for plants, animals and humans. To illustrate the essentiality of mineral nutrients we restrict ourselves to 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).

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 their protein content is low (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 source quoted in Alloway, 2009).

These examples of P and Zn clearly demonstrate what essentiality entails and what deficient intakes of essential mineral nutrients may cause. All other essential mineral nutrients in Table 1 perform many functions, which are equally vital for the physiological functioning of plants and animals. None of these essential mineral nutrients can be substituted.

3. Rising demand for biomass and essential mineral nutrients

Various developments are expected to raise global demand for biomass and, consequently, essential mineral nutrients. 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. This population growth itself, requires increased food production simply to meet nutritional standards. At the same time, rising incomes in developing countries will lead to higher demand for biomass and mineral nutrients. First, increasing affluence in these countries is likely to directly increase demand for minerals such as copper. Second, the demand for livestock products is expected to increase and, consequently, for animal feeds as well. However, the transformation of feeds into meat is rather inefficient (Tilman et al., 2002). To meet the increased demand for food and feed 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 bio-ethanol and biodiesel from food and feed crops, albeit so far only with lavish subsidies. The future production of bio-fuels is likely to compete 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 needed to achieve the required increases in biomass production, notably with respect to mineral nutrients.

Naturally agricultural production can be increased through area expansion as well as through improved yields per hectare. Increasing yields on already cultivated land is likely to require higher input levels, thus increasing demand for mineral nutrients. With respect to area expansion, there are large land areas which currently are not used or where rather extensive modes of use prevail (ref). In part, the land involved may have over-ruling constraints like too low temperatures, insufficient rainfall, steepness, shallow soils, stoniness and rockiness and chemical constraints such as severe salinity. Another part may have potential for production of biomass. However, it is natural to suspect that these lands with possibly some cultivation potential are of a lower inherent quality if compared to those lands already used for cultivation (e.g. Young, 1999). It is, therefore, likely that currently unused soils, when taken into use, require higher doses and/or a broader array of fertilizer nutrients to achieve satisfactory yield levels. This obviously affects the profitability of their use and may be a driver for increased food and feed prices. However, no matter what option is pursued, demand for mineral nutrients is very likely to increase.

With respect to bio-fuels, its advocates tend to concede that current generation bio-fuels indeed do compete with food and feed for land and inputs. But, they expect technological change in bio-fuel production using so-called second generation feed stocks. Such technologies would make it possible to harvest and use biomass, ranging from desert shrubs, to tall savannah grasses and tropical forests, from land unsuitable to grow food and feed crops. The impression is created that in this way competition for land and inputs can be avoided. This may be the case for instance in remote areas where small scale bio-fuel production takes place to satisfy local demand and where rest products, containing the essential mineral nutrients, are also locally re-cycled. However, large scale bio-fuel production has particular requirements. To be effective as little as possible energy should be used in producing the bio-fuel. To achieve the required efficiency, large volumes of biomass need to be produced in the proximity of a production plant, so as to ensure the minimization of energy losses for instance in transportation of the feed stock. This principle is precisely the reason why ethanol production from sugarcane in Brazil is particularly efficient. Obviously, the production of biomass with large yields in short distances requires good soils and fertilizer inputs. Therefore, large-scale bio-fuel production can be expected to compete for land, labour and inputs, inorganic fertilizers.

With respect to nutrient cycling, however, there may be some promising opportunities in the case of large scale bio-fuel production, again provided some requirements are met. In essence the bio-fuel product consists of carbohydrates only. Therefore, the rest product, containing essential mineral nutrients can be used to replenish soil fertility on the harvested land, thus closing the nutrient cycle. However, such options are viable only if processing the residuals and transportation to the field do not compromise the balance of energy produced and used. With respect to harvesting biomass from marginal land, first of all it must be considered that net primary production is usually low under such conditions. It is therefore unlikely that the requirement for short distances between processing plant and location of feedstock production can be met. Moreover, also on marginal land the principles of production ecology apply: without replacing the nutrients exported from the land with the feedstock, yields will inevitably decline with time. Also, because of the larger distances involved in this mode of bio-fuel production, the recycling of nutrients is likely to earlier compromise the balance of energy gains and expenses. A potential solution could consist of mobile processing plants, whereby rather than the feedstock, the fuel is transported, while nutrients can be immediately locally re-cycled. Such technologies are currently not even envisaged.

4. Mineral nutrient stocks in cultivable soils and factors affecting their availability

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.

Table 2 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 we 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 total stock of mineral nutrients in the upper 50 cm of land area of the earth 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 sketches too optimistic a picture of stocks and the duration that cultivation would be possible, since most of the total soil content cannot be accessed by plants. These mineral nutrients have different forms (chemical bonds) and are present in different pools (e.g. in soil water, organically bound, or adsorbed to clay particle). For the same plant nutrient various methods of soil analysis exist and it has been empirically established which method approximates best the level of what is available to plants. Table 3 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 in short distances. Moreover, the soil samples were taken in 1978 when there was little industrial activity in the neighbourhood 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. Thus, in the case of P and Zn, continuous cropping and removal of high yields can only be sustained for a short period of time.

Above, only absolute levels of total and available essential mineral nutrients in the soil have been considered to calculate the nutrient supplying power of soils. However, the relationship between plant growth and soil chemical properties is considerably more complex. For instance, the actual uptake of a particular nutrient may be influenced by the levels of other nutrients present in the soil. Such relationships may be synergetic as well as antagonistic (Landon, 1991). A well-known antagonism is that high P levels in the soil induce Zn deficiency, and vice-versa. Such interactions can be considered by using the ratios between individual nutrients, but little is known on how these need to be interpreted within the context of the overall chemical constellation of soils. Another knowledge gap refers to the relationships between the different pools in which the nutrients are present in the soil. In other words, to what extent are nutrients removed with crops from the available pool replaced from the unavailable pools. To address this issue obviously requires long-term dedicated research which unfortunately is scarce. Ma (2009) shows in the long-term asymptotic decreases of available nutrients, but some of the findings can also readily be explained by linear decreases. These findings indicate that either nutrients removed from the available pool are not replaced from other pools or that some replacement takes place, but only when the available pool is already very low. Under such conditions, crop yields have already substantially declined compared to the original levels. Another mechanism involved in nutrient acquisition by plants is the mutualistic relationship between higher plants and mycorrhizeae (soil fungi). The fungus can supply the higher plant (crop) with water and nutrients that are in short supply, while in return receiving assimilates from the higher plant. The workings of the mutualism have two aspects. First, the mycelia of these fungi have access to a much larger volume of soil than plant roots and, therefore, have access to a greater portion of the plant available nutrients. Second, the fungi have a capability of taking up nutrients from pools unavailable for higher plants. The mechanisms involved are also not well understood, certainly not under field conditions, where mycorrhizeae research is difficult to conduct. Moreover, it has been shown that fertilizer application may negatively affect prevalence and functioning of mycorrhizeae. Clearly, nutrient antagonisms, equilibria between nutrient pools in the soil and the role of mycorrhizeae in plant nutrition in crop production under field conditions are important issues requiring further research. Currently our knowledge is insufficiently developed to allow any generalized quantitative statements on these mechanisms involved in nutrient acquisition by crops.

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. The portion of these nutrients that is actually plant-available is a very modest portion of the total amount present in the soil. Persistent cultivation with high yields inevitably leads to soil nutrient deficiencies including micro-nutrients, even though plant requirements for the latter are minor. Achieving high yields under permanent cultivation can be prolonged somewhat by recycling of crop residues, but inevitably mineral fertilizers have to be applied eventually, and this takes us to the reserves of essential nutrients present in mineral deposits.

5. The scarcity of essential mineral nutrient stocks for fertilizer production

The present section reviews the reserves and possible scarcity of minable resources, that is of deposits of much higher concentration than in ordinary soils. Table 4 presents for a number of essential plant nutrients the reserves, the reserve base, annual production/consumption and the years left of reserves as well as reserve bases 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 is larger and consists of projected resources and those identified but not economically exploitable with current technologies and price levels the figures include reserves). Nitrogen is not included in Table 4, 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 4) 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 4. 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 4 relies on the US Geological Survey, the only comprehensive source of information. We note that the underlying data are supplied by countries that produce a particular mineral nutrient and they 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 4 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 of phosphorus use but as was mentioned in the introduction, drivers such as bio-fuel would have the opposite effect.

The reserve base of phosphate rock is not mineable with current technology or too expensive to mine and, in addition, the land based reserve base is mostly a lower grade ore with less P content. Moreover, the reserve base beyond the reserves is likely to have higher concentrations of for instance Cadmium and Uranium which could contaminate the food chain. Removal of these toxic elements is possible but will increase the price of P fertilizers. Large phosphate concentrations have also been identified on the continental shelves and sea mounts in the oceans. However, with current technology these cannot be recovered economically, and mining would presumably have significant impact on marine ecology.

Another issue of concern would be that spatial distribution of present, land-based phosphate rock 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

Zinc is mainly used for non-agricultural purposes. For instance, in the US 75 percent of the consumption is used by steel companies. In addition zinc compounds are used in the chemical, paint and rubber industries and a very minor portion is used in agriculture as fertilizer and feed additive. Depending on the purpose, zinc can be suitably substituted in many ways, except for its use in agriculture again because of its essentiality in plant, animal and human nutrition. Considerable amounts of Zinc are recycled, but the proportion is unclear. It has been estimated that of the cumulative world production of Zn only about 30% is remaining in use (Gordon et al., 2006). The losses are mainly due to dissipative uses such as using Zinc for galvanizing iron.

The global reserve of zinc is estimated at a modest 220 million tons which, at current consumption levels, is sufficient for 22 years only. Total identified zinc resources are in the order of 1.9 billion tons (USGS, 2009). However, it is unclear whether these resources are easily exploitable or not and at what costs. Zinc ores, unlike phosphate rock, occur widely spread across the globe.

Other essential mineral nutrients

From table 4 it is further evident that the reserves of micronutrients are particularly low. This is a cause of concern for two reasons. First, these mineral nutrients have applications other than agriculture e.g. Copper in electrical systems, with a fast rising demand. Secondly, it becomes increasingly evident that micro-nutrient deficiency may put a major constraint on crop yields and that these deficiencies result in human deficiencies as well (e.g. Voortman et al., 2003; Nubé and Voortman, 2006; Yang et al., 2007). These human micro-nutrient deficiencies may be attributable to high macro-nutrient applications to croplands in the past, to which we now turn.

6. Current fertilizer practice as impacting future availability of essential nutrients

In the Asian Green Revolution crop yields of rice, wheat and maize were substantially increased, while primarily relying on the application of large doses 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 on 33 long-term experiments (mostly in India but also from Bangladesh and China) showing 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 mostly lower and may reach levels even as low as 10% (Blake et al., 2000; 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.

The use of high N and P levels has important environmental impacts, 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. Such effects are well known from developed countries, but are now also reported for countries in transition, such as China, where fertilizer use has dramatically increased (Zhu and Chen, 2002). These environmental problems thus directly relate to high fertilizer doses in combination with low efficiencies of their use. Regarding N, Cassman et al. (1998) suggest that farmers probably use high N doses, because recommended levels do not account for N levels present in the soil which can be particularly high under flooded rice. Xie et al. (2007) for instance report an extreme case whereby farmers apply 200 kg N to rice while achieving a yield increase of 300 kg only (not significantly different from the control) and their general conclusion is that N doses can be reduced with 45% without affecting yields. Continuous application of high N doses, without accounting for soil N levels obviously is a certain recipe for N use inefficiency and subsequent environmental problems.

As a consequence of high dose fertilizer applications, P levels also increase in agricultural soils. For instance in a 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). P is relatively immobile in soils, hence the strong tendency to accumulate when applied in excess. Consequently, the rate of P dissipation into oceans is relatively modest and a scarce resource is mostly conserved in the soil, thus remaining available for crop nutrition in the future. However, high soil P levels also cause nutritional problems for plants finding expression in crop yields and nutritional quality of food.

As earlier observed, P accumulation may induce nutrient deficiencies because of its antagonistic effect on the micro-nutrient uptake by plants. Indeed, in the Indo-Gangetic plains micro-nutrient deficiencies are increasingly observed and 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. Chaudhary and Narwal (2005) indeed 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 % of the total land surface has micronutrient deficiencies of one of the following: Zn, Fe, Se, Mo, Cu, Mn, B or a combination suggesting that on average soils have 2 micronutrient deficiencies (Yang et al., 2007). These are particularly evident in densely inhabited areas. Here we cannot discriminate between, natural causes, 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 human food produced by crops. 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 of the P present in phytate is excreted directly. Moreover, phytate inhibits the uptake of Zn and may cause Zn deficiency, even from food that contains sufficient Zn. Indeed, human micronutrient deficiencies are widespread in China and rapidly increasing. Sub-clinical Zn deficiency is in the order of 50-60% among the Chinese population (Yang et al., 2007). Continued application of high doses of P fertilizer is likely to reduce food quality and further increase zinc deficiencies in humans.

In sum, in many parts of the world, arable soils have become intoxicated with P. This causes environmental problems and continuation of this practice is a certain recipe for lower crop yields, lower food quality and increased human micro-nutrient deficiencies. Moreover, P is a finite resource that cannot be substituted in human nutrition while it becomes increasingly scarce in the near future. Continued application of high doses of P will require the use of essential mineral nutrient which are even scarcer, run out earlier and which have applications outside agriculture.

7. Challenges in China; a case study

So far, reference was repeatedly made to China, for obvious reasons. 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 are refraining from large-scale 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 residues. 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.

A simulation exercise with a model for China using a nutrient balance shows country-wide excessive application of N and P, while the balance for K is negative implying actual K mining (Figures 1 and 2). The findings on these nutrient balances are confirmed by the literature. Further evidence of over-use of N and P derives from the environmental problems frequently observed: 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.

8. How to ensure future supply of mineral nutrients for food production?

The long-term sustained production of food, feed and fuel feed-stocks at high yield levels in agriculture essentially requires an effective use of and closing the cycle of essential mineral nutrients. This is not an easy task because spreading scarce nutrients on land may actually cause their dissipation 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 neighbourhood 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 cycles it further seem of paramount importance to improve out knowledge on 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

9. Conclusions and outlook

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, hence rising scarcity could easily become cause of international conflict.
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 because biomass production is to take place on lands of lesser quality.

7. In some parts of the world, as for instance 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 into ground and surface water (for N indirectly as methane and N_2O 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 on the one hand fertilizer resources can be saved (N and P), while other fertilizer types are insufficiently applied (K). More balanced fertilizer mixes are likely to sustain high yield level, while avoiding environmental problems. However, the development of effective nutrient conserving and recycling technologies also requires the development on an integrated body of knowledge on land resource ecology and the role of nutrients and soil organisms herein in relation to plant growth.

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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.

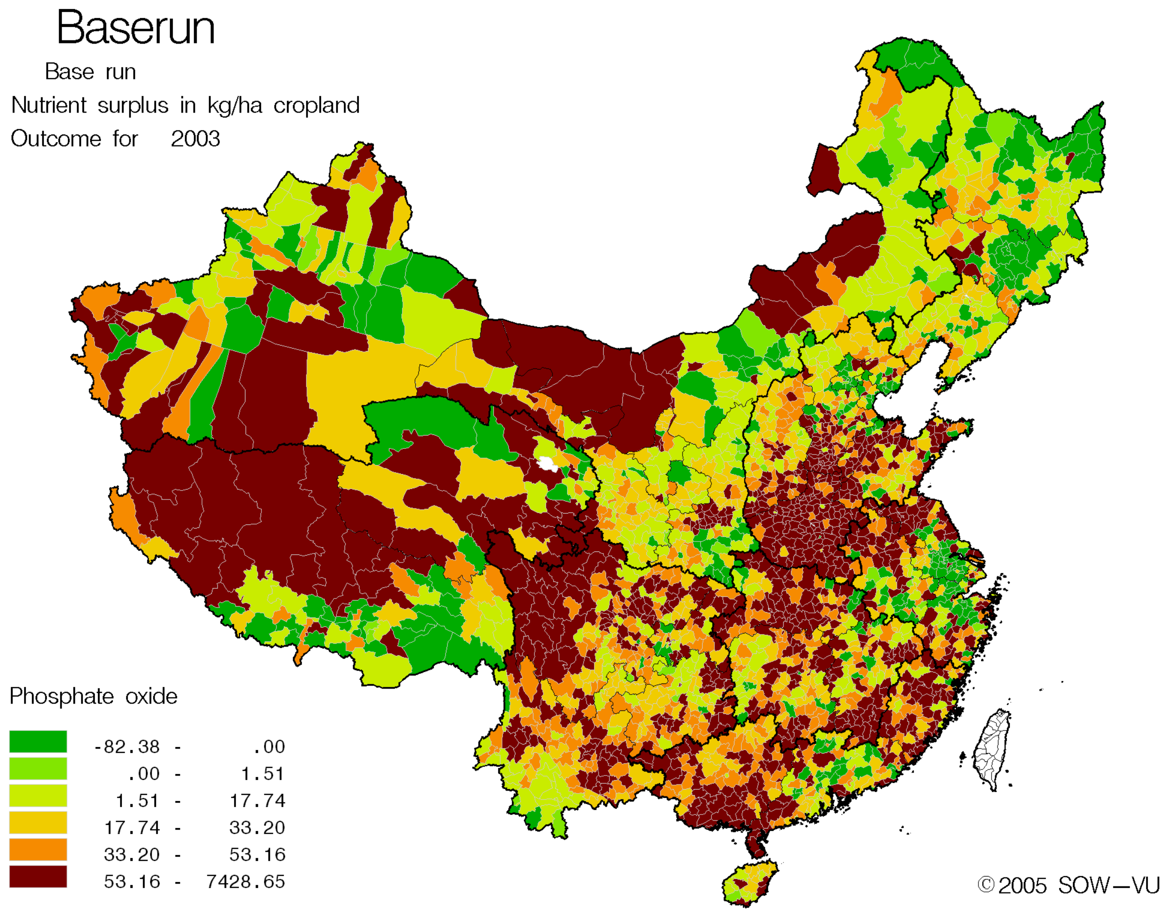

Figure 1. County level P balances in Chinese agriculture (the spatial patterns for N are similar)

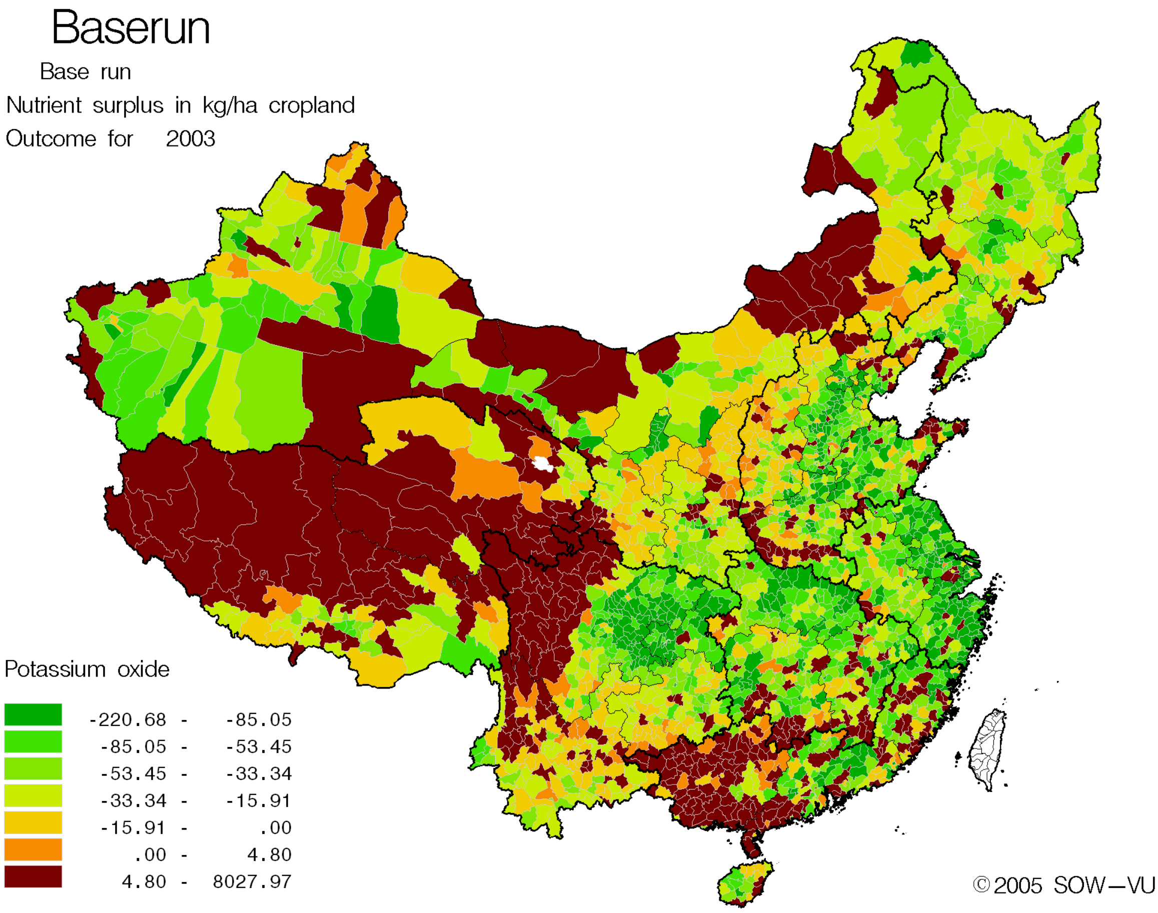

Figure 2. County level K balances in Chinese agriculture