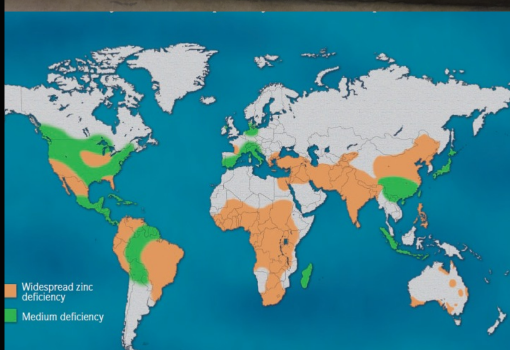
Scarcity of micronutrients in soil, feed, food, and mineral reserves

– Urgency and policy options

Platform Agriculture, Innovation & Society



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Translation: Charles Frink

Photos front cover, clockwise:

Beet leaf showing symptoms of zinc deficiency

Ramelsberg mine near Goslar in the Harz (Germany), which closed in 1988. It primarily produced silver ore, copper and lead.

Cattle showing symptoms of copper deficiency

Copper mine in Arizona

Supplementary feeding of sheep with minerals, including micronutrients

Regions in the world where economically important crops are affected by zinc deficiencies

Photo back cover:

Baby showing symptoms of zinc deficiency

Scarcity of micronutrients in soil, feed, food, and mineral reserves

Urgency and policy options

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Report and advisory memorandum for

the Dutch Minister of Agriculture and Foreign Trade

Platform for Agriculture, Innovation & Society

This memorandum is based primarily on the following background reports:

- Roelf L. Voortman 2012: Micronutrients in agriculture and the world food system – future scarcity and implications. Centre for World Food Studies (SOW-VU), VU University, Amsterdam.

- Ton Bastein and T. van Bree 2012: *Suppletie van micronutriënten vanuit de mijnbouw*. TNO, Delft.

- D.W. (Wim) Bussink 2012: *Micronutriënten in de landbouw en beschikbaarheid in de bodem: focus op koper en zink*. Nutrient Management Institute (NMI), Wageningen.

These background reports were commissioned by the Dutch Platform for Agriculture, Innovation and Society; they have been combined and issued as a separate publication. The literature references in the present report are primarily included in these background studies, unless given in its entirety. All publications can be requested from the Platform and/or downloaded from www.platformlis.nl.

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Summary

Worldwide scarcity of nutrients is likely to occur sooner than generally expected. Such scarcities will have consequences for crop yields, livestock and public health. For the European Union and its member states, these shortages also entail political risks in the form of excessive a dependency on imports from resource-rich countries.

Nutrients

Nutrients can be classified as follows: water, proteins, fats, vitamins, minerals and bioactive substances such as antioxidants. In agriculture, minerals can be applied to the soil as fertilisers. Two main groups of mineral nutrients can be distinguished: macronutrients – such as nitrogen, potassium, calcium, sulphur, magnesium and phosphorus – and micronutrients (or trace elements). The reserves of many of these mineral nutrients are limited.

The present study is about a possible worldwide shortage of micronutrients in agriculture. Its central focus is on the micronutrients that are essential for crops: boron, iron, copper, manganese, molybdenum and zinc. These are needed in much smaller quantities than the macronutrients, but are equally essential for plant growth. In the present study, we emphasize zinc because it is the best-documented micronutrient and because we consider it to be more or less representative of the group of micronutrients. In addition, we pay attention to selenium, which we consider to be representative of micronutrients that are not essential for crops, but are essential for livestock and humans.

The aim of this study was to investigate the impacts of micronutrient deficiencies on crops, livestock and people. Furthermore, we ascertained the urgency of a possible worldwide scarcity of micronutrients in mines: in the near or distant future. The consequences of micronutrient deficiencies for crops, livestock and people were also investigated. Finally, we present proposals for policy, farming practice, industry and research in the Netherlands and Europe.

Scarcity

Besides paying attention to the risks of pollution, sustainability policies are focusing increasingly on scarcity entailing a shift from "too much" to "too little". We discuss three possible forms of scarcity:

- scarcity in the *soil* as nutrients for crops;
- scarcity in *feed or food* (for livestock and humans); and

- scarcity in the *mineral reserves*[1], which can be mined for the production of chemical fertiliser to supplement the naturally occurring nutrients in soil.

Scarcity in the soil

Soil deficiencies of micronutrients that are essential for plant growth can lead to lower crop yields. During the past decade, soil micronutrient deficiencies have been ascertained primarily for zinc, and to a lesser extent for boron and molybdenum. Soil deficiencies of zinc are widespread in Asia (Turkey, India, China and Indonesia), sub-Saharan Africa and the north-western region of South America.

Besides natural causes, micronutrient deficiencies in the soil can also result from over-fertilisation with phosphate. Phosphate can restrict the availability of iron, zinc and copper for crops. As for China, it is expected that a reduction of phosphate fertilisation, combined with zinc fertilisation, will actually lead to a sharp increase in yields. In any case, it is clear that yields do not have to decrease following a strong reduction in the application rates of phosphate fertiliser. Moreover, nutrients interact in other ways. For example, molybdenum is essential for nitrogen fixation by legumes; if legumes are used in the crop rotation scheme, a deficiency of this nutrient can also lead to nitrogen deficiency and thus limit crop yields in two ways.

For selenium, large-scale deficiencies in the soil have been ascertained in parts of Asia and Africa, but these do not necessarily affect crop yields. However, consumption of crops from regions with low soil values for selenium can lead to deficiencies of this mineral in livestock and humans.

Scarcity in feed and food

In human nutrition, zinc deficiency is the most well-known micronutrient deficiency. In large parts of Asia, Africa and South America, zinc deficiency had caused disorders in humans such as retarded growth of children and a multiplicity of metabolic disturbances. It is estimated that one-third of the world population is at risk for zinc deficiency; it is the fifth most important risk factor for disease in developing countries. Worldwide, an estimated 800,000 people die every year from zinc deficiency, which is comparable to the total mortality from malaria.

Similar to zinc, selenium deficiency disorders in humans occur only in developing countries. Such deficiencies are rare in industrialised countries due to the varied diet and nutritional supplements. Regarding livestock, selenium deficiency in feed causes fertility problems in cattle in many regions, with incidental cases in the Netherlands. In Europe, zinc shortages in livestock only occur in the eastern countries.

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[1] "Mineral reserves" refers to mineable reserves only. Mineral reserves in the soil are usually referred to as "weatherable minerals".

Scarcity of mineral reserves

Deficiencies of micronutrients in agricultural soils can be replenished with mined minerals. These minerals are currently used almost exclusively for industrial applications. This is ironic, since they can be substituted in industry, but they are essential for crops, livestock and humans. The mineral reserves, in relation to their use, seem to be most restrictive for zinc. At the current production level of mining, currently known reserves are sufficient for only 21 years (the R/P value is 21[2]). The use will probably increase further, leading to expectations that around 2020 demand may outstrip supply. Selenium is somewhat less scarce, with an R/P value of 39.

The above statements about impending mineral shortages can be qualified. With increasing scarcity and prices, the data on the reserves will be updated, exploration will be intensified and new ore reserves will be discovered or will become more profitable to exploit. An example of the former is the recent upgrade of phosphate reserves in Morocco. Although such drastic upgrades are very exceptional, our primary concern is not depletion, but the fact that scarcity often leads to the discovery of lower quality mineral ore reserves. These ores tend to have higher levels of contamination and require much more energy and water for extraction. As a result, extraction costs increase and greater price fluctuations occur, possibly exacerbated by speculation.

Replenishment of deficient soils with mined minerals and supplementation of livestock feed with minerals can place a significant demand on current mineral reserves, thus exacerbating these problems. Besides zinc, this also appears to be the case for selenium. According to general estimates, current selenium production from mines will be entirely inadequate to meet the demand resulting from predicted deficiencies in the food chain.

Geopolitics

The risks of scarcity of these minerals can be amplified by geopolitics. For example, only three non-European countries are responsible for more than 50% of zinc and manganese mining and for more than 75% of molybdenum and boron mining. According to the United States Geological Survey (USGS), less than 4% of the reserves of the essential micronutrients for plants are present in EU countries. An additional risk for Europe is that among the important suppliers of these minerals, there are countries with a *World Governance Index* of between 50 and 70 (on a scale with a maximum of 100), such as China, Turkey, Argentina and Peru, which are considered less stable.

In view of the magnitude of these various problems and risks, it is surprising that micronutrient scarcity is virtually absent from Dutch and European sustainability, geopolitical and development agendas.

2 R [= reserve] / P [= production from mining] per year].

Recommendations

Recommendations for policymakers in the European Union and its Member States

- Current and expected future scarcities of micronutrients should be put on national, European and global policy agendas. At the European level, there are two strategic gaps: 1) In the Common Agricultural Policy (CAP) including the current reform proposals, soil fertility is a key aim, but no attention is being paid to deficiencies of micronutrients in soil, feed and food. 2) In the European Raw Materials Initiative no attention is being paid to impending scarcity of essential mineral nutrients in mines. The use in agriculture is even explicitly excluded from the EU list of "critical raw materials". These gaps require urgent attention.

- To avoid future scarcity, the EU should seek long-term supply agreements with countries that have large reserves of mineral micronutrients. Geopolitical risks are greatest for boron en molybdenum; for zinc and manganese they are smaller but still credible. China has large reserves of many mineral micronutrients, but the USA and several South American countries are also important potential suppliers. The most effective agreements are those based on mutual dependencies. With China, for example, the EU could trade micronutrients for agricultural products. However, such agreements are not easy to achieve and, in addition, cannot guarantee long-term supply, given the finiteness of these resources and increasing geopolitical uncertainties.

- A more sustainable long-term strategy for the EU and its Member States is fostering reduction of the use of key micronutrients. Such policies should involve more efficient use, recycling and – where possible – substitution of mineral micronutrients. This can all help to secure supply, while reducing dependence on the world market, reducing associated geopolitical risks and minimising waste and pollution.

- Priority should be given to zinc, because zinc deficiencies are already occurring in food chains in large parts of the world. It should be clarified to what extent the current tight ratio between use and known reserves for zinc is indicative of future scarcity.

- Selenium also deserves priority in view of the current regional deficiencies in food chains as well as the impossibility of sufficiently replenishing these deficiencies with co-use from copper ore (the current source of selenium).

- Current micronutrient initiatives focus on deficiencies in humans and should be expanded to include soil, crops and livestock.

Recommendations for the farming sector and the feed and food industries

- The farming sector must ensure sufficient soil fertility, including the availability of sufficient micronutrients in the soil. Key aspects are the following:
    - breaking through the dominance of the one-sided NPK fertilisation regimen;
    - preventing over-fertilisation with phosphate to avoid antagonism with iron, zinc and copper. Governments can promote such practices. For example, in a country such as China the subsidy on phosphate fertiliser could be reconsidered;
    - preventing erosion and leaching by targeted agricultural practices such as cover crops and mixed cropping;
    - using animal manure, which contains most micronutrients;
    - fertilising with micronutrients that are deficient in the soil.
- Integrate sustainable soil management and micronutrients into corporate responsibility across the agro-food chain, including the feed and food industries.

Recommendation for companies in mineral chains

- Chains of mineral micronutrients from mining, via use in industrial products and ending with recycling or disposal, should become more efficient and the loops should be closed more effectively. For zinc, this concerns applications such as galvanisation and its use in roof gutters and car tires, and for selenium its use in glass use and solar cells. It is important that the parties involved in the chain take individual responsibility. With phosphate, this process has already begun in some countries – including the Netherlands.

Recommendations for R&D

- The first priority is to make a worldwide survey of the micronutrient availability in agricultural soils, to be coordinated by the FAO. This is especially urgent in developing countries; the research currently taking place in China can serve as an example.

- Another important question is the extent to which the need from agriculture can be met by fertilising with mined micronutrients. This requires the development of various scenarios on agricultural and industrial use, combined with the magnitude of the reserves. For selenium, this question has already been answered in the sense that the present production capacity, which is linked to the production of copper, is insufficient to meet the estimated agricultural need (see above). For zinc and other micronutrients a key research question is: are we heading towards Peak Zinc, Peak Molybdenum, or other mineral micronutrient peaks, comparable with Peak Oil?

- There is a great need for technological innovations focusing on more efficient utilisation of micronutrients by crops, livestock and people. The same applies to innovations focusing on more efficient production chains of mineral micronutrients, recycling and substitution by other materials. An analysis of the sources and sinks of micronutrients in the bulk trade worldwide can indicate important flows from which micronutrients can be recovered. One example concerns “urban mining” from waste deposits.

Conclusion

The issue of micronutrients has been given remarkably little attention in the research, agricultural policy and raw materials policies of the EU; this also applies to the private agendas of the private sector, particularly the farming sector and the feed and food industries. In all these frameworks, attention for this issue is urgently needed.

1. Introduction

Resources have become a central component of the sustainability agenda. For example, besides fossil fuels, increasing attention is being paid to rare earth metals needed by the electronics industry, land availability for food production, biomass, wildlife habitats and freshwater. Recently, increasing attention is being paid to minerals as essential nutrients for crops, livestock and humans. These nutrients are essential since they cannot be replaced by other substances or technologies; this distinguishes them from rare earth metals or fossil fuels, which in theory can be replaced entirely.

In 2009, the Platform for Agriculture, Innovation and Society published a policy memorandum on phosphate.[3] In this memorandum, the transition "from excess to shortage" was addressed. Given current levels of phosphate use and the reserves known at the time, this resource could be exhausted in only 125 years (for update see Section 5.4). Partly as a result of this study, phosphate was classified as a future scarce resource in Dutch resource policy (published as the *Grondstoffennotitie* – Resource Memorandum – in July 2011). Moreover, an agreement was signed between the Dutch government, the Nutrients Platform and more than 20 important stakeholders in the nutrient product chains.[4] At the European level, phosphate is now on the research agenda. This decision was based on the geopolitical dimension rather than on global scarcity itself. This concerns the increasing dependency for phosphate on Morocco (including Western Sahara) and China; together these two countries control at least two-thirds of all known phosphate reserves.

In view of these developments involving phosphate, it is important to know the status of other essential mineral nutrients. This concerns not only the nutrients that are needed in relatively large quantities – the so-called macronutrients such as nitrogen, phosphate and potassium – but also the mineral micronutrients (or trace elements). The latter are needed in much smaller quantities, but are equally essential for crops, livestock and humans. The central question of the present study is the following: will scarcities of these micronutrients also occur in the near or more distant future?

Three types of scarcity can be distinguished:

- scarcity in the *soil* as nutrients for crops;
- scarcity in *food or feed* (plant or animal-based) for livestock and humans;
- scarcity in the *mineral reserves* that can be used for the production of chemical fertiliser to supplement the naturally occurring nutrients in soil.

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3 H.A. Udo de Haes, J.L.A. Jansen, W.J. van der Weijden and A.L. Smit. Phosphate – from surplus to shortage. Policy memorandum of the Steering Committee for Technology Assessment of the Ministry of Agriculture, Nature Management and Food Quality. Utrecht, 2009. www.platformlis.nl

4 *Ketenakkoord Fosfaatkringloop* (Phosphate Recycling Chain Agreement) 4 October 2011:http://www.rijksoverheid.nl/documenten-en-publicaties/rapporten/2011/10/04/ketenakkoord-fosfaatkringloop.html.

In this report, the central focus is on the essential micronutrients for crops, especially zinc. An additional focus is on selenium, which is not essential for crops, but is an essential micronutrient for livestock and humans.

Chapter 2 presents an overview of the various types of nutrients for crops, as well as for livestock and humans. Chapter 3 follows with a description of the currently known deficiencies in the food chain, i.e. the deficiencies of nutrients in the soil, in crops and in human nutrition. Chapter 4 concerns the role of fertilisation, both the currently dominant NPK (nitrogen, phosphorus and potassium) regimen and a broader regimen. Chapter 5 goes into possible fertilisation with mined micronutrients. Chapter 6 closes the report with recommendations for the policy of the EU and its member states, for agricultural practice, for companies in mineral chains and for research.

2. Overview of nutrients

In total, 21 mineral nutrients are essential for the health of crops, livestock and humans.[5] Table 1 provides an overview of these nutrients. Table 2 indicates the average levels of these nutrients in crops, humans and livestock.

Table 1 Essential nutrients for crops, and for humans and livestock. Left column: nutrients essential for plants. Right column: nutrients that are essential only for livestock and humans. Nutrients are ranked according to the levels in crops. (Sources: Nubé and Voortman 2006, based on Marschner 1995, Garrow et al. 2000 and Wiseman 2002).[6]

Nutrient		Crop [1)]	Humans/ livestock [2)]	Nutrient		Crop [1)]	Humans/ livestock [2)]
Nitrogen	N	+	+	Chlorine	Cl	±	+
Potassium	K	+	+	Silicon	Si	±	+
Calcium	Ca	+	+	Sodium	Na	±	+
Sulphur	S	+	+	Iodine	I	-	+
Magnesium	Mg	+	+	Nickel	Ni	±	(+)
Phosphorus	P	+	+	Chrome	Cr	-	+
Manganese	Mn	+	+	Cobalt	Co	±	+
Iron	Fe	+	+	Selenium	Se	±	+
Zinc	Zn	+	+				
Boron	B	+	-				
Copper	Cu	+	+				
Molybdenum	Mo	+	+				

1) + = essential; - = nonessential; ± = necessity not demonstrated, but assumed to be beneficial
2) + = essential; - = nonessential; (+) = necessity not demonstrated, but not excluded

Table 2 Nutrient levels in plants, and in livestock and humans, as a percentage of dry matter (Sources: for plants: Markert 1992; for humans (except molybdenum): Iyengar 1998; other: compilation of internet sources).

Nutrient	Plants	Humans/ livestock	Nutrient	Plants	Humans/ livestock
Nitrogen	2.5	9	Chlorine	0.2	0.45
Potassium	1.9	0.75	Silicon	0.1	0.0036
Calcium	1.0	4.2	Sodium	0.015	0.45
Sulphur	0.3	0.75	Iodine	0.0003	0.00002
Magnesium	0.2	0.15	Nickel	0.00015	0.000007
Phosphorus	0.2	3.3	Chrome	0.00015	0.000001
Manganese	0.02	0.000016	Cobalt	0.00002	0.000002
Iron	0.015	0.007	Selenium	0.000002	0.00002
Zinc	0.005	0.003			
Boron	0.004	0.00002			
Copper	0.001	0.0002			
Molybdenum	0.00005	0.000039			

5 In this report, the term “micronutrients” will be used to indicate mineral nutrients, not organic nutrients such as vitamins.

6 The partial literature references included with the tables and figures are shown in full in the reference listings of the background reports.

Table 3 classifies the important nutrients for crops. It makes a distinction between macro-, meso- and micronutrients that are essential for plant growth, and additional nutrients that are beneficial for plant growth. In the rest of this report, macro- and mesonutrients are both classified as “macronutrients”.

Table 3 Nutrients for crops grouped according to the quantities needed by the crop, the increased yield per kilogram in case of severe deficiency and the duration of the residual effect (i.e. the duration of the replenishment in subsequent years).

Nutrient group	Elements	Increased yield/kg	Residual effect
Macronutrients	N, K	Low	Short-average
Mesonutrients	Ca, Mg, P, S	Average	Average-long
Micronutrients	B, Cu, Fe, Mn, Mo, Zn	High	Long
Supplementary	Al, Cl, Co, Na, Ni, Se, Si	??	??

As stated in the Introduction, the essential micronutrients for plants are the primary topic of this report. These nutrients are: manganese, iron, zinc boron, copper and molybdenum. We have focused primarily on zinc because it is relatively well studied and we consider it more or less representative for this group. In addition, we pay attention to selenium, which we consider to be representative for those micronutrients that are not essential for crops, but are essential for livestock and humans.

3. Deficiencies in soil and in food

3.1 Natural soil reserves

The primary source of nutrients in the soil is the weathering of the parent material in the Earth's crust. Table 4 shows the presence of the key elements in the Earth's crust. Except for nitrogen, all the other essential elements for plant growth – potassium, calcium, magnesium and iron – are widespread in the crust. Manganese, phosphorus and sulphur are less widespread, and zinc, boron and molybdenum are relatively scarce.

Table 4 Average levels of micronutrient elements in the Earth's crust, ranked according to level (Source: Rudnick and Gao 2003). ppm = parts per million.

Nutrient	ppm	Nutrient	ppm
Silicon	311,000	Chlorine	370
Iron	39,200	Chrome	92
Calcium	25,600	Zinc	67
Sodium	24,300	Nickel	47
Potassium	23,200	Copper	28
Magnesium	15,000	Cobalt	17
Aluminium	8,150	Boron	17
Manganese	775	Iodine	1.4
Phosphorus	655	Molybdenum	1.1
Sulphur	621	Selenium	0.09

Figure 1 shows the various forms in which the nutrients can occur in the soil. The levels of metals in the soil are initially determined by the composition of the parent material, and therefore differ greatly between locations. In the soil solution, nutrients occur partly as soluble, free ions, and partly as complexes. They can also bind to organic matter and clay particles (the soil adsorption complex).

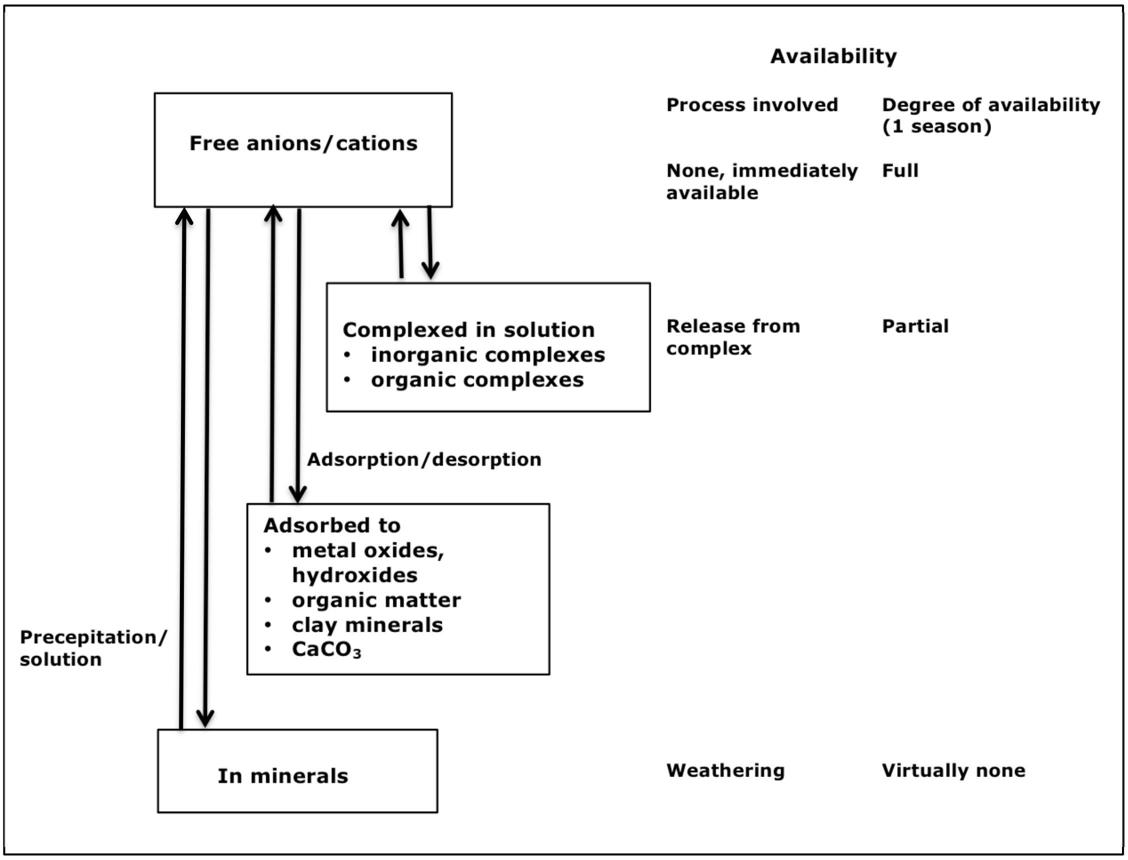

Figure 1 **Diagram of the most important soil fractions in which the nutrients occur. Shown are the processes that affect the availability of a specific fraction and the degree with which the various factions can become available for uptake within one growing season (Source: Bussink & Temminghoff. Soil and tissue testing for micronutrient status. The International Fertiliser Society (IFS). Proceedings 548. 2004 York, UK).**

Table 5 **Total levels of Cu and Zn found in the soil worldwide and the concentration of these metals in the soil solution (Sources: Mengel & Kirkby 1987 and Kabata-Pendias & Pendias 2001).**

Element	Total level mg/kg	Concentration in soil solution mg/kg
Copper	1 – 140	0.0018 – 0.135
Zinc	3.5 – 770	0.021 – 0.570

What is the total amount of micronutrients present in agricultural soils worldwide? To answer this question, we will use zinc as an example. Assuming that all zinc in the upper 20 cm of the soil is available for crops, then it can be calculated that the total quantity present would be sufficient for approximately 1000 years of agricultural production at the current level. This appears to be a reassuring figure, even more so because the soil reserve, with the exception of heavily eroded soils, is continuously being resupplied with zinc from the parent material. However, this figure does not say very much by itself. The most important aspect is not the total quantity present, but the quantity that is available to the crop. For example, for zinc (and copper) only 0.1% of the total content in the soil is available on average (rising to 1%) in the form of free ions in the soil solution, which can be taken up directly by plants (see Table 5).

This is often insufficient for optimal crop growth; the amount of zinc and copper that the soil can supply therefore determines whether these nutrients are sufficiently available for plants. Soil researchers have attempted to quantify this amount (see Section 3.2). The possibilities for increasing this availability are discussed in Section 3.4.

3.2 Deficiencies of micronutrients for crops

Deficiencies of metals are caused by inadequate replenishment in the soil from the parent material and from the adsorbed and complexed fractions. Deficiency in agricultural soils can occur due to natural factors, such as highly acidic or alkaline soils, and due to human activity, such as soil depletion caused by farming without adequate fertilisation. Important examples of countries with deficient soils are India and China, where much systematic research has been done into the causes of the current stagnation in agricultural yields (see Figures 2 and 3). In both of these countries boron deficiency occurs in more than 30% of agricultural soils and zinc deficiency is even more widespread, affecting approximately 50% of the soils. Molybdenum deficiency occurs in 15% of agricultural soils in India and 47% in China. Elsewhere, significant zinc deficiencies occur in soils in Turkey, Iran and Pakistan, and in sub-Saharan Africa. Figure 4 shows zinc deficiency in soils worldwide.

In low concentrations, zinc is essential for plant growth, but in high concentrations it is toxic. It is involved in many processes including enzymatic reactions, such as carbohydrate metabolism and protein synthesis. Zinc deficiency results in discolouration of the foliage and growth abnormalities, such as a drastic reduction in leaf area and necrosis of upper foliage. All these problems together lead to reduced yields, and in severe cases to plant death. Selenium, as stated previously, is not essential for plant growth, but added selenium can be beneficial. Soil deficiencies that are particularly relevant for livestock and humans occur in the northern and eastern parts of Asia as well as parts of Africa.

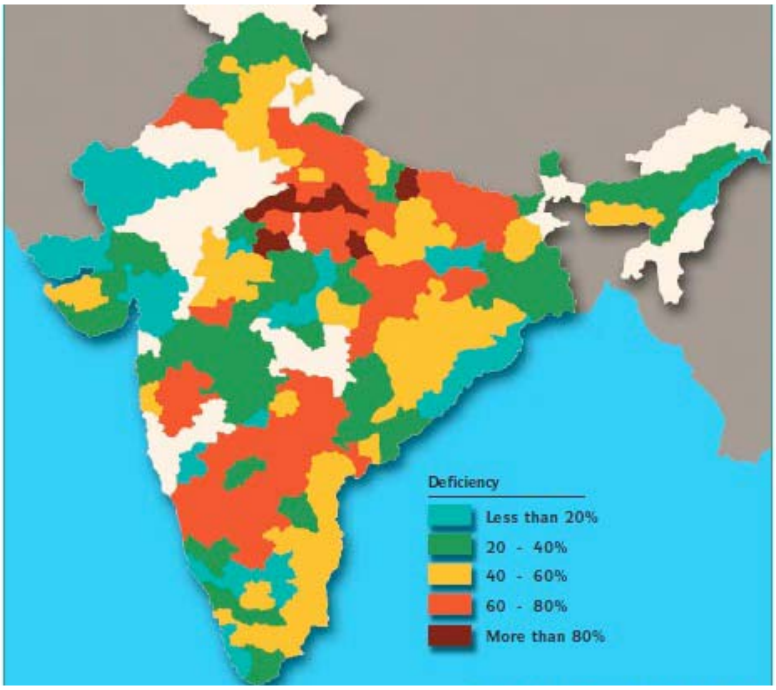

Figure 2 **Percentages of agricultural land with zinc deficiency in India (Source: Alloway 2008).**

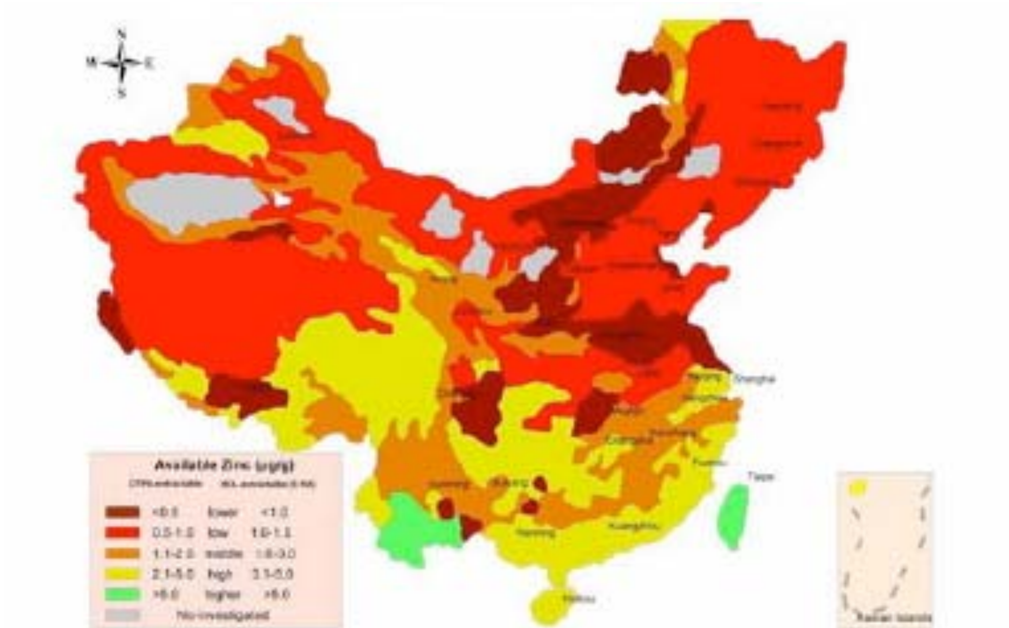

Figure 3 **Percentages of agricultural land with zinc deficiency in China (Source: Yang et al. 2007, based on Liu 1994).**

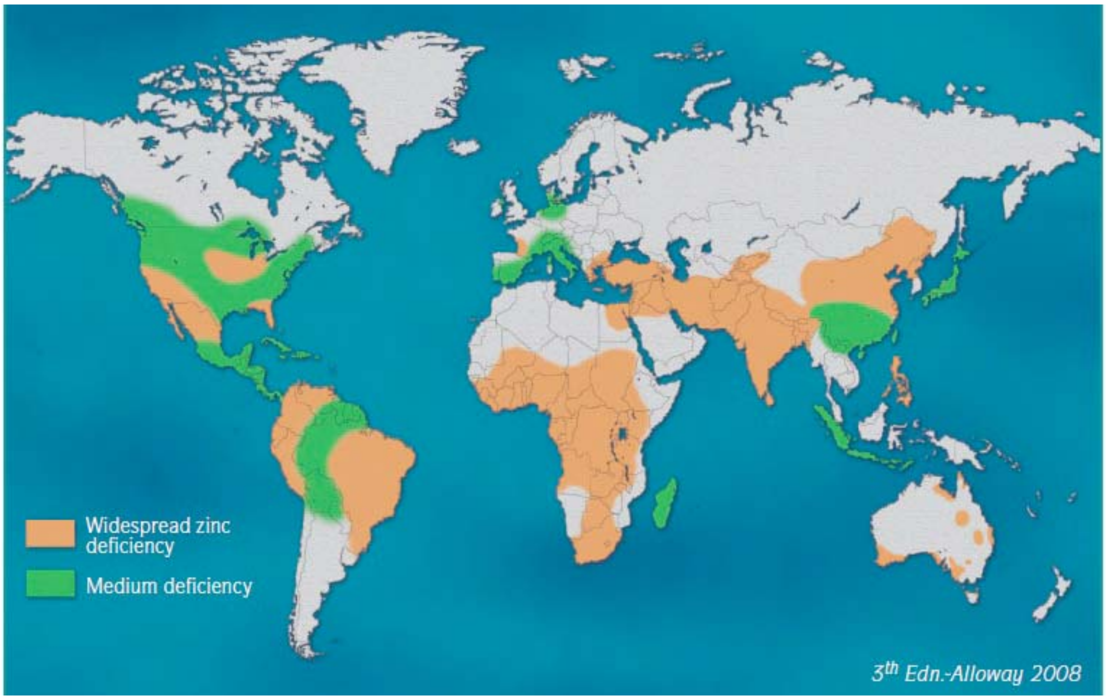

Figure 4 Areas with zinc deficiency at the world scale (Source: Alloway 2008).

3.3 Deficiencies of micronutrients for livestock and humans

Inadequate attention is still paid to the effects of micronutrient deficiencies in soils and crops on livestock and human deficiency diseases. We will first consider zinc deficiencies.

Zinc plays an important role, especially in protein synthesis. Zinc deficiency causes problems such as growth disorders, delayed sexual development, increased susceptibility to infection, immune suppression, skin rashes and chronic diarrhoea. Moderate zinc deficiency is widespread among children in developing countries and affects their physical and psychosocial development. Comparable phenomena also occur to a certain extent in livestock, such as skin disorders, immune suppression and growth retardation (see Box 1).

An estimated one-third of the world population is at risk for zinc deficiency; this deficiency is the fifth most important risk factor for diseases in developing countries. Worldwide, it is estimated that 800,000 people die every year from zinc deficiency. Although this is comparable to the global mortality from malaria, zinc deficiency is almost absent from Dutch and European development policy agendas.

Box 1. Key deficiency diseases in humans caused by lack of zinc and selenium (Source: background report Voortman 2012).

Zinc

- growth disorders
- delayed sexual development
- increased susceptibility for infections
- immune suppression
- skin rashes
- chronic diarrhoea

Selenium

- Keshan disease (heart disorders)
- Kaschin-Beck disease (deterioration of cartilage and joints)

In addition, there are indications that selenium deficiency exacerbates other disorders such as iodine deficiency diseases, cancer and cardiovascular disease, fertility problems, viral diseases (including HIV), muscular dystrophy, and – with 30% of women – insufficient selenium in milk during breast-feeding.

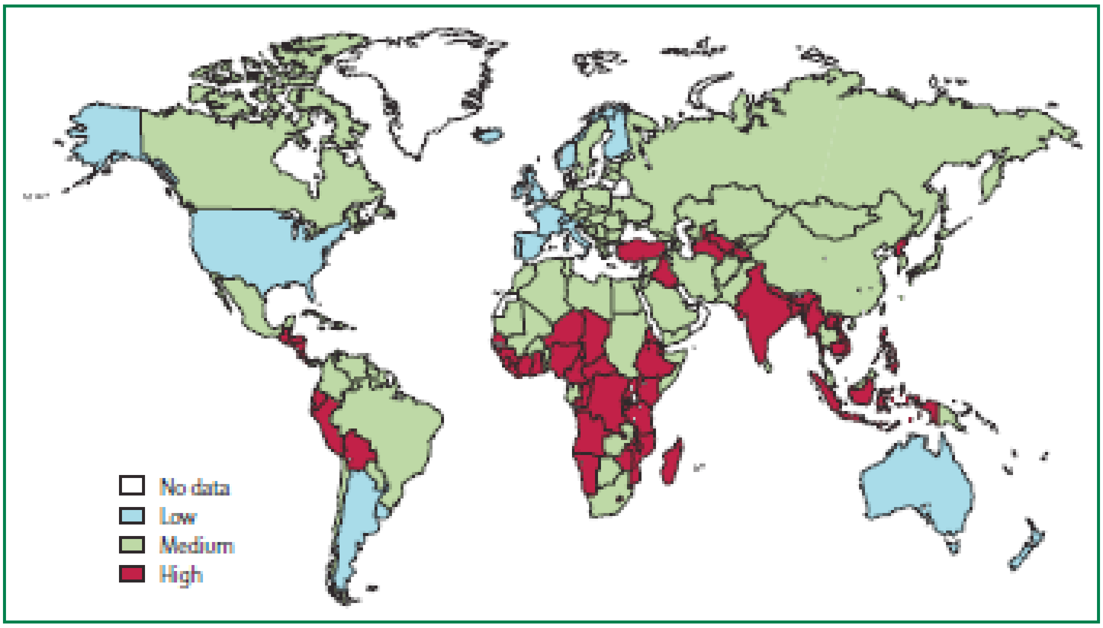

Figure 5 National risk of zinc deficiencies in children younger than 5. (Source: Black et al. 2008). Note: The moderate risks of zinc deficiencies in China are not in accordance with Chinese scientific publications, which have ascertained widespread, severe zinc deficiency.

Figure 5 presents an overview of zinc deficiency among children worldwide, with growth retardation as a clear symptom. The geographical distribution of zinc deficiencies in humans shows roughly the same spatial pattern as zinc deficiency in the soil (see Figure 4). Zinc deficiencies in humans occur primarily in sub-Saharan Africa, North Africa, the Middle East and southern Asia. Moreover it is striking that severe deficiencies in children only occur in developing countries. In industrialised countries this problem does not occur, even where zinc is deficient in the soil. In these countries, zinc deficiencies are compensated by a more varied diet, including animal products, and by nutritional supplements. However, deficiencies have been ascertained in livestock in eastern European countries.

A correlation between deficiencies in the soil and human deficiency diseases can also be ascertained at a smaller scale. Once again, the best data are available for China, where no less than 60% of the rural population suffers from zinc deficiency, related to zinc deficiency in the soil (see Figure 3). The same applies to the state of Haryana in India. Elsewhere, regional studies in countries in sub-Saharan Africa (Burkina Faso, South Africa, Rwanda, Uganda and Tanzania) have indicated zinc deficiencies among children and pregnant women.

Selenium also provides a clear example of the effect of deficient soils on humans and livestock. This element is an important antioxidant that can also bind to heavy metals and is present in all protein-rich foods. The most important symptoms of selenium deficiency are the following:

- Keshan disease (heart disorders) and
- Kaschin-Beck disease (deterioration of cartilage and joints)

In addition there are indications that selenium deficiency exacerbates iodine deficiency diseases, increases the incidence of cancer and cardiovascular disease, fertility problems, viral diseases (including HIV) and muscular dystrophy. Finally, there are indications that approximately 30% of selenium-deficient lactating women cannot provide their breast-feeding babies with sufficient selenium (see Box 1). A number of these diseases have also been detected in livestock, in particular muscular diseases and heart and lung diseases, which can also be passed on to offspring.

Selenium deficiencies occur in all developing countries. For this element as well, in China a clear relationship has been ascertained between selenium deficiency in the human body and selenium deficiency in the soil (see Figures 6 and 7). Areas with selenium deficiency appear to be thinly populated. This is not coincidental, because such areas were previously avoided by human settlers. In industrialised countries, selenium deficiencies are rare due to the mixed diet, but research in England and elsewhere has shown that human intake of this mineral is declining rapidly.

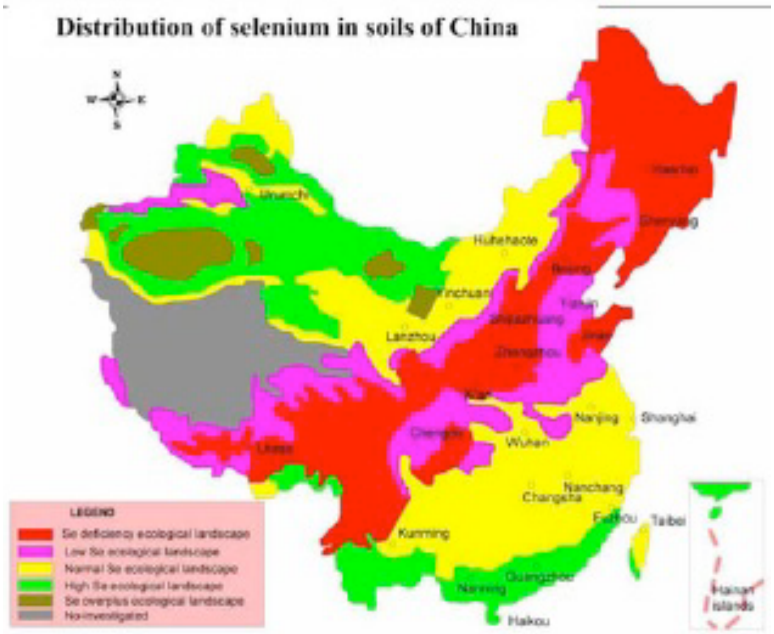

Figure 6 Level of selenium deficiency in agricultural soils in China; red shades indicate a severe deficiency (Source: Tan 2004). Grey = no data.

Figure 7 Occurrence of diseases caused by selenium deficiency (Keshan disease and Kaschin-Beck disease, and combinations thereof) in China (Source: Tan 2004).

4. Solutions for shortages

4.1 Reducing the gap between total and available elemental content

An initial priority for combating deficiencies is to improve the availability of micronutrients in the soil. Recommended measures are preventing erosion and leaching. To prevent leaching, it is essential to have good water management and sufficient levels of clay and/or organic matter.

More specifically, the availability of metals is determined primarily by the balance between their various chemical forms. During this process, the soil adsorption complex is the most important buffer for the available free, dissolved ions. The key factors for the release of ions are the pH, moisture content, temperature and the interactions with other nutrients. The pH has a major influence: if the pH increases by one unit, for example from pH 5 to pH 6, then the availability of zinc and copper falls by a factor of 100. This also applies to other metals, with the exception of molybdenum, where the opposite effect takes place. In addition, soil biology plays an important role, especially the mycorrhizas. Due to their vast network of mycelium, they have much more contact with the mineral reserves and can also absorb minerals in forms that are normally unavailable to plants and make them accessible (see Box 2). However, mycorrhizas also require calcium and copper as nutrients. Hence a copper deficiency can limit the growth of mycorrhizas and thereby exacerbate deficiencies of other micronutrients. Finally, the crop itself can affect soil pH due to nutrient absorption and excretion through the roots, which can in turn influence the availability of micronutrients. The free ions in the soil solution ultimately determine the micronutrient deficiencies for plants, and to a large extent the deficiencies for humans and livestock as well.

Box 2. Role of mycorrhizas (beneficial root fungi) and their presence in the soil

Mycorrhizas are soil fungi that form a relationship with the roots of higher plant species, including agricultural crops. These fungi can make otherwise inaccessible or scarce nutrients and water available to plants in exchange for sugars (mutualism). This is possible because the mycelia of the fungi are in contact with a much larger soil volume than the plant roots themselves and because they can absorb forms of nutrients that cannot be taken up directly by plants. Mycorrhizas also improve soil structure and disease resistance. For most agricultural crops, mycorrhizas contribute to increased yields, increased nutrient efficiency and reduced use of pesticides.

Mycorrhizas require calcium and copper to function properly. High fertilisation levels often restrict their activity.

For agricultural practice, the organic matter content in field soils and the correct pH are important priorities for improving general soil fertility, which is expressed in terms of soil structure, rooting properties, soil water retention and nutrient availability.

4.2 Broadening the current NPK regimen

Besides the natural processes that determine the availability of nutrients, fertilisation by the farmer is crucial for eliminating deficiencies. Fertilisation is required only to the extent that replenishment in the soil from the soil adsorption complex and from the dissolved complex compounds is insufficient for plant uptake. Historically, nitrogen and phosphate were scarce in most soils, so natural replenishment was commonly insufficient. Farmers struggled constantly to maintain soil fertility by using supplements such as animal manure, human faeces, fish waste, wood ashes, soot and heather sods, which contain both macronutrients and micronutrients. Beginning in the middle of the 19^{th} century, this situation changed drastically due to the introduction of fertiliser from mining (see section 5.1).

The result was a spectacular increase in agricultural yields. In this way, mineral phosphate fertilisation was one of the preconditions that enabled the world population to increase from 1 billion to the current 7 billion people. However, this one-sided attention for NPK, sometimes together with calcium (lime), began to completely dominate the generally accepted fertilisation strategy. This standardised use of chemical fertilisers has a number of serious disadvantages for agriculture and the world food supply.

First of all, fertilisation with chemical fertilisers is only beneficial if the corresponding nutrients are limiting factors for crop growth. If this aspect is not taken into account, the fertiliser is wasted.

Secondly, there is little attention – at the global level – for the problem of diminishing returns, i.e., where increased fertilisation with a limiting nutrient does not result in a proportionately increased yield. Beyond a certain dosage, the yield can even decline compared with the initial production level (see Figure 8 for phosphate). This is both wasteful and counterproductive.

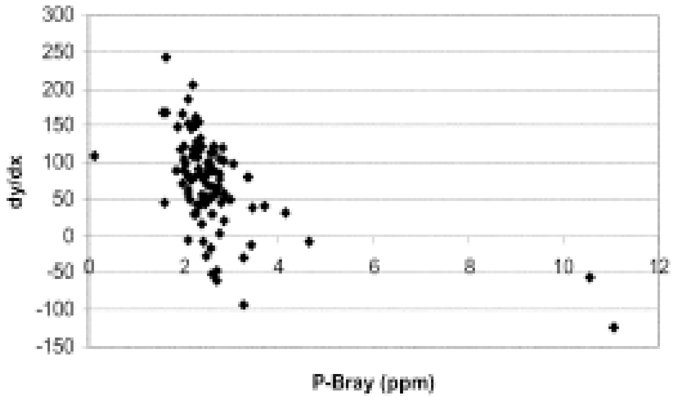

Figure 8 **Changes in crop yields in response to a variable phosphate application (the latter is expressed as P-Bray, see background report by Voortman) (Source: Voortman and Brouwer 2003).**

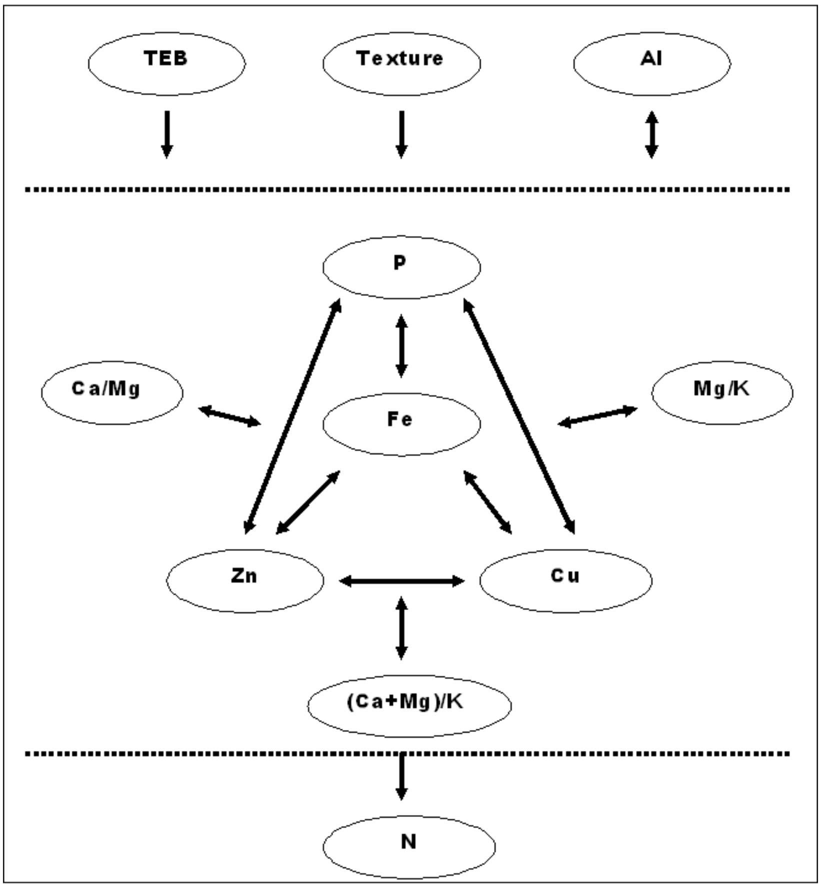

Figure 9 **Schematic diagram of interactions between nutrients and chemical soil characteristics in relationship to plant nutrition (Source: Voortman and Spiers 2010). TEB = total base saturation.**

Thirdly, little attention is paid to interactions with other nutrients. Figure 9 shows a schematic diagram of the primary negative effects of phosphate application on the availability of a number of micronutrients. Briefly summarised: too much phosphate inhibits crop uptake of iron, zinc and copper. Moreover, to indicate the complexity of the soil processes, too much zinc inhibits the uptake of phosphorus, manganese, iron and copper. These balances also depend on the ratios between various cations in the soil, especially calcium, magnesium and potassium. However, the central mechanism is that the addition of too much phosphate can lead to a decline in crop production caused by an induced deficiency of micronutrients. This is a severe, but still widespread form of counterproductive use of chemical fertiliser. A striking example has emerged from crop research in Zimbabwe, where the yields of the velvet bean, a nitrogen-binding legume, can vary within a single region from 317 to 5250 kg per ha when it is grown without chemical fertiliser; within the same area (with comparable yields without chemical fertiliser) additional phosphate did affect yield, ranging from 90% positive to 50% negative (see Table 6).

Countries in sub-Saharan Africa are given standard recommendations across the board for NPK fertilisation that have been derived from green revolution practices in Asia, but are often excessive or even very excessive for the local conditions. This problem is even more severe for agricultural areas in southern and eastern Asia. For example, agricultural soils in China have the lowest efficiency ranking in the world for phosphate fertilisation. The previously described antagonistic mechanisms that result from constantly high P fertilisation lead to decreased micronutrient uptake, especially of zinc, which in turn causes not only a decline in agricultural production, but also the dietary zinc deficiency mentioned in section 3.3.[7]

Table 6 Biomass production (kg dry matter/ha) of velvet beans *(Mucuna pruriens)* with and without phosphate, on depleted sandy soils in six village communities in northern Zimbabwe in 1996/97 (Source: Hikwa et al. 1998).

Village area	Production without P	Production with P	Difference %
Mangwende (1)	317	318	0.3
Zvimba (1)	1,260	2,410	91.3
Zvimba (2)	1,620	850	-47.5
Chiduku (1)	1,865	1,757	-5.8
Gokwe South (1)	1,916	2,368	23.6
Gokwe South (2)	1,964	1,826	-7.0
Chiduku (2)	2,703	4,538	67.9
Chihota (2)	3,405	4,275	25.6
Mangwende (2)	5,250	5,351	1.9
Chihota (1)	5,290	10,665	101.6
Nyazura (2)	6,610	6,490	-1.8
Nyazura (1)	7,240	8,020	10.8

[7] The dietary zinc deficiency is exacerbated by the fact that the additional phosphorus content in food is in the form of phytate, which is indigestible for humans; it binds to micronutrients such as zinc, which are then excreted.

The same problem occurs in the Indus-Ganges plain in northern India, where it has been shown that high yields of wheat and rice can be sustained only by providing supplemental fertilisation with zinc in addition to NPK fertiliser. Even better results are attained by applying organic fertiliser, which contains iron, manganese and copper as well as zinc, also in the absence of supplemented livestock feed. However, such a broad fertilisation scheme is effective only over the long term, so the problem is expected to become worse in the near future. Zinc fertilisation is already being used more extensively and systematically in Turkey, with yield increases of up to 600%!

In industrialised countries with large livestock sectors, such as the Netherlands, the problem of phosphate-induced zinc deficiency is negligible due to the intensive use of animal manure, which contains sufficient levels of zinc. However, it must be noted that the high levels of copper and zinc in the manure are primarily the result of the supplementation of these metals in the feed concentrate used for cattle and pigs. In southern Europe and parts of the USA, soils are deficient in zinc, but this does not lead to zinc deficiency in humans due to the broader composition of the diet in these regions (see Section 3.2).

Considering the urgency of the situation, it is striking how little attention is being paid to fertilisation with micronutrients, and how virtually no attention is paid to the natural processes that determine their availability for crops. Key priorities for a broader fertilisation regimen, which also pays explicit attention to micronutrients, are the following complementary and mutually reinforcing actions:

- avoiding over-fertilisation with phosphate to prevent antagonism with iron, zinc and copper;
- applying animal manure, which already contains most micronutrients; and
- using additional mineral fertilisation with deficient micronutrients (see next chapter).

To apply such a broad fertilisation regimen, sufficient expertise must be available. Some of the required measures are generic in nature: counteracting erosion, and maintaining a good soil with a sufficiently high level of organic matter. Some specific factors are also involved, particularly deficiencies of certain micronutrients. For the latter, soil research is required worldwide, focusing on developing countries.

Research into soil deficiencies began in the 1920s and intensified greatly after World War II. During the initial period, the levels of soil components were determined exclusively with strong extraction agents (such as nitric acid), with which the total levels of micronutrients present in the soil could be determined. Later on, these methods were supplemented with weak extraction agents (such as $CaCl_2$), which provide a much better indication of the actual availability of the micronutrients for crops. Recent research has focused on the development of less costly methods, based on infrared radiation measurements of soil samples. For example, mid infrared spectroscopy (MIR) is being used in Australia and near infrared spectroscopy (NIR) in the Netherlands for measuring levels of clay, silt and sand, total carbon, cation-exchange capacity and the various cations that play a role in this process.

These new methods are less expensive and therefore offer opportunities for developing countries.

4.3 Nutritional supplementation for livestock, fish and humans

Nutrients can also be added directly to feed (for livestock) and food (for humans). In Section 4.2, zinc and copper supplementation of cattle and pig feed was briefly discussed. Regarding human nutrition, all nutrients listed in Table 1 can be added to food. For those micronutrients not essential for plants, supplementation in feed and food is an obvious solution, but fertilisation is also a possibility. Selenium, for example, can be supplemented directly by means of pills, licking blocks, or as an additive to feed, food and drinking water, but it can also be applied to the soil in fertiliser.

As for food supplementation and fortification, several initiatives are underway. In 1997 in Canada, the Micronutrient Initiative was launched (www.micronutrient.org). This is “an Ottawa-based, international not-for-profit organisation dedicated to ensuring that the world's most vulnerable - especially women and children - in developing countries get the vitamins and minerals they need to survive and thrive through supplementation and food fortification programs. Its mission is to develop, implement and monitor innovative, cost effective and sustainable solutions for hidden hunger, in partnership with others.” The initiative claims: “With Canadian support, the organisation is saving and improving the lives of 500 million people annually in more than 70 countries with its child survival, child development and women´s health programs.”

Recently the Micronutrient Initiative started the Zinc Alliance for Child Health (ZACH) in cooperation with the Canadian International Development Agency and Teck, a Vancouver-based mining company. Its aim is to supply zinc in combination with oral rehydration salts (ORS) to young children in order to control diarrhoea and thereby reduce child mortality in developing countries.[8] The project started in Senegal, West Africa, where one-quarter of the children under five are affected by severe diarrhoea. The organisation plans to broaden the initiative to include at least four other countries in Africa and Asia, where deaths from diarrhoea are among the highest.

In addition, the Grand Challenges in Global Health initiative of the Bill & Melinda Gates Foundation is funding bio-fortification through genetic modification in banana, cassava and sorghum for Africa. They all include efforts to produce and accumulate carotenoids and other micronutrients in these crops.

However, these initiatives do not target livestock and soils, so they may not always apply the best strategy. In many cases it actually is not yet clear which strategy is most effective: food supplementation, food fortification, breeding of micronutrient-rich varieties, or soil

[8] http://www.micronutrient.org

fertilisation. Soil fertilisation has the potential of combining higher crop yields, higher nutrient density of the product, and better uptake of micronutrients by the human or animal body.[9] In which situations these advantages apply, requires basic as well as applied case-by-case studies.

For the sake of completeness, a few words on fish. Micronutrient deficiencies are also a problem with fish farming. Fish require primarily zinc, iron, manganese, copper, iodine (in freshwater) and cobalt (in the form of vitamin B12). Fish absorb little of these micronutrients from water, so these elements must be supplemented in their feed. Now that the fishmeal is increasingly being replaced by plant-based ingredients such as soy, maize and wheat, micronutrient deficiencies are increasing. To compensate for this, feed suppliers have started adding minerals to the feed. Moreover, enzymes are added which can enhance the availability of the minerals in the feed. Finally, fish farmers are aiming to recover and recycle minerals from the effluent of fishponds and waste.

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9 Nubé, M. and Voortman, R.L. 2011. Human micronutrient deficiencies: Linkages with micronutrient deficiencies in soils, crops and animals. In: Thompson, B. and Amoroso, L. (eds) Combating micronutrient deficiencies: Food-based approaches pp. 289-311. FAO, Rome. Other students claim: “health comes from the farm, not the pharmacy”.

5. Fertilisation with mined micronutrients

5.1 General aspects

Supplementing minerals from non-agricultural sources has been practiced for centuries. Wood ash – which contains high levels of potassium carbonate in addition to many other minerals – has traditionally been used to make potash; about 1870, the extraction of potassium carbonate from mined minerals began. Around 1850, phosphate became available for agriculture from phosphate-rich bird manure from South America (guano), which was later followed by “basic slag”, a waste product from the steel industry, which was in turn followed by mined mineral phosphate. In 1909, atmospheric nitrogen was first used to synthesise ammonia in the Haber process; in 1913, Bosch succeeded in using this process at an industrial scale, after which chemical nitrogen fertiliser became available. Atmospheric nitrogen is available in unlimited quantities, as long as sufficient energy is available for the oxidation process. According to the United States Geological Survey (USGS), at current levels of use, the known potassium reserves will be sufficient for approximately 300 years. For phosphate, until recently the projected reserves were estimated to last about 125 years at the current use level. However, this projection was recently upgraded to about 370 years (see additional details in Section 5.4).

Now the question is: are the mineral micronutrients that are essential for plant growth also sufficiently available from mineral reserves? Is scarcity of these minerals a problem or will it be in the near future? To answer these questions, we can view scarcity of ores in two ways: as a static concept or as a dynamic concept.

5.2 Scarcity of micronutrients – static view

A static view of ore scarcity is based on the currently known reserves (R) and a constant use (and related production from mining [P]). Consequently, the ratio between reserves in mining and production from mining (R/P) can be used as an indicator of expected availability (see Table 7). In this case, the low R/P values for micronutrients are notable, especially for zinc, which has an expected availability of only 21 years. These values do not provide an absolute indication but are primarily useful for comparative purposes: the R/P value means that within the group of the mineral micronutrients, zinc may well be the first mineral micronutrient to become scarce. Consequently, the R/P value can be used as an indicator of the priority for further policy and research.

Table 7 Reserves, production figures and types of uses for the micronutrients essential for crops, and for selenium, an essential nutrient for humans and livestock, in 2010 (Source: USGS Minerals Information 2011). Nutrients are ranked according to the ratio between reserves (R) and annual production from mining (P), both in 1000 tonne units.

Nutrient	R x 1000 tonnes	P x 1000 tonnes/yr	R/P yr	% R in EU	Share in production from mining	Types of uses	Remarks
Zn zinc	250,000	12,000	21	1%	>50% from China, Peru and Australia	Galvanisation, bronze, alloys	Currently 50% recycling
Cu copper	630,000	16,200	39	4%	>50% from Chile, Peru, China and the USA	Electrical conductors, construction	30% recycling
Se selenium	88	2. 26	39	0%	by-product of copper refining; >75% from Germany, Japan, Canada and Belgium	Glass, electronics, photovoltaic cells	Prices rising, substitution difficult
Mo molybdenum	9,800	234	42	0%	>75% from the USA, China, Chile	Alloys	>25% recycling; Substitution possible, but requires other scarce metals
Mn manganese	630,000	13,000	48	0%	50% from South Africa, Chile, China	Steel and aluminium alloys	>50% recycling; deep-sea mining? no substitutes known
B boron	210,000	3,500	60	0%	>75% Turkey, Chile, Argentina	Chemistry (bleach), glass	No recycling, but substitution possible
Fe iron	180,000,000	2,400,000	75	2%	low, many producing countries	Steel, construction, many other uses	>50% recycling

5.3 Scarcity of micronutrients – dynamic view

In an absolute sense, the R/P value does not say very much about the scarcity of minerals, because both P and R are subject to change. First of all, production from mining is not constant, but tends to increase with increasing use. And according to expectations, the use will continue to increase as a result of the growth in population and prosperity (see Figures 10 and 11 for the world mine-production of zinc and copper, respectively). However, in industrialised countries a certain decoupling has occurred recently between the level of prosperity and the magnitude of use for both of these elements, due to ongoing efficiency measures; thus, in several centuries, use per capita has declined. However, at the global level, this is not the case. Increasing prosperity will therefore result in increased production from mining that is greater than can be expected from population growth alone.

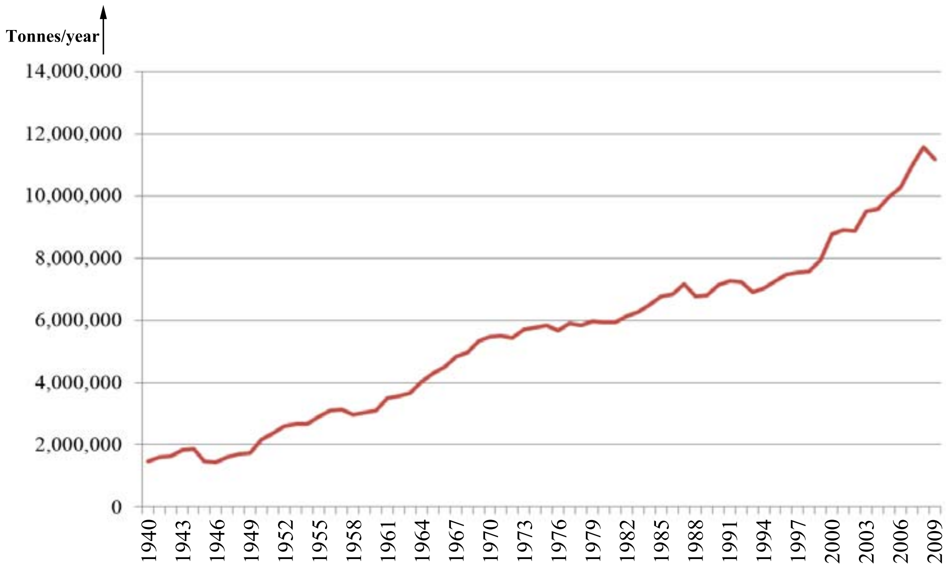

Figure 10 Global production of zinc from mining 1940-2009 (Source: USGS 2011).

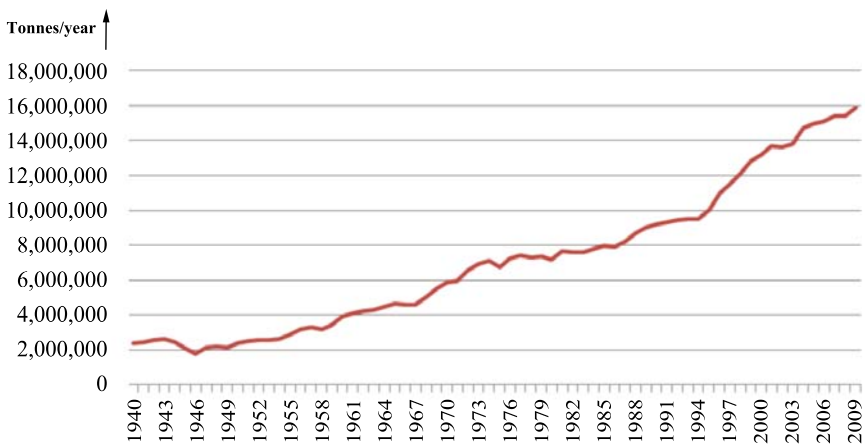

Figure 11 Global production of copper from mining 1940-2009 (Source: USGS 2011).

In addition, R is not a static unit either. As a result of production from mines – which continues to increase – the known recoverable reserves are declining, which will lead to higher prices. These higher prices will in turn lead to more exploration and improved recovery technologies, and thereby to an increase in the recoverable reserves. In technical terms, the hypothetical and speculative reserves are gradually upgraded to demonstrated (recoverable) reserves.

In practice, the value of R is largely determined by the exploration activities of mining companies. Exploration is often expensive, so exploration activities are usually not undertaken with R/P values above 30 to 40 years. Consequently, the market has a stabilising effect on the availability of the resources. On the other hand, the fact that the R/P value for zinc is only 21 years could be an indication that this element may become scarce within a single generation (see also Section 5.5).

5.4 Uncertainties in the data from USGS

The exploration activities of mining companies are decisive for the USGS data. But other types of inaccuracies can also be present in the data that the USGS receives from the mining companies. In Section 5.1, we referred to the sudden upgrading of the phosphate reserve figures from Morocco. This change took place due to a publication from the International Fertilizer Development Center (IFDC) in Alabama (USA) in 2010, which actually upgraded the phosphate reserves in Morocco in one step from 5.7 million tonnes to more than 50 million tonnes. As a result, it suddenly appeared that Morocco (with Western Sahara) possessed 85% of the world phosphate reserves.

Such adjustments to the known reserves can result from several causes: political considerations, changes in definitions and technological developments.[10] Perhaps this upward adjustment of phosphate reserves was based on politics. For example, following the export levy on phosphate imposed by China in 2008, Morocco may have wanted to emphasise its reliability as a producer and trading partner. Be that as it may, such a drastic modification is exceptional, and took the sector entirely by surprise. It demonstrates even more clearly that we must interpret the figures from the USGS cautiously. At the same time, it means that we must pay even more attention to geopolitical risks, and to the various types of side effects of mineral mining and processing.

5.5 Side effects – linkages of sustainability

Even with a constant ratio between recoverable reserves in the mines and production from mining, important underlying developments can be involved. In particular, there will often be a continuing decline in the richness of the ores (see Figure 12, which includes figures for zinc

[10] Prof. C. van der Linde, personal communication.

and copper). As a result, increasing amounts of energy and fresh water are needed for extraction and refining, which also affects the price. Figure 13 shows that lower ore quality (on the left) increases the need for energy and water by a factor of 10 to 20 relative to the initial high-grade ores. As a result, one type of scarcity leads to another type of scarcity. This link between scarcity problems and environmental problems has recently been referred to with the term "linkages of sustainability" (Graedel and Van der Voet 2010[11]).

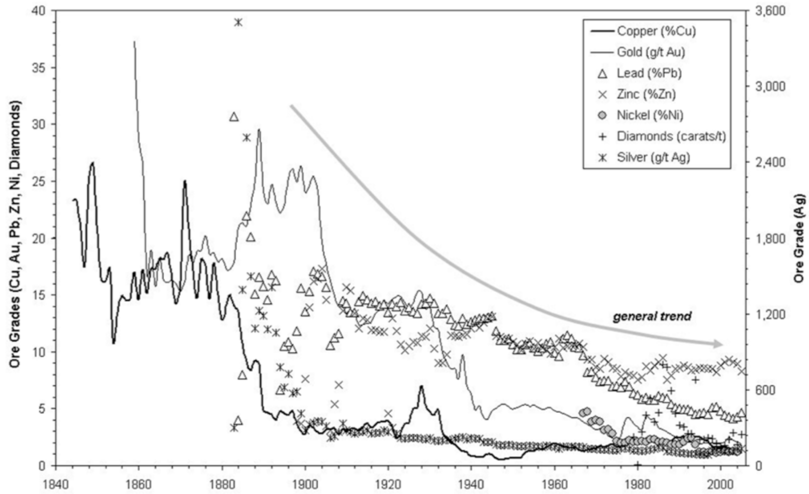

Figure 12 Declining ore grade of seven minerals since 1840 (Source: Mudd 2009).

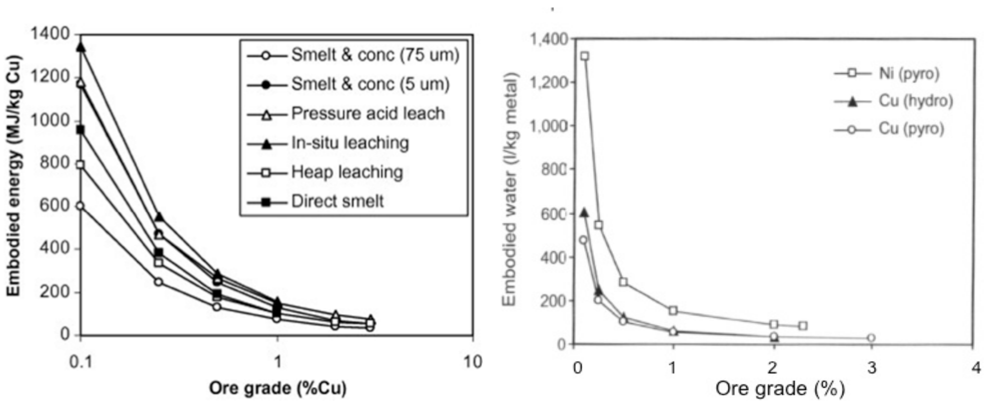

Figure 13 Required amounts of water and energy for copper mining as a function of the ore grade (Source: Norgate 2010).

At the world scale, the micronutrient ores discussed here will probably not become scarce very soon. However, the grade of the ores will decline, resulting in increased environmental burden. Prices will also increase, and increasing price fluctuations can be expected, possibly exacerbated by speculation. Developing countries will not have much chance on this market,

[11] Graedel , T.E. and Van der Voet, E. (eds.) 2010. Linkages of sustainability. Strüngman Forum Report. MIT Press, Cambridge.

even though they are facing the most severe deficiencies. In a related note, this problem is exacerbated by the cultivation of biomass for energy production. In the following sections we address the availability of zinc and selenium in greater detail.

5.6 Zinc

The current ratio between reserves and production (R/P) for zinc is only 21 years, which in itself can be seen as a reason for concern. However, this mineral is supplied by a relatively wide range of countries. As a result, the geopolitical risks – i.e., risks resulting from a deliberate manipulation of trade flows – are not very large. But it is expected that the increase of the use will continue in the future. As illustrated in Figure 14, if current developments continue, then industrial use will be greater than the supply in about 10 years. This suggests the possibility of Peak Zinc, similar to the much-discussed Peak Oil (according to King Hubbert 2004).[12] This certainly requires further analysis.

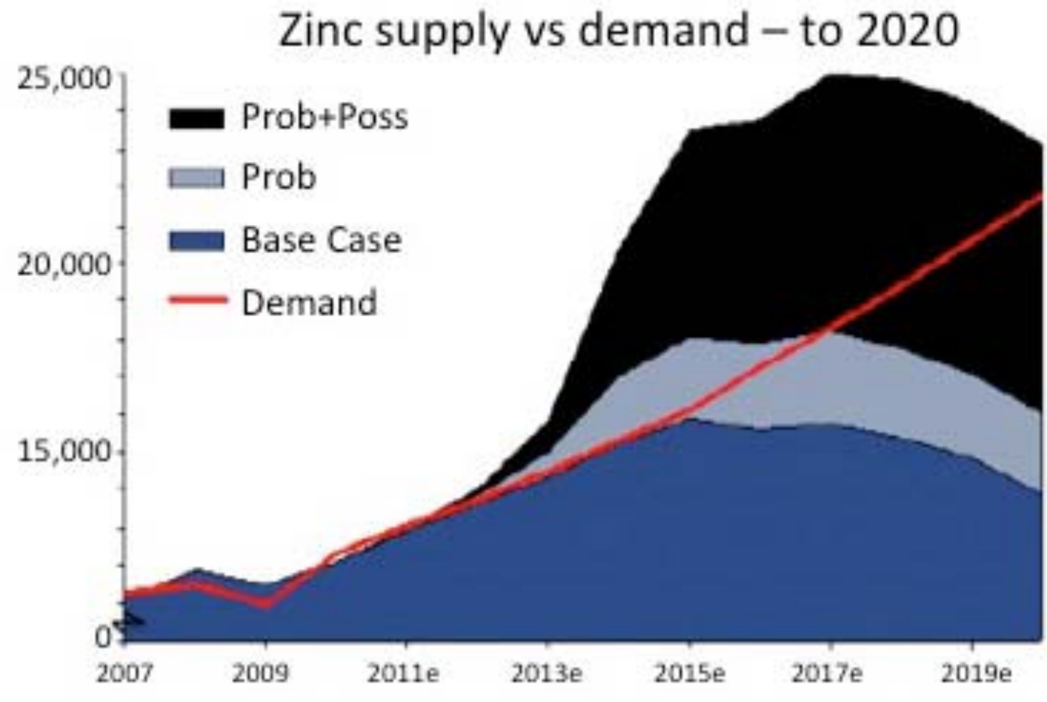

Figure 14 The global demand for zinc (red line) in the case of various scenarios (base case, probable, and probable + possible) for the total supply of zinc; 2007-2010: actual. 2011-2019: expected (Source: Citigroup Global Markets 2011). Y axis: annual zinc production from mines (x 1000 tonnes).

In addition to industry, the demand from agriculture must also be taken into account – or even prioritised. Can this demand be estimated? Given that:
- half of the current area of agricultural land is affected by zinc deficiency,

[12] For a discussion on this topic, see: R.A. Kerr: Even oil optimists expect energy demand to outstrip supply. *Science* 317, p 437, 2007. And: http://www.springerlink.com/content/vv58q21652jh185j/?MUD=MP.

- a one-time application of 10 kg of zinc per hectare is required,
it follows that there is a one-time need of 25 million tonnes of zinc, equivalent to twice the annual world use. In addition, to maintain a crop yield of 5 t/ha per year, on average 0.15 kg zinc per ha is required, i.e. 750,000 tonnes per year in total, or 6% of current world use.

These are substantial quantities, especially if the industrial demand by itself would lead to market shortages. Then there is a high risk that demand from agriculture will be outcompeted by industrial demand based on its greater purchasing power.

5.7 Selenium

Table 7 shows that the R/P value for selenium is 39 years; the statically determined level of scarcity is consequently similar to that for copper, molybdenum and manganese. Key applications are the glass industry, electronics and solar cells. Substitution is possible with these applications, but at higher prices. More than 75% of the global industrial selenium *production* is concentrated in four countries: Germany, Japan, Canada, and Belgium. The most important *mines* (not included in the table) are located in Chile, Russia, Peru and the USA. As a result, there is a geopolitical risk, though the industrial production takes place in countries that seem sufficiently stable for trade.

Similar to the situation with zinc, a key question is: to what extent can the demand for selenium for applications in the food chain be met by the market? No data are available about the worldwide area of selenium-deficient agricultural land, but there are indications that this area is significant. Assuming that:
- 50% of farmland is selenium deficient,
- to counteract ascertained selenium deficiencies (in livestock), 2 g/ha of selenium is applied,
then there would be a global need of 5,000 tonnes for a one-time application of selenium. This would comprise 2.5 times the current annual use of this mineral. After this, if all farmland were to be given an annual maintenance application of 0.1 g selenium per hectare, even this low dosage would require 25% of current annual world use. For nutritional supplementation for livestock, a dosage of approximately 1 mg per 100 kg animal weight per day is required, equivalent to 1.5 times the current annual world use of selenium.

These global estimates indicate that current industrial production is entirely insufficient to meet a possible demand from the food chain. Moreover, the production is inherently difficult to increase, since selenium is recovered primarily as a by-product of copper refining.

5.8 Towards reduced dependence on the world market

At least two approaches are possible to estimate the risk of dependence on the world market:

- a formalised classification of critical minerals,
- assessing vulnerability to geopolitics.

These will be discussed briefly, together with possible approaches to avoid the risks.

Classification

Classifications of critical minerals are available from both the EU and the USA; these classifications combine the economic importance with supply security. The critical minerals classification from the USA does not include any nutrients, but the EU classification (from 2010) includes zinc and copper, however, as minerals with a low risk. These optimistic assessments can be explained by the fact they concern only the next 10 years – a very short time period. In addition, the economic importance concerns only the importance for industry; the importance for agriculture and the world food supply has not been taken into consideration. Consequently, this approach is inadequate to indicate risks in the supply security of micronutrients.

Assessing vulnerability to geopolitics

The supply security of minerals depends on geopolitics. The risk is that countries with relatively large shares in the reserves and/or processing capacity could dominate and manipulate the market, e.g., by establishing cartels. With phosphate, this risk is obvious due to the large share – about 85% – of world reserves in Morocco (including Western Sahara) and China But geopolitics could play an important role with the micronutrients as well. For zinc and manganese, Table 7 shows that more than 50% of overall production from mining comes from only three countries, and for boron and molybdenum more than 75%. This includes less stable countries with a World Governance Index[13] between 40 and 70 (where 100 is most stable) such as China, Turkey, Argentina and Peru.

Securing supply

In the Netherlands, the government has chosen a standard solution with respect to trade risks: promoting adequate functioning of regional and global markets. Until recently, this approach appeared to be adequate, but it is becoming increasingly doubtful whether that will continue to be the case. To create more security, the EU could opt for bilateral trade agreements. For example, a bilateral phosphate trade agreement with Morocco and perhaps China appears to be an obvious step. Such agreements are most feasible if there is *mutual* dependency.[14] With Morocco and perhaps China, minerals could for instance be traded for food.

[13] The World Governance Index was developed in 2008 by the Forum for a new World Governance, based on the Millennium Development Goals of the United Nations.

[14] See R. de Wijk: *Honger is wegbereider van oorlog*, *de Volkskrant* 5 March 2012.

The world market offers other opportunities: the unintended presence of micronutrient elements in global trade flows of raw materials and semi-finished and finished products. At present, the possible magnitude of this micronutrient component is unclear, although some information is known about flows of macronutrients. For example, the Netherlands is accumulating phosphorus due to soybean meal imports, and in the future possibly due to imports of biofuels. From a fertilisation perspective, this is beneficial for the Netherlands, and for the EU as a whole, given the virtual absence of phosphate ore on the continent. But at the same time it creates just another dependency, and thereby a vulnerability. For example, if China were to purchase the entire soya supply from Brazil and Argentina, then the Netherlands would lose a major source of phosphate. It is also important to specify the risks of depletion and accumulation of micronutrients resulting from such non-targeted flows. For European countries it could be interesting to recover the micronutrients from such trade flows and market them independently.

Reducing use
A more fundamental solution lies in limiting the demand for newly mined ores. This can be achieved by:

- increasing efficiency of extraction and use
- increasing recycling
- substituting for less scarce materials.

These options all require technical innovation.

Regarding increased *efficiency of extraction*, substantial improvements appear to be feasible, given the overall high losses in mining tailings. Regarding increased *efficiency of use*, one possibility – relatively easy to realise – is available in the European livestock sector: reducing the supplementation of zinc and copper in livestock feed. This supplementation has already been greatly reduced, but feed still contains approximately twice as much as required from a nutritional perspective.

Regarding *recycling*, significant percentages are recycled primarily for iron, zinc, manganese, copper and molybdenum, related to large-scale industrial production (see Table 7). Boron is not recycled. No clear picture is available about how recycling can be initiated for the elements concerned, or how existing recycling processes can be intensified.

Regarding *substitution*, all the aforementioned elements are essential as nutrients, but substitution in industry is possible. With respect to zinc, for example, it is important to aim for a replacement of the galvanisation process and the use in car tyres, the most important industrial applications of this metal. These are dissipative applications, i.e., the metal is applied in such a way that recycling is impossible. Coating of iron or steel with plastics is an alternative, although more expensive. For copper, replacement is already taking place; in power transmission it is being replaced by aluminium, and in telecom it is being replaced by optical fibre. Substitutes also exist for many applications of boron (for example in washing powders and insulators). However, no realistic alternatives for the metallurgical applications of manganese (used in steel production) currently exist.

6. Recommendations for policymakers, the farming sector, the feed and food industries and R&D

6.1 Current policy

Both at EU level and that of the individual member states, there are overlaps between the micronutrients problem and other policy areas, notably fertiliser legislation, regulation of feed and veterinary drugs, and legislation on water and soil quality. Until now, all this legislation has focussed on the issue of excess: maximum limit values have been imposed to protect quality. No attention has been paid to the issue of potential scarcity. For example, the recent Dutch policy of public-private financing of R&D for so-called top sectors (sectors with high economic potential) does not address the scarcity of mineral resources in any of the selected sectors.

We see the same picture at the global level. In the Codex Alimentarius of the FAO and WHO, only the maximum values for micronutrients are specified.[15] There are reference points in the WHO/FAO report "Vitamin and mineral requirements in human nutrition", which addresses the need of consumers for various nutrients. However, these needs are converted only into requirements for the human diet; they are not addressed in relation to the fertilisation of farmland.

Consequently, new policy is needed at the national, European and global levels. In the section below, we primarily discuss the policy of the Dutch government, which can take initiatives in various frameworks. We also make recommendations for current agricultural practice, for companies in the food chain and in mineral chains, as well as recommendations for research.

6.2 Recommendations for the EU and its Member States

- Put the current and future scarcity of micronutrients in agricultural soils, feed and food, and the mineral reserves on policy agendas at the national, European and global levels.
- Pay ample attention to micronutrients when elaborating measures in the EU Common Agricultural Policy to stimulate improvement of soil quality.
- Assess agricultural nutrients in the European Raw Materials Initiative regarding their function for agriculture, and choose a significantly longer time horizon than the current10 years.

[15] World Health Organization and Food and Agriculture Organization of the United Nations, 2004.

- Break through the dominance of the NPK fertilisation regimen, both in European and global organisations (such as FAO, WHO and World Bank). Replace this NPK regimen with a broader regimen which also takes account of the current and future scarcity of mineral micronutrients.
- Seek long-term supply agreements with countries that have large reserves of mineral micronutrients, to avoid future scarcity. This is the strategy the EU has chosen in its Raw Material Initiative for industrial resources. Geopolitical risks are greatest for boron and molybdenum; for zinc and manganese the risks are smaller but still credible. China has large reserves of many mineral micronutrients, but the USA and several South American countries are also important potential suppliers. The most effective agreements are those based on mutual dependencies. With China, for example, the EU could trade micronutrients for agricultural products. However, such agreements are not easily achieved and, in addition, cannot guarantee long-term supply, given the finiteness of these resources and increasing geopolitical uncertainties.
- Foster reduction of the use of key micronutrients as a more sustainable long-term strategy. Such policies should involve more efficient use, recycling and – where possible – substitution of mineral micronutrients. This can all help secure the supply while reducing dependence on the world market and associated geopolitical risk as well as minimising pollution.
- Give high priority to zinc and selenium. For zinc, severe deficiencies are occurring in food chains in large parts of the world, and zinc mining shows the most critical ratio between production and known reserves. Priority areas include increased recycling and development of alternatives for galvanisation. For selenium, important health problems are being observed both for people and livestock, particularly in developing countries. A start should be made with recycling, and R&D should focus on the development of substitutes for industrial use.
- In global forums, call for broader attention for micronutrient deficiencies from governments, agro-chains and private foundations. Current micronutrient programmes focus on deficiencies in humans and should be broadened to include soil and livestock. As for selenium, which is not essential to crops, it may be more efficient to supply it to livestock and humans only.

6.3 Recommendations for the farming sector and the feed and food industries

- Avoid over-fertilisation with phosphate to prevent antagonism with zinc, copper and iron. Governments can promote such a policy. For example, in China the subsidy on phosphate fertiliser use could be reconsidered.
- Take agricultural measures to prevent erosion and leaching, such as year-round cover crops and mixed cropping.
- Apply animal manure, which already contains most micronutrients.
- Apply fertilisation with micronutrients that are deficient in the soil.

- Integrate sustainable soil management and micronutrients into corporate responsibility across the agro-food chain, including the feed and food industries.

6.4 Recommendation for companies in mineral chains

- Make the chains of mineral micronutrients – beginning with mining, followed by use in industrial products and ending with recycling – more efficient and effectively closed. Substitutes should be developed for zinc in galvanisation, in roof gutters and in car tyres, and for selenium in glass and solar cells. It is important that the individual parties in the chains all take responsibility. With phosphate, this process has already begun in some countries – such as the Netherlands.

6.5 Recommendations for R&D

- Conduct an improved and larger scale survey, especially in developing countries, of micronutrient availability in soils, partly in relationship to macronutrients like phosphate (comparable with the soil research in China). The survey would be coordinated by the FAO. This would render fertiliser use more efficient and achieve higher yields and better food quality. Also further research is needed into methods and techniques for soil assessment at affordable prices.[16]
- Study the behaviour of micronutrients, including their interactions, in the soil and their uptake by crops, including research into measures to increase nutrient availability to the crop.
- For a range of combinations of soils, crops, livestock and populations, study which is the optimal strategy: food supplementation, food fortification, breeding of micronutrient-rich varieties, or actually down-to-earth soil fertilisation. As far as essential plant micronutrients are concerned, fertilisation has the potential of combining higher crop yields, higher micronutrient densities and better bio-availability. In which situations do these advantages apply?
- Conduct a broad study into the sustainability of supplementing the various micronutrients from mining, as part of a strategy to shift from nonessential industrial to essential agricultural uses. This requires sensitivity analyses concerning the reserves and the use of the key micronutrients, in relationship to various scenarios for the development of industrial and agricultural use. For example, what are the effects of increased agricultural acreage, more livestock, more biofuel production and higher yields per hectare on the demand for mineral micronutrients? At what scale and to what extent can soil depletion

[16] Very recently, research was launched aiming at low-cost techniques for micronutrient assessment in soils, followed by large area soil surveillance in Africa. The project also includes capacity building. It is a collaborative effort by the World Agroforestry Centre (ICRAF), MTT Agrifood Research in Finland and the University of Nairobi.
https://portal.mtt.fi/portal/page/portal/mtt_en/projects/foodafrica/Workpackage1

be expected and what is the effect of solving these shortages on the production of mineral micronutrients?

- Study the possibility of whether we are heading towards Peak Zinc, Peak Molybdenum etc., analogous to the research into Peak Oil. Such a study cannot be based only on country-by-country data from the USGS. In addition, cumulative availability curves can be made in relationship to the price of zinc.[17] As for selenium, a complication is that it is typically produced as a by-product of copper mining.
- Analyse the non-targeted global flows of micronutrients in the trade of raw materials, intermediate products and finished products, with their various sources and sinks, as a possible basis for recovery and marketing of the micronutrients.
- Pursue agro-technological innovations to improve the efficiency of micronutrient utilisation by crops, livestock and humans.
- Develop technological innovations towards closed-loop chains in the extraction, use and recycling of mineral micronutrients. This includes increased recycling in the form of urban mining.

[17] For example, see: A. Yaksic and J.E.Tilton: Using the cumulative availability curve to assess the threat of mineral depletion: the case of lithium. *Resources Policy* 34, pp 185-194, 2009.

Appendix 1 Reserves and geographical concentration of key mineral nutrients

Risk data for key micronutrients and several macronutrients, ranked according to R/P ratio (reserves in mines/annual production from mines) (Source R and P data: USGS).

Mineral	Reserve x 1000 tonnes	Production x 1000 tonnes/yr	R/P yr	By-product?	Geographical concentration?[1]	% R in mines EU[2]	Substitutes available?	Supply risk on scale 0-5[3]
Zinc	250,000	12,000	21	No	Low	1%	Difficult	0.4
Copper	630,000	16,200	39	No	Low	4%	Partial	0.2
Selenium	88,000	2,260	39	Yes	High	0%	Yes	
Molybdenum	9,800,000	234,000	42	No	High	0%	Yes, but by other critical minerals such as V, Nb, C, W, Ta	0.5
Manganese	630,000[4]	13,000	48	No	Low	0%	No	0.4
Borium	210,000	3,500	60	No	High	0%	Yes	0.6
Iron	180,000,000	2,400,000	75	No	Low	2%	-	
Potassium	9,500,000	33,000	288	No	Low	2%	-	-
Phosphate ore	65,000,000[5]	176,000	370	No	High	0%	No	
Magnesium	2,400,000	5,580	430	No	High	4%	Yes	2.6[6]
Nitrogen	Abundantly available from the air	131,000	n.a.[7]	No	Low		No	
Calcium (lime)	Abundantly available	310,000		-	Low		-	-
Sulphur	In crude oil: abundantly available	68,000	n.a.	-	Low		-	-
Sodium	Abundantly available	n.a.	n.a.	-	Low			

1 High = the top 3 countries have > 75% of the production
2 Expressed as a percentage of the reserves, according to the USGS.
3 According to the definition in Appendix 1 of the Raw Materials Initiative of the EU (RMI) report of June 2010, supply risk (SR) consists of a national component (concentration and stability) and indicators for substitutability and recycling.
4 This reserve does not include the manganese nodules on the ocean floor because mining is not yet economically feasible.
5 These are estimates for 2010. USGS Commodity Summaries 2011: “Significant revisions were made to reserves data for Morocco, using information from the Moroccan producer and a report by the International Fertilizer Development Center”; in 2009, the estimated phosphate reserve was 16,000,000 (x 1000 tonnes) and the annual production 158,000 (x 1000 tonnes), resulting in a R/P value of approximately 100 years.
6 USGS Mineral Commodities estimated a very low supply risk – in contrast to the RMI.
7 n.a. = not applicable

Appendix 2 Mandate and composition of the Dutch Platform for Agriculture, Innovation and Society

The work of the Dutch Platform for Agriculture, Innovation and Society contributes to the knowledge policy of the Ministry of Economic Affairs, Agriculture and Innovation through:

1. Exploring the consequences of possible technological developments and considering alternatives and/or;
2. Exploring possible technological contributions to the solution of societal problems relevant to the policy fields of the Ministry and/or;
3. Exploring and making explicit the standards and values that are involved with specific developments, as well as the differences in standards and values between various groups in society.

The following people, all in an individual capacity, are members of the Steering Committee:

- *Drs.* W.J. (Wouter) van der Weijden, Chair (Centre for Agriculture and Environment Foundation)*
- Dr A.M.C. (Anne) Loeber (Researcher and assistant Professor, University of Amsterdam)
- Prof. H.A. (Helias) Udo de Haes (Emeritus Professor of Environmental Studies, CML, Leiden University)*
- *Drs.* J.A.C. (Hans) Vink (General Manager Nutreco Aquaculture [Skretting] NW-Europe)
- Prof. G. (Guido) Ruivenkamp (Professor of Critical Technology Construction, Wageningen UR)
- Mr J.C.P. (Jan Cees) Vogelaar (Dairy farmer, initiator of HarvestaGG)*

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