Stichting Onderzoek Wereldvoedselvoorziening van de Vrije Universiteit

Centre for World Food Studies

Simultaneously addressing micronutrient deficiencies in soils, crops, animal and human nutrition: opportunities for higher yields and better health

by

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Staff Working Paper **WP - 06 - 02** **September 2006**

Contents

Abstract

A study was done on the relationships between micronutrient deficiencies in soils, in food and fodder crops, in animal nutrition, and in human nutrition. While positive relationships between low soil contents and the occurrence of human deficiencies are since long known to exist for micronutrients such as iodine and selenium, the situation is less clear for other micronutrients, including iron and zinc.

Results indicate that not only for iodine and selenium, but also for zinc, there are strong indications of direct linkages between soil zinc contents and human zinc status. For iron, uptake by plants and also by humans is highly complex, yet a positive relationship between poor iron availability from soils and the occurrence of human iron deficiency cannot be excluded. For other micronutrients, such as copper, magnesium and manganese, linkages between soils, food crops, and animal and human nutrition may well exist but currently available information is insufficient to analyze such relationship in full detail.

It is further explored to what extent there are possibilities for simultaneously increasing crop yield and crop micronutrient contents through application of micronutrients to crops. Where this is possible, there would be a simultaneous benefit both for farmers in the form of higher incomes and for consumers in the form of better health.

Results show that for zinc, there are strong opportunities for both increasing crop yields and increasing crop micronutrient contents for major crops such as wheat, maize and rice. For iodine, application to fodder crops might result in better growth of animals, higher iodine contents of animal products such as meat and milk, and on its turn contribute to improved human iodine status. For iron, positive effects on both yields and crop iron contents are, in principle, possible, but chemistry and physiology of iron is highly complex, and there is a strong need for further research into agriculturally based approaches aimed at increasing crop iron contents. For selenium, experiences in Finland and China have shown that crop selenium contents, and as a result human selenium intake, can be increased by adding selenium to common fertilizer.

When selecting appropriate technologies for applying micronutrients to crops, best results are most likely to be obtained by applying micronutrients separately on a one by one basis to crops, or in combinations of a few carefully selected micronutrients, in order to prevent antagonistic interactions between traditional fertilizers and supplementary micronutrients. It is speculated that, in particular in Sub Sahara Africa, controlled and site-specific application of micronutrients to crops, in combination with well-balanced usage of traditional fertilizer (N, P and K) might help break the vicious cycles of low yields, poverty, and poor human nutrition.

1. Introduction

Dietary micronutrient[1] deficiencies affect a large part of the global population. The World Health Organization estimates that globally some two billion people are affected by iron deficiency and that some 750 million people suffer from iodine deficiency (WHO, 2006; Unicef, 2006). Also zinc deficiency is increasingly recognized as an important public health problem (Ramakrishnan, 2002; Black, 2003a, 2003b). In recent years interest in the occurrence of human micronutrient deficiencies has been growing strongly, for several reasons. In the first place, human micronutrient deficiencies appear to be much more widely spread than previously thought and information on their geographical distribution is rapidly increasing (ACC/SCN, 2004). In the second place, there is a considerable amount of new information on the adverse health affects of various micronutrient deficiencies (Black, 2001). For example, over past decades it has become increasingly clear that iodine deficiency, apart from causing an enlarged thyroid gland (goiter), can also seriously impair intellectual development of infants and children (WHO, 2004). And while some years ago there was only limited public health interest in zinc, now it is widely recognized that zinc deficiency is associated with suboptimal growth and reduced immuno-competence in children. In the third place, evidence is increasing that for certain micronutrients, also marginal intakes can have adverse health effects, with for example a marginal selenium intake playing a role in the aetiology of certain types of cancer (Finley, 2006).

There are a number of reasons for the occurrence of dietary micronutrient deficiencies. First, among poor populations overall food intakes are often below minimum requirements and as a result not only the intake of macronutrients (carbohydrate, fat, protein), but also the consumption of micronutrients (minerals, trace elements and vitamins) can be inadequate. Second, among poor communities diets are often highly monotonous, which increases the risk that the dietary intake of one or more specific micronutrients is below the amounts required for good health. A more specific situation arises when in a country or region the majority of locally produced foods have a low content of a specific mineral or micronutrient, as a result of the fact that the soils on which local foods are grown are low in their contents or availability of this nutrient. When in such places the people are largely dependent on locally produced foods, the intake of this nutrient will most likely be inadequate. Perhaps the oldest and most well known example is iodine. In various regions in the world (India, China) iodine deficiency disorders, such as cretinism and goiter, are widely prevalent and strongly related with low levels of iodine in local soils and, as a result, in foods grown on these soils or in drinking water derived from these soils (Abrahams, 2002).

Also in agriculture, micronutrients are an issue of increasing interest and concern. Many research activities are being undertaken which address the relationships between micronutrient provision to plants and associated crop growth, and trace elements such as zinc, manganese and copper are increasingly recognized as essential when aiming for better yields (White and Zasoski, 1999; Mann et al., 2002; Bhadoria et al., 2003; Sotomayor-Ramirez et al., 2003; Fageria and Breseghello, 2004; Rashid and Ryan, 2004; Welch and Graham, 2004; Gupta, 2005; He et al., 2005). In addition, various studies suggest that better micronutrient provision to crops might

[1] In this report the term “micronutrient deficiency” is not only used to indicate deficiencies in trace elements essential in human nutrition, such as iodine, zinc and iron, but also deficiencies in essential minerals such as magnesium and calcium. In agriculture these last elements (magnesium, calcium) are generally classified as macronutrients, but not in human nutrition (macronutrients in human nutrition are carbohydrates, fats and proteins). In human nutrition also vitamins are classified as micronutrients, but vitamins are largely outside the scope of this report.

result in more vigorous seedlings, lower vulnerability to plant diseases, and possibly also improved drought resistance (Frossard et al. 2000; Welch and Graham, 2002; Bouis, 2003; Welch and Graham, 2004). In fact, the ‘green revolution’, which is based on high-yielding varieties, large-scale application of irrigation, and usage of fertilizers that mainly contain major nutrients (nitrogen, phosphorus, potassium), might well have contributed to an increasing prevalence of micronutrient deficiencies in soils, and consequently in human nutrition (Biswas and Benbi, 1997; Welch and Graham, 1999; Dar, 2004). Finally, it should be noted that also in livestock production and animal husbandry the importance of minerals and trace elements has been well established (Kincaid, 1999; Lee et al., 1999; Ellison, 2002).

The first objective of the present paper is to investigate the occurrences and the strengths of the relationships between micronutrient deficiencies in soils, in crops, and in animal and human nutrition. While for iodine, and also for selenium, such relationships are well known, for other micronutrients such as zinc, iron, or magnesium, the situation is less clear. Yet, as point of departure in the present paper, it is presumed that for those areas where soils are very low in absolute content or in bioavailability of certain micronutrients, and where at the same time local people largely depend on these soils for their food production and consumption, human micronutrient deficiencies are bound to occur. The second objective of this report is to explore opportunities for addressing micronutrient deficiencies, as these occur simultaneously in agriculture and in human nutrition, in a way that would benefit both farmers and consumers[2]. For example, where addition of micronutrients to crops would result both in higher yields and in higher nutrient contents of the crops, there would be gains both in economic terms for farmers and in health terms for consumers. Under such conditions, a direct contribution from agriculture in addressing human micronutrient deficiencies is most likely to be attractive and feasible.

From the outset it is important to note that minerals and trace elements which are essential in human nutrition are not necessarily the same that are essential in plant nutrition or vice versa (Table 1). It should also be stressed that not only the absolute soil contents of minerals and trace elements affect crop growth and crop nutrient contents, but also their availability for uptake by plants. Minerals and trace elements can be present in the form of readily soluble salts, but also as highly insoluble compounds incorporated in soil particles, being unavailable for plant nutrition, or incorporated in organic substances. Furthermore, the processes of nutrient uptake by plants are associated with numerous interactions and antagonisms between the various nutrients, and between nutrients and other substances present in soils, while also moisture status, pH and temperature affect nutrient uptake by plants. And finally, plants may engage in mutualistic cooperation with other soil organisms in order to obtain scarce nutrients. For instance mycorrhizal fungi can supply nutrients to the plant in exchange for organic substances assimilated by the host plant. Thus, in many cases other factors than just absolute soil concentrations themselves are the major determinants of nutrient uptake by plants (House, 1999; Rengel et al., 1999; Frossard et al., 2000; Gupta, 2005).

Similarly, also in human nutrition, the absolute concentration of a nutrient in food is only one factor that determines how much of the nutrient will enter the human body. Also here, other factors can strongly affect the actual uptake and absorption of a nutrient from food, such as the form in which it is available, the presence or absence of substances that inhibit or promote

[2] Under subsistence conditions households are of course mainly consuming own produced food and farmers and consumers are therefore to a large extent the same people.

intestinal absorption (e.g. phytic acid, ascorbic acid), the way food has been stored, processed or cooked, the combinations with other foods when being consumed, and finally the health conditions of the person consuming the food (Welch and Graham, 2000).

Table 1. Essential minerals and trace elements in plant and human nutrition

	Essential minerals and trace elements in higher plant nutrition [1)]	Essential minerals and trace elements in human nutrition [2)]
Phosphorus	+	+
Potassium	+	+
Sodium	±	+
Calcium	+	+
Magnesium	+	+
Sulphur	+	+
Manganese	+	+
Iron	+	+
Zinc	+	+
Copper	+	+
Cobalt	±	+
Chromium	-	+
Boron	+	-
Molybdenum	+	+
Nickel	+	(+)
Aluminium	±	-
Chlorine	+	+
Iodine	-	+
Silicon	±	+
Selenium	±	+

1) '+' : essential; '–' : not required; '±' : essentiality not established, but considered beneficial

2) '+' : essential; (+) : essentiality not established, but possibly required

Sources: Marschner, 1995; Garrow et al., 2000; Wiseman, 2002.

This report consists of nine sections. After this introduction follow four sections in which the micronutrients iodine, iron, zinc and selenium are presented in separate sections, with for each micronutrient an exploration of possibilities and opportunities for joint approaches in agriculture and human nutrition. In two subsequent short sections, currently available information on three other micronutrients (copper, magnesium and manganese) is briefly presented, followed by a discussion on multiple micronutrient deficiencies, as these occur in agriculture or in human nutrition. The next section discusses, from a practical point of view, possibilities for providing crops with required micronutrients. The report ends with a discussion and conclusions.

2. Iodine deficiency

One of the most widespread human micronutrient deficiencies in the world is iodine deficiency. In its severe forms, it manifests itself as cretinism and mental retardation. Milder forms may result in goiter, characterized by an enlarged thyroid gland, a condition which occurs in millions of people in various parts of the world. But also without visible effects, a suboptimal intake of iodine can have adverse effects, for example on learning capacities, in particular of children (WHO, 2004).

Iodine deficiency is a micronutrient disorder since long known to be related with local geological conditions (White and Zasoski, 1999). As a result of low iodine contents of soils, food crops grown on these soils, and also ground water being used for drinking, are low in iodine content and the total dietary intake of iodine is likely to be below human requirements. Iodine contents of soils may vary strongly, and regions where soil iodine contents are low occur throughout the world (FAO, 2002). Probably the most comprehensive currently available dataset on iodine contents of soils is the compilation by Johnson (Johnson, 2003). It provides information on iodine content of over 2200 samples from a wide range of locations, including large numbers of soil samples from New Zealand, Japan, USA and Germany. However, for many other parts of the world, and in particular for low-income countries, only limited information on soil iodine contents is available. The oldest reports on the linkages between environmental iodine deficiency and the occurrence of goiter date back to the 1920s, based on findings in Switzerland and New Zealand (Saikat et al., 2004). Shortly thereafter, in the late 1930s, epidemiological investigations in the United States established direct relationships between low iodine contents of soils and the occurrence of endemic goiter (White and Zasoski, 1999). More recent publications report on the linkages between soil iodine content and the occurrence of goiter in many other countries, including Australia, New Zealand, Egypt, Nigeria, Myanmar, Italy and India (Khin-Maung-Naing et al., 1989; Ubom, 1991; El-Sayad et al., 1998; Li et al, 2001; Ghose et al., 2003; Thomson, 2004; Valentino et al., 2004). Based on recent information on urinary iodine concentrations in population samples, the World Health Organization has categorized countries in the world in various classes of iodine status, ranging from severe deficiency to excess (WHO, 2004). On this basis, one country, Pakistan, is classified as severely iodine deficient, and 13 other countries are considered moderately iodine deficient (Figure 1). Such national averages provide only partial information, as intra-country variation can be very large. In many countries high rates of iodine deficiency occur in remote, often poor regions or provinces.

Although a deficiency in iodine has serious health effects in humans, it is not essential for higher plants (Table 1). Therefore, in principle the application of iodine to crops is unlikely to have an effect on crop yields. Yet, there are some exceptions, such as results from greenhouse studies with leafy vegetables, where the application of iodine resulted in increased yields (Weng et al., 2003; Dai et al., 2004). But also without having an effect on yields, from a nutritional point of view it is important to know what possibilities there are for increasing crop iodine contents. Interesting results have been reported from China where the addition of iodine to irrigation water resulted in up to threefold increases in soil iodine levels, which was accompanied by an increase in iodine levels in animals, and in humans relying on local food crops and on locally produced meat (Cao et al., 1994; Delong et al., 1997; Rengel et al., 1999). It should be noted that in greenhouse studies with rice, application of iodine (in the form of KIO3) resulted mainly in increased iodine concentration of straw and not of grain (Mackowiak and Grossl, 1999).

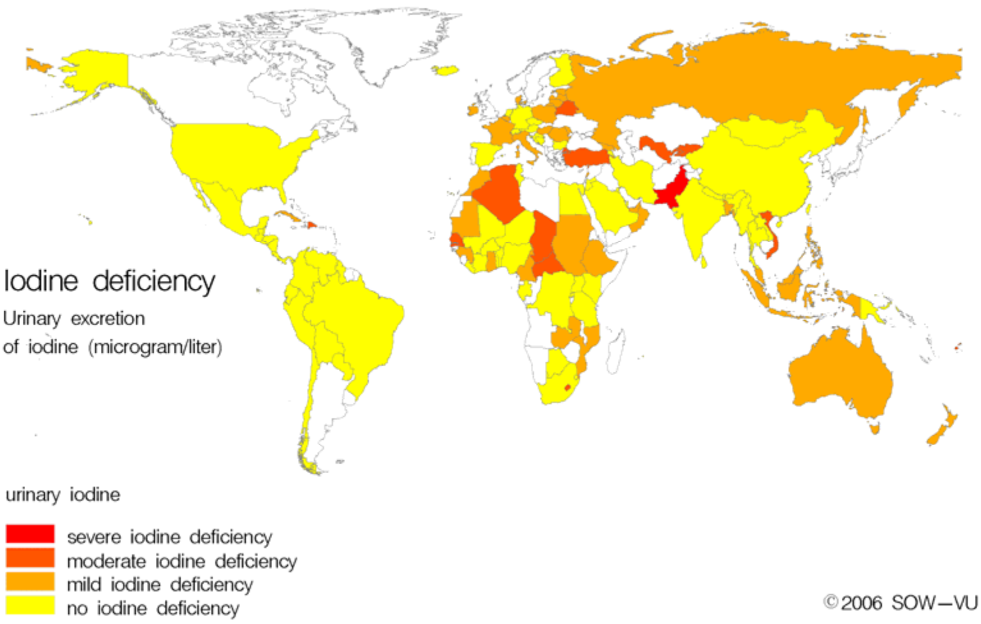

Figure 1. Iodine deficiency in the world, at the level of countries, based on urinary iodine (UI) excretion; colour codes for various degrees of iodine deficiency; when blank no data available. Source: Figure based on data from WHO, 2004 [3] .

Apart from soil iodine contents and availability, other factors can play a role in the etiology of iodine deficiency disorders. For example, a number of studies report on interactions and physiological relationships between selenium and iodine, and in China a strong overlap between the occurrence of selenium deficiency and the occurrence of iodine deficiency has been reported (Vanderpas et al., 1990; Ngo et al., 1997; Arthur et al., 1999; Lyons et al., 2003, 2004). Furthermore, in Sri Lanka even an inverse relationship between iodine content of soil and prevalence of iodine deficiency has been observed, which has been partially ascribed to metabolic interactions between iodine and selenium (Fordyce, 2000a). In addition, it is known since long that foods such as cassava and millet may contain goitrogens, substances that negatively affect thyroid functioning and that can induce or aggravate iodine deficiency (Delange, 1994; Abrahams, 2002; Chandra et al., 2005). Still, the primary cause of iodine deficiency in the world is a low iodine content of soil and water.

The most widely followed approach to address human iodine deficiency is fortification of salt with iodine, and many countries have a long record of law-enforced salt iodination. Yet, success is not always complete, and in particular in developing countries salt iodination did not always fully eliminate iodine deficiency. For example, in India iodized salt is practically universally available, yet in several districts urinary iodine excretion is below the minimum threshold level of 100 microgram/day (Kapil and Singh, 2004; Toteja et al., 2004). In China, despite large-scale promotion of iodized salt, iodine deficiency remains a public health problem in some remote

[3] Software for generating the map has been described in Overbosch, 2006.

provinces, such as Xinjiang, which can be partially explained by the fact that people use freely available rock salts, which are very low in iodine (Zhu et al., 2003). In Australia, re-emergence of iodine deficiency has been reported, and partially ascribed to the fact that currently only about 10% of the population is using iodized salt (Li et al., 2001).

Finally, it should be noted that also most animals require iodine in their diet, and a deficiency of iodine can affect growth and health of in particular goats, but also sheep, cattle and pigs (Lee et al., 1999; Meschy, 2000; Pattanaik et al., 2004). Figure 2 shows for the United States in which regions iodine contents of soils are low and where, as a result, livestock may develop goiter when iodine is not added to feeds (Pfalzbot, 2006). It is also interesting to note that supplementation of animal feed with iodine has been shown to result in higher iodine concentrations in meat and milk (Kaufmann et al., 1998; Schone, 1999; He et al., 2002). Thus, enriching animal feed with iodine can simultaneously improve both animal and human health. In fact, it has been claimed that the elimination of human iodine deficiency in the Czech Republic can be partially attributed to iodine supplementation of livestock (Zamrazil et al., 2004).

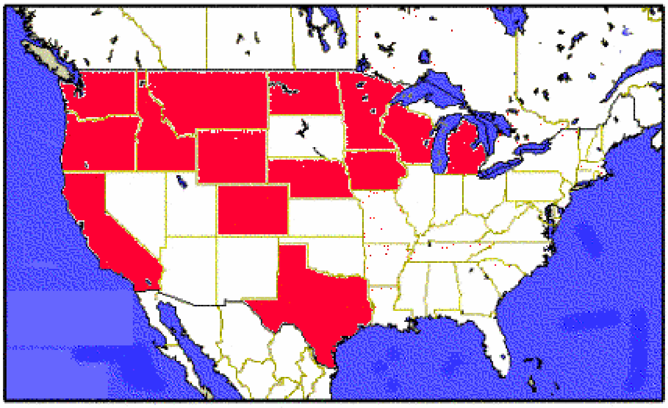

Figure 2. Iodine deficient soils in the United States (Pfalzbot, 2006)

In conclusion, iodine deficiency occurs world wide and is the classic example of a strong relationship between a low content of a micronutrient in soils and food crops and, consequently, the occurrence of a deficiency in humans. Iodination of salt is the most widely followed approach in addressing human iodine deficiency, but there may be room for agriculture based approaches, aiming at increased iodine contents of food crops. However, as iodine is not an essential nutrient for food crops, agricultural benefits are generally absent, which reduces the scope for a concerted agricultural and nutritional approach. In some countries a contribution towards eliminating iodine deficiency might come from the livestock sector, as iodine supplementation, may not only improve animal health, but also result in increased iodine contents of meat, milk and other dairy products. Currently, in particular for developing countries good information on soil iodine contents is highly inadequate, which makes proper analysis of the situation and identification of needed approaches complex.

3. Iron deficiency

More than two billion people are reported to be iron deficient, which makes iron deficiency the most widespread human micronutrient deficiency in the world (Rengel et al., 1999; ACC/SCN, 2000). Among the consequences of iron deficiency are nutritional anemia, lower resistance to infection, reduced learning abilities, stunted growth, fatigue and reduced productivity (Lawless et al., 1994; Welch, 2002). Iron deficiency affects in particular women of reproductive age, resulting in adverse pregnancy outcomes, such as low birth weight and still birth, and high rates of maternal mortality. In view of its effects on working capacity, iron deficiency clearly also has economic implications (Thomas and Frankenberg, 2002).

Iron is an essential nutrient for crops, and plant iron deficiency is since long known to occur in many regions of the world. It can be recognized by the occurrence of intraveinal chlorosis, the appearance of yellow or pale spots on the leaves of plants. Crops suffering from iron deficiency will grow slower than normal and are more susceptible to disease (Cakmak, 2002; Kulandaivel et al., 2004; Rashid and Ryan, 2004; Wiersma, 2005; Chatterjee et al., 2006). In terms of yields, estimated soybean losses in the north and central United States as a result of iron deficiency have been estimated to be in the order of magnitude of 300.000 tons a year (Hansen et al., 2004).

In most soils iron is present in large quantities. On average, between 3-5% of soils consists of iron, which makes it the fourth most abundant element in the earth crust, after oxygen, silicon and aluminum. However, most iron in soils is unavailable for plant absorption (Meng et al., 2005). For example, iron deficiency is common on calcareous soils (which have a high pH), as iron availability to plants decreases with increasing pH. On the other hand, availability of iron for plants is generally high in acid tropical soils. Copper, zinc, manganese and phosphate are iron antagonists, and high levels of these elements in soils (or in fertilizer) can reduce iron uptake by plants. Thus, information on extractable iron, for example using DTPA[4], is generally of much more relevance than information on the absolute levels of iron contents in soils.

Iron contents of crops can show wide variations (Meng, 2005) (Table 2). There are not only considerable differences between mean iron contents of different crops (rice, wheat, maize, soybeans), but also within a single crop species variability can be very large (Graham et al., 1999; Welch and Graham, 1999; Frossard et al., 2000; Monasterio and Graham, 2000; Cakmak, 2002; Kennedy and Burlingame, 2003). Also, green revolution cultivars tend to have lower iron contents in comparison with traditional genotypes (Monasterio and Graham, 2000; Khush, 2001). Yields of iron deficient crops can, in principle, be increased through application of iron to soils. However, as the uptake of iron from soils is highly complex, improving crop yields through fertilization with iron has been shown to be difficult (Schulte, 2004). For example, application of iron to soils in the form of ferrosulfate (FeSO4) has generally resulted in at most limited effects on crop yields (Frossard et al., 2000). Other forms in which iron might be added to soils (e.g. as chelates) are possibly more effective, but also expensive, and generally too costly for use on low value staple crops (Goos et al., 2004). In fact, only (repeated) foliar application of iron compounds has been shown to have some positive effects on yields of grains (Rengel et al., 1999; Savithri et al., 1999; Sadana and Nayyar, 2000; Goos et al., 2004). As regards the effects of iron fertilizer on the iron *contents* of crops, available information is very scarce. Limitedly available

[4] DTPA= diethylenetriaminepentaacetate, used for extracting minerals from soil.

data indicate that increasing the iron content of crops through iron fertilization is not easily achieved, and again foliar application might be the only feasible approach (Rengel et al., 1999). Yet, in pot experiments iron contents of leafy vegetables could be significantly increased by fortifying the soil with iron (Reddy and Bhatt, 2001).

Another approach when aiming for higher iron contents of crops is plant breeding. At the International Rice Research Institute in the Philippines, a new rice variety has been developed with 400-500% higher iron content than common varieties (Haas et al., 2005). It may be noted that no information is available how soil iron content or availability affects the iron content of this "high-iron" variety.

Table 2 Iron concentration in various crops

	Median Fe concentration µg /g dry wt	Range Fe concentration µg /g dry wt
Rice	3	2-10
Wheat	37	24-61
Corn	20	16-30
Soya bean	70	48-110
Bean	-	33-80

Source: Welch and Graham, 1999.

Just like in crops, also in human nutrition iron uptake is complex, and absorption into the human body depends on many factors (Lopez and Martos, 2004; Meng et al., 2005). Most well known are differences in bio-availability between iron present in plant and animal products, with iron absorption from meat generally 10 to 20 times higher than from plant products. As a result, a low level of consumption of animal foods, which is common in low income countries, tends to be associated with high levels of iron deficiency and anemia (Ahmed et al., 2003; Hop, 2003; Murphy and Allen, 2003; Sharma et al., 2003), and a high level of consumption of animal food tends to be associated with better growth of children (Grillenberger et al., 2006).

Literature provides little information on possible linkages between contents or availability of iron in soil and the occurrence of human iron deficiency. One of the few countries for which an attempt could be made to investigate such a relationship is India, as for a number of Indian states data are available both on the percentages of soils considered iron deficient and on the occurrence of anemia in these states (IIPS, 2000; Gupta, 2005). Results are presented in Table 3. There appears to be no positive relationship between the state-level percentages of soil iron deficiency and prevalence rates of anemia. Several reasons can be drawn up to explain the absence of such a relationship. A first requirement for finding a positive relationship would be that people residing in a particular area are largely dependant on locally produced foods. If a significant share comes from other regions, it will dilute the possible linkages between local soil conditions and human nutrient intake. In the second place, the data on the occurrence of soil iron deficiency are averages for sets of samples which show wide variation in iron contents. Therefore an analysis at the level of states might not be the most appropriate approach. And in the third place, though iron deficiency is an important determinant of anemia, there are other factors that can contribute to the development of anemia. For example, intestinal worms, high reproductive physiological demands of women, deficiencies in folic acid and copper, or deficiencies in other vitamins and minerals or trace elements are known to be associated with anemia, and it is estimated that on average about 50% of anemia is caused by iron deficiency (Zimmerman, 2002). Nevertheless, the data as presented in Table 3 may serve as an example how the possible linkages between conditions of soils with respect to micronutrients and the occurrence of a micronutrient deficiency in humans could be explored.

Table 3 Iron deficiency in soils and prevalence of anemia in Indian states

	Percentage of soils iron deficient	Anemia (1), moderate+severe	Anemia (2), mild+moderate+severe
Andra Pradesh	3	17.3	49.8
Gujarat	8	16.9	46.3
Haryana	20	16.1	47
Himachal Pradesh	27	9.1	40.5
Karnataka	35	15.7	42.4
Madhya Pradesh	7	16.6	54.3
Maharashtra	24	17.0	48.5
Punjab	14	13.0	41.4
Tamil Nadu	17	20.8	56.5
Uttar Pradesh	6	17.4	62.7

Source: IIPS, 2000; Gupta, 2005; Regression of ‘percentage iron deficient soils’ vs ‘anemia (1)’: r^2 =0.133, P=0.30; and ‘percentage iron deficient soils’ vs ‘anemia (2)’: r^2 =0.324, P=0.09.

In human nutrition, the most common approach to improve iron-status, in particular of women, is the provision of iron supplements (Black, 2001; WHO, 2001). However, selecting appropriate modes for effective iron supplementation, in particular as preventive intervention, is still an issue of debate (Shrimpton et al., 2002). One of the reasons is that adherence and compliance are often problematic, partially because of adverse side effects of iron tablets (Winichagoon, 2002). Another approach is fortification of common foods (sugar) with iron, but also here effectiveness has not clearly been established (Lynch, 2005). Among the problems are poor bioavailability of iron in the iron-fortified foods, while also changes in product taste may cause resistance by consumers to accept the fortified products (Frossard et al., 2000). Yet, there are also accounts of highly successful iron supplementation programs (Zimmermann et al., 2003). It is further important to note that it has been shown, in a trial in the Philippines, that consumption of the recently developed “high-iron” rice can significantly contribute to women’s iron status (Haas et al., 2005).

Of relatively recent date are concerns that, under particular conditions, supplementation with iron can also have adverse health effects. In a large-scale study in Zanzibar, in a region with very high malaria pressure, supplementation of 1-35 months old children with iron and folic acid (either with or without zinc) resulted in increased risks for morbidity and mortality, in the order of magnitude of 10-15% (Sazawal et al., 2006). Only children with iron deficiency benefited from supplementation with iron and folic acid. In another large-scale study in Nepal, with similar forms of supplementation (iron and folic acid, with or without zinc), but where malaria pressure was relatively low, there were no effects on mortality and modest beneficial (but insignificant) effects on illnesses such as diarrhea (Tielsch et al., 2006). These and other results stress that for iron supplementation, appropriate targeting (e.g. along WHO-guidelines) remains very important, and that under acute and severe disease conditions iron supplementation could be detrimental and should be withheld, unless at the same time treatment of infectious disease (and in particular malaria) is well in place (English and Snow, 2006).

To conclude, worldwide iron deficiency and anemia are major health problems affecting millions of people. An important factor in the causation of iron deficiency is that iron uptake and absorption is complex, both for plants from soils and for humans from food. Another complicating factor is that anemia, which is generally considered the main indicator of iron deficiency, is also caused by other factors, such as intestinal worms, other dietary deficiencies (folic acid, copper), and physiological status. Because of these complexities, linkages between iron availability from soils and the occurrence of human iron deficiency and anemia might be weak or even totally absent. Yet, there appears to be clearly a need for research to find ways for achieving higher iron contents and improved iron bioavailability in food. At this moment, there are no economically feasible approaches available which combine direct agricultural benefits with improved human iron provision. From a human nutrition point of view the development of a "high iron" rice variety is very promising.

4. Zinc deficiency

In recent years, interest in the occurrence of human zinc deficiency, in particular among children, has been growing strongly. In various studies, in different parts of the world, zinc deficiency has been shown to be associated with increased morbidity and mortality, in particular from diarrhea, possibly also from malaria, and also with reduced child growth (Brown et al., 2002; Black, 2003b; Brown, 2003; Rosado, 2003; Hotz and Brown, 2004). Also, a low zinc status of pregnant women has been reported to be associated with poor birth outcomes (Huddle et al., 1998; de Jong et al., 2002; Meram et al., 2003; Villalpando et al., 2003; Pathak et al., 2003a; Hotz and Brown, 2004; Pathak and Kapil, 2004). In several studies, dietary supplementation with zinc resulted in health improvements, such as better growth of children and reductions in morbidity or mortality, and also in improvements in children's motoric development (Osendarp et al., 2001; Müller et al., 2003; Rivera et al., 2003; Black et al., 2004; Walker and Black, 2004). In one meta-analysis it is concluded that zinc supplementation has a significant positive effect on length gain in children (Bhandari et al., 2001). At the same time, it should be noted that there is no full consensus whether mass-scale zinc supplementation would be the most appropriate approach for alleviating zinc deficiency (Shah and Sachdev, 2006).

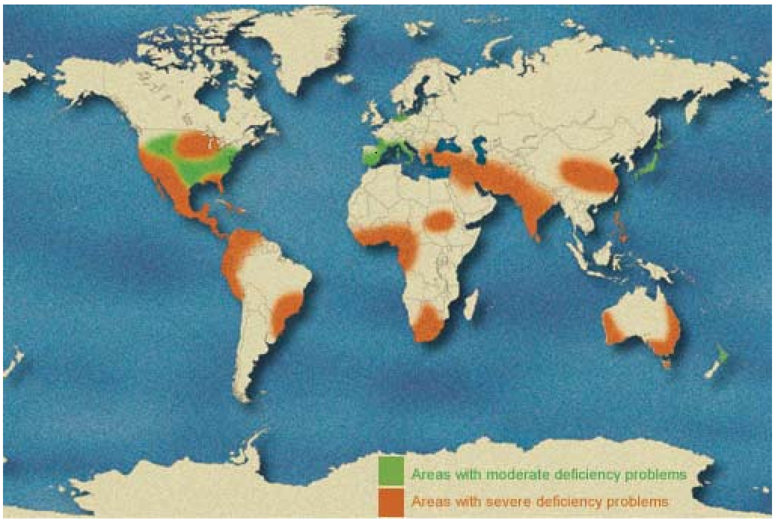

Figure 3. World zinc deficiency in soils: major areas of reported problems (Alloway, 2002)

As regards agriculture, according to Cakmak (2002) zinc deficiency is the most widespread *soil* micronutrient deficiency in the world. Availability of zinc for plants is particularly low in calcareous and alkaline soils, while absolute zinc contents tend to be low in highly weathered acid tropical soils. Almost half of the agricultural soils from India, one third of the agricultural soils in China, and 50 per cent of cultivated land in Turkey are considered zinc-deficient for plants (Frossard et al., 2000; Gupta, 2005). Other more location specific studies report on low soil zinc contents in, for example, Malawi, Mali and Burkina Faso (Snapp, 1998; Soumare et al., 2003; van Asten et al., 2004). A most comprehensive report on various aspects of zinc availability in soils and zinc physiology in crops is a review by Alloway (2004). The report identifies areas in the world which can be considered either moderately or severely deficient in zinc, with, for example, a large area stretching out from Turkey up to India being classified as severely zinc deficient (Figure 3).

Zinc is an essential nutrient for all plant crops. Chemically, zinc has some similarities with iron and magnesium, and in plant uptake there can be competition between these elements (Neue et al., 1998). Furthermore, high levels of phosphate in soils can strongly reduce zinc availability (Marschner, 1995). As for iron, there is large variation in zinc contents of foods. For example, most green vegetables are rather rich in zinc, but zinc contents of root crops such as cassava and yams are very low. More importantly, for one and the same crop the zinc content can show wide variation (Frossard et al., 2000). Table 4 gives an indication how levels of zinc may vary in main staple foods such as wheat, maize and rice. It should be noted that in developing countries cereals are generally the main source of dietary zinc intake. Furthermore, with respect to crop zinc contents it is important to note that, according to some studies, problems of zinc deficiency have been aggravated in the process of the green revolution (Dar, 2004), and several studies report lower levels of micronutrients, including zinc, in modern varieties of rice and wheat in comparison with traditional varieties (Buerkert et al., 2001; Khush, 2001; Cakmak, 2002; Kennedy and Burlingham, 2003). Also, flooding of soils as practiced with irrigated rice production may cause deficiencies in micronutrients (Moslehuddin et al., 1997; Neue et al., 1998; Savithri et al., 1999).

Table 4. Variability of zinc content in seeds of wheat, maize and rice

	Number of cultivars tested	Zn (range) μg /g dry weight
Wheat	170	25-64
Maize	126	11-95
Brown rice	1138	17-52
Polished rice	386	8-95

Source: Frossard et al., 2000 (based on studies by Maziya-Dixon et al., Ortiz-Monasterio and Graham, Gregorio et al., and Yang et al.).

Both greenhouse studies and field experiments have shown, for various food crops, that fertilization with zinc can result in significant increases in yields. For example, in field experiments in Turkey application of zinc resulted in wheat yield increases up to 500%, depending on local soil conditions and method of zinc application (Cakmak, 2002). While leaf application of zinc fertilizer (eg ZnSO4) had the largest positive effect, simple addition of zinc fertilizer to soils can already have a significant yield increasing effect. Also in studies in Australia, Brazil, Ghana, India and Malawi, positive effects of zinc fertilization on yields of rice, wheat, maize and soybean have been reported (Saxena and Chandel, 1997; Wendt and Rijpma, 1997; Savithri et al., 1999; Cakmak, 2002; Fageria, 2002; Abunyewa and Mercer-Quarshie, 2004; Kulandaivel et al., 2004). In the United States zinc is currently the most common micronutrient being applied to rice (Slaton et al., 2005b).

Apart from the effects on crop yields, for human nutrition it is equally important how the zinc status of soils is related to the zinc *contents* of crops, and whether the zinc concentration of crops, and in particular in the edible parts, can be increased through fertilizer. The relationship between soil zinc and zinc contents of crops has been investigated by, among others, Rengel et al.(1999), and it has been shown that increasing zinc in nutrient solutions can result in increased zinc concentrations in grain by a factor ten or even more (Table 5). Also other studies report positive effects of zinc fertilization on zinc concentration in grains, although some concern has been expressed whether under field conditions the zinc concentration can be sufficiently increased to prevent human zinc deficiency (Cakmak, 2002; Welch, 2002; Slaton, 2005a).

Table 5. Zinc fertilization, grain yield and grain Zn concentration of wheat

Zn fertilization (μg/g soil)	Grain yield (g dry weight per plant)	Grain Zn concentration (μg/g dry weight)
0	1.00	9.1
0.05	2.20	9.9
0.2	2.24	14
0.8	2.51	83
3.2	1.70	145

Source: Frossard et al., 2000, adapted from Rengel et al, 1999

In human nutrition, the absorption of zinc from food is complex. For example, organic acids such as phytic acid and phenolic acid can significantly inhibit human zinc absorption (Frossard et al., 2000; Hotz and Gibson, 2001; Hotz and Brown, 2004). Phytic acid is a phosphor containing organic acid which may be present in rather high concentrations in cereals and in particular in unleavened bread. In fact, already since long endemic zinc deficiency is known to occur among populations whose diet is predominantly cereal based (Cheek et al., 1981; Galal, 2000, Manary et al., 2002). In view of the negative effects of phytic acid on zinc absorption, it is important to note that fertilization with phosphate tends to increase crop phytic acid concentrations, and research is being undertaken which aims for reductions of phytic acid concentrations in plants (Buerkert et al., 1998). Apart from these organic acids, other micronutrients, for example iron can compete with zinc in human nutrition (Lind et al., 2003; Berger et al., 2006).

Also in animal nutrition is zinc an essential micronutrient, and positive relationships between soil zinc contents or availability, zinc contents of forage and fodders, and animal zinc status have been clearly established. A typical example is a study in Haryana, India, where low levels of zinc in buffalo milk could be directly linked to low zinc levels in local soils and in fodder produced on these soils (Yadav and Khirwar, 2000). In another study in India, zinc deficiency in goats was most likely caused by excessive use of calcium and phosphorus fertilizer, both making zinc unavailable to plants (Ray et al., 1997). And in studies in Zimbabwe, low absolute zinc levels in soils appeared to be responsible for low zinc levels in forage or fodders (Ndebele et al., 2005).

In conclusion, available information indicates that adding zinc to zinc deficient soils may result both in higher yields and in higher zinc contents of crops. The positive effects on both yields and crop zinc contents have been shown for major food crops such as rice and wheat. While higher yields are of direct benefit to farmers, higher zinc contents of crops have the potential to contribute to a reduction in the occurrence of zinc deficiency in humans. For some countries or regions there are clear indications of a direct relationship between low soil zinc contents and the occurrence of deficiency. For example, a study on Bangladesh reports a direct link between soil zinc contents, zinc contents of crops (rice), and human zinc deficiency (Mayer et al., 2003). Another indirect example can be drawn from data on Haryana, India. This region has a very high percentage of zinc deficient soils (Gupta, 2005), and at the same time it is one of the few regions for which a high rate of human zinc deficiency, among pregnant women, has been reported. It could thus be speculated that for rural areas in Haryana State there is indeed a direct linkage between low soil zinc contents and the occurrence of human zinc deficiency (Pathak et al., 2003a). Another study, which also investigated the possible relationship between soil zinc contents and human zinc intake, is a study in Andra Pradesh, India, but here results were inconclusive (Sunanda et al., 1995). More geographical information on both the occurrence of soil zinc deficiency and the occurrence of human zinc deficiency is needed, to assess the degree at which soil zinc conditions and human micronutrient status are directly related. For example, in Mexico a poor zinc status in children and in women is much more common in southern Mexico in comparison with the northern parts of the country, but at present no studies are available which report on zinc content of soils and food crops in different regions of Mexico (Villalpando et al., 2003). In West African lowlands, soils are reported to be severely zinc deficient, but it is not known whether this is associated with the occurrence of zinc deficiency in children or adults. (Buri, et al. 2000). Despite these limitations in availability of data, currently available information on the positive effects of zinc fertilization on both yields and zinc contents of crops, in combination with the known positive effects of zinc supplementation in human nutrition, renders zinc fertilization a promising approach for simultaneously addressing zinc deficiency in agriculture and human nutrition.

5. Selenium deficiency

In comparison with iron and iodine, selenium deficiency is, at global level, not a major public health problem. Only in a few regions in the world, notably in China, human selenium deficiency is known to occur, but even here its public health importance is of limited scope, with estimated prevalence rates in affected regions in the order of magnitude of 5 per 100.000 (Fordyce et al., 2000b). Apart from China, selenium deficiency has been reported to occur in the Andes in South America (Combs, 2001; Sempertegui et al., 2003; Lin et al., 2004).

There are two disorders that are caused by or at least associated with selenium deficiency: Keshan disease and Kaschin-Beck disease. Keshan disease, named after the Chinese province where it was first described, occurs mainly in children and women of child-bearing age, and impairs cardiac functioning (Ge and Yang, 1993). Kaschin-Beck disease is an osteo-arthropathy, causing deformity of affected joints (Fordyce et al., 2000b; Tan et al., 2002; Lyons et al., 2003). While on a global scale these serious forms of selenium deficiency are rare, interest in the selenium contents of human diets has been increasing strongly over past years. The main reason is that there is growing evidence that also marginal intakes of selenium can have adverse health effects, and in various studies suboptimal intakes of selenium have been associated with, among others, reduced immuno-competence and increased cancer mortality. Also, low dietary intakes of selenium have been associated with the HIV/AIDS epidemic (Rayman, 2000, 2002; Kupka et al. 2004). It is of interest to note that the soils of Senegal, which are relatively high in selenium, are claimed to be responsible for the low HIV/AIDS incidence in that country (Foster, 2003). Limited available information suggests that in Europe and Australia, and possibly also in other regions in the world, selenium intakes have been decreasing over past decades, reaching levels below requirements (Rayman, 2000; Dorea, 2002; Lyons et al., 2005). Sub-optimal dietary intakes of selenium, though not manifested in clinical features, have also been reported for other countries, including the Russian Federation, Finland, and New Zealand, while parts of Africa are also reported to be selenium deficient (Combs, 2001; Lyons, 2003). Finally, a comprehensive review on selenium and breastfeeding suggests that worldwide for about 30% of women the selenium concentrations in breast milk are inadequate for satisfying the selenium requirements of their breastfed children (Zachara and Pilecki, 2000; Dorea, 2002).

Selenium in soils is ubiquitous, with most soils containing between 1.0 and 1.5 μg/g (Lyons et al., 2003). Yet, there is a wide range of concentrations, from 0.1 to over 100 μg/g, and soil selenium contents can show wide variations within short distances. As for other minerals and trace elements, not only absolute soil selenium contents, but also various other factors affect the amounts of selenium being taken up by plants. Selenium can be present in soils as elemental selenium, as selenide, selenite, or selenate, or as organically bound selenium, and of these different forms, selenate is most mobile and best taken up by plants. Other factors affecting selenium uptake by plants are the degree of sandiness of soils, and also the pH, with more selenium being available at higher pH (Lyons et al., 2003, 2005; Wang et al., 2005). Furthermore, both iron and sulphur have a negative effect on soil selenium availability. In fact, it has been suggested that increased sulphur concentrations in soils, resulting from high global levels of fossil fuel burning and related emission of sulphur, are partially responsible for globally decreasing levels of selenium availability (Lyons et al., 2003).

The linkages between selenium contents of soils and crops and the occurrence of human selenium deficiency have been well established. On a global basis, foods with the lowest selenium contents and associated low human selenium-intakes are found in those regions of China where soil selenium contents are very low (Combs, 2001; Fang et al., 2002; Lyons et al., 2003, 2004; Lin et al., 2004). Table 6 provides some quantitative data on soil selenium contents as measured in areas of China where Keshan Disease (KD) and Kaschin-Beck disease are prevalent and in areas where these diseases do not occur (Tan et al., 2002). Even more telling in establishing the causal relationship between selenium deficiency and Keshan disease has been the fact that prophylactic administration of oral tablets containing selenium, or the addition of selenium (as selenite) to table salt, has resulted in drastic reductions of Keshan disease. For Kaschin-Beck disease it is less clear whether selenium deficiency is the primary cause of this disorder, or whether it is mainly a predisposing factor (Combs, 2001).

Table 6. Selenium contents in soil in areas with and without Kashin-Beck and Keshan Disease in China

	Area with KBD/KSD			Area without KBD/KSD		
	X (SD)	G (SD)	N	X (SD)	G (SD)	N
T-Se (mg/kg)						
Cultivated	0.112 (0.057)	0.100 (0.182)	35	0.224 (0.134)	0.219 (0.330)	161
Natural	0.119 (0.075)	0.105 (0.218)	69	0.227 (0.141)	0.211 (0.319)	86
WS-Se (μg/kg)						
Cultivated	2.5 (1.0)	2.5 (0.391)	25	6.8 (9.1)	4.7 (0.311)	151
Natural	2.8 (2.2)	2.2 (0.265)	22	6.7 (13.2)	4.7 (0.445)	71

Note: KBD/KSD: Kashin-Beck Disease/Keshan Disease; T-Se:total Se; WS-Se:water soluble Se; N: number of sample; X (SD): arithmetic mean and standard deviation; G (SD): geographic mean and standard deviation. Source: Tan et al., 2002.

A most interesting case in addressing human selenium deficiency is Finland (Rengel et al., 1999; Lyons et al., 2003). Already in the 1970s it was recognized that people's dietary intakes of selenium were very low and related to the low selenium contents of Finland's soils. In 1984 the Finnish government decided that all fertilizer (for crops and fodder) had to be enriched with selenium. As a result of this measure, food contents of selenium increased, and human dietary intake increased up to a level where deficiency was no longer a public health concern (Aro et al., 1995). In fact, Finland is probably the first country were such an agriculture based approach was followed in order to remedy a nutritional micronutrient deficiency. Similar experiences, though on a smaller scale, have been reported for China (Xu et al., 1991). Nowadays, the use of fertilizer enriched with selenium has become common practice in many countries (Combs, 2001).

As for iodine, a "disadvantage" of selenium is its non-essentiality for plants. According to Marschner (1995), selenium is to be classified under the beneficial elements for plants. These are elements that are not essential, but can stimulate plant growth and plant health. Increased selenium contents in soils generally do not result in increased yields, but might provide some protection to certain plant diseases. Yet, there are some studies which even showed some positive effect of selenium application on yields (Combs, 2001; Dong et al., 2003; Turakainen et al., 2004). While thus selenium application has no or at most minor effects on yields, the possibility of increasing crop selenium contents by adding selenium fertilizer has been clearly shown (Welch

2002; Lyons et al., 2005). In China, the selenium content of rice could be enormously increased (approximately 20 to 25-fold) by application of only 20 g of selenium per hectare, with selenate being more efficient than selenite (Chen et al., 2002).

Also for selenium, there are complex interactions with other micronutrients. In human nutrition, various studies have shown metabolic interactions between iodine and selenium, and selenium deficient areas in China are also those regions where iodine deficiency disorders are endemic (Fordyce et al., 2000b; Lyons et al., 2003, 2004). Also in Central Africa, goiter and cretinism are most widely prevalent in regions where both iodine and selenium are deficient. (Vanderpas et al., 1990; Ngo et al., 1997).

Finally, also in animal nutrition selenium is nowadays receiving increasingly attention (Gupta and Gupta, 2000; Meschy, 2000; Tinggi, 2003). Selenium is an essential element for animals such as cows, pigs, sheep and goats, and animal growth, and perhaps also milk production, may be negatively affected by low selenium contents in feed, fodder or forage. In a study in the United States, selenium contents of beef appeared to be highly correlated both with selenium contents of forage grasses and with selenium contents of local soils (Hintze et al., 2001). Thus, apart from the direct effects on animal health, sufficient selenium nutrition for animals may lead to higher selenium concentrations in meat and milk, and thus in the end contribute to increased dietary selenium intakes by humans (Hintze et al., 2001).

In conclusion, next to iodine, also for selenium there are strong and direct linkages between its contents in soils and food crops, and the resulting human selenium status. These linkages are most clearly revealed in China, where various studies have established strong relationships between low levels of selenium in soils, low dietary selenium intakes, and the prevalence of the established selenium deficiency disorders, Keshan disease and Kashin-Beck disease (Fang et al., 2002). Application of selenium to crops can significantly increase crop selenium contents. However, as selenium is not an essential nutrient for plants, the application of selenium to crops generally has no effects on yields, and from a farmers point of view not much benefit can be expected from the addition of selenium to fertilizer.

6. Deficiencies in other minerals or trace elements

Contrary to iodine, iron, zinc and selenium, for other minerals and trace elements that are essential in human nutrition, such as copper, magnesium and manganese, there is only limited information on the occurrence of diet related human deficiencies (Black, 2001). As regards copper, in the 1960s a number of studies reported on deficiencies in children in Peru (Cordano, 1998), and recently, copper deficiency has been reported in Chile, in children recovering from malnutrition (Olivares et al., 2004). Furthermore, low serum copper levels have been reported for severely malnourished children in Lucknow, India, and in Cape Town, South Africa (Subotzky et al., 1992; Thakur et al., 2004). It should also be noted that there are interlinkages between copper deficiency and iron deficiency, and it has been argued that the globally high levels of anemia might be partially caused by copper deficiency (Sharp, 2004). Among the few reports on magnesium deficiency are accounts of its occurrence among pregnant women in Haryana, India, and among children in Egypt (Black, 2001; Ibrahim et al., 2002; Pathak et al., 2003b; Pathak and Kapil, 2004). For manganese, one study in Mexico revealed low serum manganese levels in severely malnourished children (Garcia-Aranda et al., 1990).

Also in agriculture deficiencies in these micronutrients have been reported to occur (Wade et al., 1999a). For example, for wheat in Western Australia, for upland rice in Brazil, and for irrigated rice in Bangladesh deficiencies have been reported in copper (Brennan, 1990; Savithri et al., 1999; Fageria, 2002; Fageria and Breseghello, 2004), and it has been shown that copper application can result in significant increases in yield. Magnesium deficiency appears to occur less frequently, but has been reported for banana and plantain in Puerto Rico and for rice in Bangladesh (Moslehuddin et al., 1997; Martinez et al., 2002). In a study in Ghana, application of magnesium to maize crops resulted in modest yield increases (Abunyewa and Mercer-Quarshie, 2004). With respect to manganese, deficiency has been reported for soybean and for palm trees (Graham et al., 1995; Kee et al., 1995), and both greenhouse and field studies in Brazil have shown that application of this micronutrient may result in yield increases of soybean, wheat and corn (Soni et al., 1996; Fageria, 2002; Mann et al., 2002). Furthermore, for wheat the application of manganese did not only increase yields but also crop manganese content, however to some extent at the expense of the crop's copper and iron content.

Finally, also in animal nutrition, the occurrence of deficiencies in micronutrients such as copper, magnesium and manganese, are known to occur (Lee et al., 1999; Moraes et al., 1999; Prasad and Gowda, 2005). Copper deficiency is reported with some frequency in goats, sheep, and cattle, for example in Brazil (Tokarnia et al., 1999), in Ireland (Moraes et al., 1999; Mee and Rogers, 1996; Malafaia et al., 2004) and in Zimbabwe (Ndebele et al., 2005). In France copper deficiency in goats has been attributed to excess sulphur application on pastures (Lebreton et al., 2002). Magnesium deficiency has been described for livestock in Australia (Judson and McFarlane, 1998) and New Zealand (Edmeades, 2004). Deficiencies in manganese in animal nutrition are rarely reported but might, for example, occur in cattle and sheep in some parts of Brazil (Moraes et al., 1999). In many of these studies in animal nutrition, direct linkages between low soil micronutrient contents and low nutrient contents of forage and fodders have been clearly established (Trengove, 2000; Gowda et al., 2001; Das et al., 2002; Singh et al., 2002; Edmeades, 2004; Ndebele et al., 2005; Yadav and Khirwar, 2005; Khan et al., 2006).

Summarizing, for micronutrients such as copper, magnesium and manganese, there are reports on the occurrence of deficiencies in agriculture, in livestock, and also in human nutrition. However, currently available information is still fragmentary, and does not allow for a more systematic assessment, as done in the previous sections for iodine, iron, zinc and selenium. Yet, in coming years information might well become increasingly available, and also here direct relationships between deficiencies in soils, crops and human nutrition may well be established.

7. Combinations of micronutrient deficiencies

In the previous sections the various micronutrients have largely been discussed on a one by one basis. However, in soils and in crops, and also in human nutrition, micronutrient deficiencies rarely occur in isolation (Kang and Osiname, 1985; Jiang et al., 2005). Therefore, both in agriculture and in human nutrition, there may often be a need to address several micronutrient deficiencies simultaneously.

As regards agriculture, there are various studies in which the effects of mixtures containing several macronutrients and micronutrients have been studied, with varying results (Wade, 1999b; Asad and Rafique, 2002). In a number of these studies, positive effects have been reported on yields, on crop contents of micronutrients, or on both. For example, in experiments in which the effects of zinc and iron fertilizer on micronutrient contents of leafy vegetables was investigated, in most cases combinations of zinc and iron gave best results on crop contents of zinc, iron, copper and magnesium (Reddy and Bhatt, 2001). However, it may be noted that, in agriculture, very little research considers the entire range of micronutrients that are essential for plants. In India a nation-wide survey of micronutrient deficiencies revealed that, based on deficiency criteria for zinc, iron, copper and manganese, by and large a single nutrient deficiency (mostly zinc) is most common, and that only in about 12 % of investigated locations two or more micronutrient deficiencies are present (Gupta, 2005). However, in these studies boron was dealt with separately (with less samples taken), and it appeared that the percentage of soils deficient in boron varied from 0 to 69 percent, thus suggesting that multiple micronutrient deficiencies at more localized level might be much more common than based on only zinc, iron, copper and manganese.

Several of these studies also reveal the complexity of the chemistry and physiology of micronutrient provision to crops. For example, in studies in Malawi it has been shown that at some sites maize responds well to a combination of sulphur, zinc and boron (Wendt and Rijpma, 1997). However, detailed missing nutrient trials suggest that responses are very site-specific. At some sites withholding micronutrients had no effect, implying sufficiency for these micronutrients, but at other individual sites dramatic yield declines derive from withholding a single micronutrient only (either zinc or boron). These and other studies clearly illustrate that with the use of mixtures of minerals and trace elements the effects on yields or on crop micronutrient contents will often be difficult to predict, and irrationally adding mixtures of micronutrients to fertilizer might result in unexpected and perhaps even highly undesirable effects.

Also in human nutrition, micronutrient deficiencies rarely occur in isolation, and there are many studies in which the effects of multiple micronutrient supplementations to infants, children, or pregnant women have been investigated (Pathak et al., 2004; Christian et al., 2006; Hettiarachchi, 2006). Often, positive effects on, for example, birth weight, child growth, morbidity, or other nutrition related health indicators have been reported (Rosado, 1999; Thu et al., 1999; Tatala et al., 2002; Hininger et al., 2004; Lopez de Romana et al,, 2005; Kaestel et al., 2005). For example, in a study in India, 1-3 years old children in peri-urban Delhi were supplemented with zinc, iron, vitamin A, vitamin C, vitamin E, selenium and copper. The children who received this micronutrient mixture showed better growth and fewer illnesses than a control group (Juyal et al., 2004). In two studies in Tanzania and the Philippines, the provision of mixtures of micronutrients to primary school children in the form of a drink, yielded positive effects in terms of better child growth and better vitamin status, and reductions in anemia and iodine deficiency (Latham et al., 2003; Solon et al., 2003). And in a recent study in South Africa, a multiple micronutrient supplementation program in children aged 6-12 months resulted in significantly improved micronutrient status, though there was no difference in growth or morbidity in comparison with a control group (Gross et al., 2005; Smuts et al., 2005). In a joint statement by the World Health Organization, The World Food Programme and Unicef, it is recommended that under emergency conditions multiple micronutrient supplements are given to pregnant and lactating women, and to children from 6-59 months of age (WHO, 2006).

It should, however, be noted that there are also studies in which the positive effects of supplementation with micronutrient mixtures have been much less clear, absent, or where supplementation with micronutrient mixtures appeared to have even adverse health effects. In a study in 17-32 months old children in Benin supplementation with multivitamin-multimineral supplements did not reveal any positive effect on child growth or morbidity (Dossa et al., 2002). In a study in Bangladesh the effects of various micronutrient combinations on morbidity in 6-12 months old infants were compared. Results of the study are difficult to interpret, but tend to indicate a reducing effect on diarrhea of a combination of iron and zinc, but an increasing effect on diarrhea of a complete multimicronutrient mixture, including vitamins (Baqui et al., 2003). Similarly, in a study in Peru supplementation of children with zinc resulted in a reduction of diarrhea, while supplementation with zinc in combination with vitamins and other minerals resulted in an increase in diarrhea (Penny et al., 2004).

Finally, results have been published from recent studies in Nepal on the effects of antenatal micronutrient supplementation, and also here interpretation of the outcomes appears to be complex. While initially adverse effects on perinatal mortality were reported, these negative effects were not repeated in subsequent reports on these intervention studies (Christian et al., 2005, Huffman et al., 2005; Shrimpton et al., 2005; Christian et al., 2006; Katz et al., 2006).

Thus, on the one hand there are a considerable number of reports where indeed supplementation of children or adults with mixtures of micronutrients resulted in significant health gains. These studies strongly suggest that diets, and people consuming these diets, are often deficient in several micronutrients, including vitamins, and that supplementation with micronutrient mixtures is beneficial. At the same time, research with micronutrient supplementation reveals also unexpected and sometimes adverse health effects, and at least caution is warranted when considering large scale supplementation with multiple micronutrients mixtures.

Within the context of the present paper it is important to note that much less, if any, adverse effects are known to result from consumption of foods which are richer in specific nutrients, for example as a result of the application of fertilizer enriched with certain trace elements. Therefore, in the long run, aiming for consumption of foods of which the nutritional quality has been improved through agricultural methods, may well prove to be a more effective and more safe approach in ameliorating human micronutrient deficiencies, than micronutrient supplementation programs.

8. Micronutrient fertilizer technologies with specific attention to Sub Sahara Africa

As shown in the individual sections on iodine, iron, zinc and selenium, the application of micronutrients to crops can, depending on crop type and local soils conditions, result in higher yields, higher crop micronutrient contents, or both. However, the magnitudes of these effects may vary strongly.

Both from an agricultural point of view and from a human nutrition point of view, it might seem appealing, after having established crop macronutrient requirements (nitrogen, phosphorus and potassium) for particular soil types and crops, to add just on a routine basis a standard package of all micronutrients known to affect plant growth in general, and also to include micronutrients not required by plants but essential in human nutrition. However, there are a number of reasons on the basis of which such an approach seems unlikely to be very successful. This will be discussed in some detail below, with specific attention to the situation in Sub Sahara Africa.

In the first place, as already noted in previous sections of this report, there are many possible interactions between minerals and trace elements that may affect their availability for plants (for an overview, see e.g. Landon, 1991). As an example, Rebafka et al. (1993) observed the occurrence of molybdenum deficiency after fertilizing groundnuts with Single Super Phosphate (SSP). SSP is primarily a phosphorus fertilizer, but it also contains large amounts of calcium and sulphur of which in particular sulphur has an antagonistic effect on molybdenum uptake. Thus, the occurrence of molybdenum deficiency might well be a consequence of the application of SSP. As another example, results from India have shown that over-liming and excessive application of super phosphate may cause zinc deficiency in soils, leading to low zinc contents in fodder produced on it, and the occurrence of zinc deficiency in goats fed these fodders (Ray et al., 1997). And in Kenya, in some experiments the application of 25 kg phosphorus gave higher yield increases than the application of 75 kg of phosphorus and also the ratio of kg yield per kg of nutrient applied was higher at the lowest dose (Ayaga et al., 2006). In these experiments nitrogen was amply applied and the results thus indicate that high doses of phosphate may be intoxicating rather than fertilizing the soil. The negative effect of high phosphorus suggest an induced deficiency of an other element, possibly zinc, copper, iron or manganese (or a combination of these micronutrients), as phosphorus is known to have an antagonistic effect on these micronutrients.

In the second place, as already argued in a previous section, requirements for (additional) micronutrients can be very site specific. While in one area zinc availability may be problematic, in another area it might be abundantly present in soil but here possibly other micronutrients are poorly available. This spatial variability is, for example, coming to expression in reported yields of Velvet beans (*Mucuna pruriens*) as observed in six smallholder communal areas in Zimbabwe. Under unfertilized conditions there was a very large range in biomass yield, from just over 300 kg to over 7000 kg, between the various locations. Also, the effect of applying phosphorus to this nitrogen-fixing legume showed very large variation, from a doubling of yield to a reduction with 50% (Hikwa et al., 1998). These findings are a strong indication of micro-level variability of the environment.

An additional problem, when considering the manufacturing of fertilizer mixtures that contain fixed amounts of micronutrients, is the fact that currently commercially available fertilizer types show very wide variations in their micronutrient contents. In particular if these fertilizers derive from natural sources, such as rock phosphate, various micronutrients may already be present as impurities and their quantities may vary strongly, depending on the source materials (Rengel et al., 1999; McBride and Spiers, 2001; Rauf et al., 2002; Zapata and Roy, 2004). As an example, Table 7 shows for some commercial fertilizer types their contents in iron, zinc and selenium. It appears that they vary by factors of approximately 10, 100 and 500 for respectively selenium, zinc and iron (Raven and Loeppert, 1997). Clearly, when the need for more balanced approaches with respect to micronutrient supplies to crops would be recognized, full and detailed control over and information on the actual mineral and trace element contents of the fertilizer mixtures will be needed, and this will have major implications for the manufacturing process. In this respect, it is also important to note that for certain micronutrients the range between human requirements and toxic levels is not very wide. For example, while human selenium requirements are estimated to be in the order of magnitude of 50 microgram per day, toxicity begins at intakes at around 500 micrograms per day, which is only a factor ten higher (Koller and Exon, 1986, Combs, 2001; Goldhaber, 2003). This puts further constraints on the flexibility with which micronutrients can be safely added to fertilizer.

Table 7. **Iron, selenium and zinc contents in some commonly used fertilizer types**

	Iron µg/g	Selenium µg/g	Zinc µg/g
Ammonium sulfate-2	115 ± 16	< 0.22	6.40 ± 0.56
Monoammonium phosphate-1	5050 ± 410	1.18 ± 0.58	10.3 ± 2.6
Diammonium phosphate-2	2600 ± 240	< 1.16	386 ± 17
Triple superphosphate-1	17300 ± 1400	< 1.2	61.3 ± 4.2
Potassium chloride-1	1440 ± 120	< 0.22	4.59 ± 0.58
Potassium-magnesium sulfate-1	245 ± 28	< 0.2	8.75 ± 0.79
North Carolina rock phosphate	4920 ± 410	2.17 ± 0.81	382 ± 16
Tilemsi rock phosphate	47300 ± 4110	< 1.40	78.8 ± 6.0
Dolomite	970 ± 88	< 0.33	8.01 ± 0.93
Corn leaves	85.5 ± 16.5	< 0.16	192 ± 9
Compost-2	6460 ± 420	0.48 ± 0.27	164 ± 8
Austinite	24600 ± 1900	2.57 ± 0.91	563 ± 26
Milorganite	58200 ± 3600	1.04 ± 0.4	450 ± 21

Source: Raven and Loeppert, 1997.

A third issue when considering the enrichment of commonly available fertilizer types with micronutrients, is that such approach would only be effective in areas where fertilizer application, in substantial quantities, is common practice. Figure 4 provides some crude information on the levels of fertilizer application in different regions of the world. High levels of fertilizer use are common in East Asia, in particular China, and in Western Europe, and intermediate levels are reported for the America’s and South Asia. However, in Sub Sahara Africa average fertilizer consumption is extremely low, in an order of magnitude of less than 10 kg/ha, and concentrated in a few countries. Clearly, under such conditions fertilizer enrichment would have not much impact, just because of the fact that overall fertilizer usage is so low. A final point to be noted is that in Sub Sahara Africa only a few countries have the capacity to produce fertilizers. Therefore, if the knowledge would exist as to what micronutrients to add, and in what amounts, foreign companies would have to be convinced to do so and this would seem unlikely to occur in view of the very small demand for fertilizers in SSA. In view of the above listed considerations, enrichment of commonly available fertilizer types with a standard package of micronutrients appears not to be the most appropriate approach in addressing micronutrient deficiencies. Besides, an at this stage important question to be answered appears to be what the underlying reasons are for the currently very low levels of fertilizer use in Sub Sahara Africa.

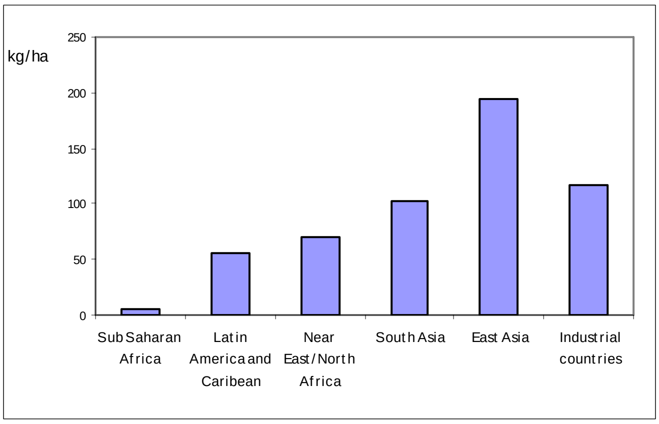

Figure 4. Fertilizer use in different regions in the world.
Source: FAO, 2002

There seems to be at least a combination of reasons why fertilizer usage is so low in Sub Sahara Africa. A first and major reason is undoubtedly the generally high cost of fertilizer, caused by the long distances over which the fertilizers have to be transported, this in combination with high transaction costs. For instance, while a ton of urea in Europe costs around US$ 90, when arriving in Malawi the price has increased to US$ 770 (Sanchez, 2002). Another reason is the fact that recommended fertilizer technologies often consist of high doses. African farmers are generally seriously cash constrained, their effective demand for fertilizer is low, and the marketing system for fertilizer is poorly developed. Clearly, at current high fertilizer prices in Sub Sahara Africa, physical yield increases derived from their use must be spectacular, are they to be profitable. Indeed, a large portion of farmers following recommended fertilizer types and doses is often left indebted (e.g. Conroy, 1993; Page and Chonyera, 1994). Furthermore, apart from the profit aspect, it appears that often the application of fertilizers has not been giving the expected physical yield increases. For instance, farmers in Ghana using hybrid maize varieties and applying fertilizers only harvested about 1 ton per hectare (Abunyewa and Mercer-Quarshie, 2004). Similar results with commonly used macronutrient fertilizers (N, P and K), whereby yields only marginally increased or even declined, have been obtained at several other locations in Africa (Rodel and Hopley, 1973; APMEU, 1987; Howard et al., 2003). Again, interactions between the applied fertilizer mixtures and micronutrients being present in local soils might be at the root of the often disappointing results, and in many instances it may be highly rational for farmers not to apply the recommended fertilizer types and doses.

The question thus remains what other approach would be feasible for improving micronutrient provision to soils, when aiming for higher yields and higher micronutrient crop contents. Perhaps the most feasible method would be to add micronutrients completely separately from the traditional fertilizer mixtures, either on a one by one basis, or in the form of packages in which a few micronutrients are combined, making use of knowledge which micronutrient deficiencies, at specific locations, tend to occur in combination. Mixing these micronutrients with local soil, followed by spreading it over the land, would probably be a feasible approach for thinly distributing the micronutrients, while at the same time preventing localized overdoses and possibly crop accumulation or damage. Also in financial terms, such an approach may well appear to be feasible as micronutrients are generally cheap, they are needed in small amounts, and there are also likely to be residual effects for some years after their application. Furthermore, availability of individual micronutrients, or combinations of a few of them, would allow farmers to experiment on small parts of their land, and become more knowledgeable on the variability of local soil conditions and crop response.

As a final note, it should be stressed that in particular for Sub Sahara Africa, the need for improved micronutrient management seems so urgently needed. Though knowledge on actual soil conditions is very weak, micronutrient deficiencies are most likely to be widely prevalent, be it already on the basis of the parent rock in which soils have developed (Voortman et al., 2003). And also in terms of human nutrition, in particular in Sub Sahara Africa the linkages between the micronutrient contents of diets and the micronutrient contents of soils and crops are most likely to be rather strong, this in view of the fact that agriculture is in many regions still largely subsistence based, implying that people mainly consume locally produced food.

9. Discussion and conclusion

The present study has two main objectives. In the first place, it investigates the linkages between micronutrient deficiencies in soils, whether in terms of absolute levels or in terms of availability, and the occurrence of micronutrient deficiencies in plants, animals and humans. Iodine can be considered the classic example of a strong relationship between low soil micronutrient content and the occurrence of human deficiency, and recognition of the relationships between soil iodine contents and the prevalence of goiter dates back to the beginning of the twentieth century. For iron, which plays a very important role in human nutrition and for which deficiencies are widely prevalent, it is less clear whether there is a direct relationship between soil iron content or availability and the occurrence of human iron deficiency. For zinc, available information is of more recent date, but there are clear indications that there are direct linkages between low soil zinc contents, low zinc contents in crops, and the occurrence of human zinc deficiency. Finally, also for selenium such a relationship exists, although from a public health perspective, selenium deficiency appears to be of less importance. For other micronutrients for which diet related human deficiencies have been occasionally described, such as copper, magnesium and manganese, currently available information is insufficient to assess the possible linkages between deficiencies in these nutrients in soils and crops, and in animal and human nutrition, but such relationships may well be uncovered in coming years.

In the second place, it is explored to what extent there are opportunities for simultaneously addressing micronutrient deficiencies as these occur in soils, in plants and animals, and in humans, with specific attention to the possibility of the application of micronutrients as fertilizer to crops. Point of departure in this review has been that the application of micronutrients should simultaneously result in both higher yields and higher crop micronutrient contents. Only then there will be a direct benefit for both farmers and consumers, for the first in the form of higher incomes, for the last in the form of better health.

For iodine and selenium, the possibilities for combining higher yields with higher crop micronutrient contents are limited, as these micronutrients are not essential for plants, and the application of iodine or selenium will have no or at most very modest effects on plant growth or plant health. Yet, application of iodine or selenium to soils, or to irrigation water, may result in higher crop contents of these micronutrients. For zinc on the other hand, available information indicates that its application to crops can result both in considerably higher crop yields and also in higher crop zinc contents. This has been shown for major food crops such as wheat, rice and maize. Yet, still insufficient information is available on the direct linkages between soil zinc deficiencies and human zinc deficiencies, and there is a need for investigating in much greater depth the geographical aspects of human zinc deficiency and its relationship with zinc deficiency in soils and plants. Finally, for iron available information confirms the complexity of iron chemistry and physiology, and effective and efficient approaches for simultaneously addressing plant and human iron deficiency are not readily available. Nevertheless, in view of the high prevalence of iron deficiency in the world, investigations aimed at increasing food iron contents, possibly in combination with increased crop yields, should remain high on the research agenda.

As to the way in which supplementary micronutrients could by applied to crops, enrichment of commonly used fertilizer mixtures with micronutrients is most likely not the most appropriate approach. In the first place, when combining relative small amounts of micronutrients with large amounts of traditional fertilizer minerals, such as calcium and phosphate, antagonistic interactions between the various minerals and trace elements might occur, making the micronutrients unavailable for uptake by plants. In fact, it cannot be excluded that already at present the application of traditional fertilizer mixtures is sometimes detrimental for crop growth, just because of their antagonistic effects on micronutrient availability. Another important reason why enrichment of fertilizer with micronutrients is unlikely to be successful, is that in particular in Sub Sahara Africa current levels of fertilizer usage is very low, and therefore the addition of micronutrients to commonly used fertilizer mixtures would have very little impact. It is for these reasons that a direct application of micronutrients, either on a one by one basis or in well-designed combinations, would most likely be the preferred technology. Availability of single micronutrient supplements or well-balanced combinations of a few micronutrients would allow for highly site-specific micronutrient applications, and also for undertaking simple on-site experiments in order to achieve optimal results.

Apart from the expected benefits, as argued in this paper, from a balanced and controlled application of micronutrient fertilizers, there are other food based approaches that are being promoted and part of intensive research, also with the objective to address human micronutrient deficiencies (Welch and Graham, 2000, 2002, 2004; Gibson, 2004). Of these, the most important ones are breeding for micronutrient rich varieties and developing new varieties through genetic manipulation (Bouis, 1999, 2003; Graham et al., 1999). A promising example is the recently developed “high-iron” rice. While also these approaches might well contribute in alleviating human micronutrient deficiencies, one major question is what the response of such breeds or varieties will be, when grown on micronutrient deficient soils. When a soil is highly deficient in a certain micronutrient, even the best breeds or varieties will not be able to incorporate sufficient amounts of these micronutrients into the food crops.

A specific problem with micronutrients is that there are manifold chemical and physiological interactions, mutually between them, and between micronutrients and other substances. In human nutrition, these interactions could perhaps partially explain the sometimes unexpected and occasionally even adverse results when mixtures of micronutrients are given to children or adults as nutritional supplements. In view of such interactions, increasing micronutrient contents of food crops through a “fertilizer approach” might well be a safer and more physiological way to increase human micronutrient intakes.

Finally, a specific note should be made on the fact that over past decades not only a vast amount of knowledge and experience has been built up on the occurrence of micronutrient deficiencies in crops and in human nutrition, but also in animal husbandry and livestock raising. Deficiencies in almost all micronutrients have been described for different types of animals, giving almost the impression that knowledge on micronutrient deficiencies in animal nutrition is sometimes even more extensively available than knowledge on human micronutrient deficiencies. In a number of these studies direct linkages between soil micronutrient contents and micronutrient contents of forage and fodders have been clearly established. Results from these and other studies in animal feeding are considered highly relevant when further investigating relationships between micronutrient deficiencies in soils, food crops, and in animal and human nutrition. A more intensive exchange of information and cooperation between soil science, agriculture, animal science and human nutrition may well prove to be highly valuable in finding new approaches for addressing micronutrient deficiencies, in ways beneficial for both farmers and consumers.

Table 8. Schematic overview of (1) possible effects of micronutrient application on yields of crops and/or animal produce, (2) possible effects on micronutrient contents in crops and/or animal products, and (3) possible benefits for farmers and/or consumers

	(1) Positive effect on crop yield/animal produce	(2) Positive effect on micronutrient contents of crops or animal produce	(3) Benefits for farmers and/or consumers
Iodine	+ (animal produce only, no effect on crop yield) [1)]	+	farmers (animal produce) and consumers
Iron	+	(+)	farmers, possibly also consumers
Zinc	+	+	farmers and consumers
Selenium	-	+	consumers
Other micronutrients	+ (for some micro-nutrients)	+ (for some micro-nutrients)	needs further research and confirmation

[1)] "+": positive effect established; "(+)": positive possible but difficult to achieve; "-": no or hardly positive effects.

In conclusion, for a number of micronutrients there are clearly direct linkages between the occurrence of deficiencies in soils, in food crops, and in animal and human nutrition. For some micronutrients which are essential in both plant and human nutrition, there may be opportunities for simultaneously addressing the deficiencies by applying them as supplemental fertilizer to crops, benefiting both farmers (better yields) and consumers (higher micronutrient contents of consumed foods). At present, opportunities for such an approach appear to be most feasible for zinc, but there may be opportunities for other micronutrients as well. In a very schematic way, the findings of this report are summarized in Table 8. It is speculated that controlled and site-specific application of micronutrients to crops, in combination with well-dosed usage of traditional fertilizer (N, P and K) might help break the vicious cycles of low yields, poverty and poor human nutrition in Sub Sahara Africa, and possible also in other poor regions of the world.

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The Centre for World Food Studies (Dutch acronym SOW-VU) is a research institute related to the Department of Economics and Econometrics of the Vrije Universiteit Amsterdam. It was established in 1977 and engages in quantitative analyses to support national and international policy formulation in the areas of food, agriculture and development cooperation.

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