Micronutrient management for improving harvests, human nutrition, and the environment

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Table of Contents

Table of Contents 1

Preface 2

Executive Summary 3

Definitions 5

1 Introduction: Agronomic biofortification to alleviate micronutrient deficiencies 6

2 Impact of agronomic bio-fortification on yield and nutritional quality of crops 9

3 Impact on bioavailability of micronutrients and human health using enriched fertilizers 12

4 Impact of agronomic biofortification on environment 14

5 Comparison between different intervention approaches for improving micronutrient status in humans 15

6 Potential and constraints of using agronomic biofortification in sub-Saharan Africa 17

References 18

Preface

Soil micronutrient availability is a limiting factor in crop productivity and quality in sub-Saharan Africa. Agronomic biofortification is an agronomic strategy to increase micronutrient content and bioavailability for human nutrition in the edible parts of crops by adding micronutrient fertilizers to the soil or plant leaves. This will not only improve soil and plant performance, but could also have impacts on human health through increased micronutrient consumption. This essay considers the potential of agronomic biofortification by exploring the effectiveness of micronutrient fertilization to improve crop productivity, the nutritional quality of edible plant parts, the bioavailability for human uptake and human nutrition. Furthermore, pathways to make these fertilizers available to resource poor farmers in sub-Saharan Africa are explored by taking into account the local production conditions and socio-economic context. This paper is a background document for the participants of the Micronutrients Stakeholder Workshop on April 5 2016, organized by the Food & Business Knowledge Platform in collaboration with IFDC (VFRC) and WUR in Utrecht, The Netherlands.

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Executive Summary

Micronutrient deficiencies in soils limit crop yields and nutritional quality, which in turn negatively affect human health. Especially in sub-Saharan Africa, soils have multiple micronutrient deficiencies what makes soils non-responsive to NPK fertilization. Poor crop yields in combination with diets that are mainly based on staple crops, causes widespread micronutrient deficiencies among the population, with severe health problems as a consequence. A suggested strategy to alleviate micronutrient deficiencies in this region is agronomic biofortification, particularly of staple foods. This is the fertilization of soils or plant leaves with mineral micronutrient fertilizers in order to increase certain micronutrient contents in the edible part of crops to alleviate micronutrient deficiencies among humans. The impact of agronomic biofortification largely depends on the bioavailability of micronutrients throughout the entire pathway from soil to plant, from plant to food and uptake by the human body. Factors that determine bioavailability are mainly soil conditions, crop variety, food processing, concentration of micronutrient inhibitors or enhancers in food, dietary intake, the forms of micronutrients in food, interactions among nutrients, and physiological condition of individuals. The effects of agronomic biofortification on yields, nutritional quality of crops and human health are discussed in this paper.

Some studies have shown a positive impact of agronomic biofortification on yields and nutritional quality of crops, but the impact largely depends on interactions between specific soil conditions, crop (varieties), nutrients and fertilizer blends, fertilizer application techniques and further soil management practices. Positive impacts on yields and nutritional quality of crops have been observed in several studies, mainly on Se and Zn. Also Fe has been studied regularly, but has so far shown little potential for successful impact through fertilizer application. From the two fertilizer application techniques, foliar application seems to be more effective than soil application in increasing nutrient content in the harvested product, and the combinations of both give the strongest impact. However, foliar application is often rejected as suitable strategy, because it is costly and difficult to implement for resource poor farmers. Unfortunately, studies from Africa are scarce, so it is difficult to make strong conclusions and recommendations for this region. Interactions between micro- and macro-nutrients influence the effectiveness so that generally best yield and nutritional quality improvement is observed when micronutrient-enriched NPK fertilizers are used. Soil micronutrient availability for crop uptake is even further enhanced under good soil conditions, which highlights the importance of proper soil management. Integrated Soil Fertility Management (ISFM) is suggested as a robust approach to optimize nutrient use efficiency, using a combination of improved germplasm, mineral fertilizers and organic inputs. The bioavailability of micronutrients within the edible part of the crop depends on characteristics of the crop (variety), which determines the (re-) localization pathways. Breeding is still considered as the most effective way to influence these characteristics. Agronomic biofortification is mainly seen as a complementary approach next to breeding to make micronutrients available for the improved breed to allocate within the harvestable food.

The impact of agronomic biofortification on human health depends on the bioavailability of micronutrients within the edible part of crops and following the bioavailability of processed foods for uptake in the human body. The current approach to measure the impact of agronomic biofortification in human is to measure the phytate level for Zn bioavailability , GSHPx activity in serum/blood for Se and using feeding trials for Fe. Using micronutrient-containing fertilizer could lead to decrease on phytate concentration increasing bioavailability of Zn and Fe. However, studies that link micronutrient-enriched fertilizer application to increased bioavailability leading to improved human health status are scarce, especially for sub-Saharan Africa. This might be because there are many factors affecting the micronutrient status even after the consumption of the staple foods. The physiological status of an individual also determines the capacity to absorb and metabolise these micronutrients. The fact that studies to estimate the accurate bioavailability are costly and determination of micronutrient absorption and its utilization in the human body is practically not feasible, makes it difficult to reach firm conclusions about increased bioavailability and impacts on human micronutrient intake. The lack of evidence hampers definite conclusions about the effectiveness of agronomic fortification to alleviate micronutrient deficiencies among humans.

When micronutrient demand and supply are synchronized, there should be no serious negative environmental effects within the agricultural ecosystem. Micronutrients generally bind strongly to the soil and thus are not susceptible to be lost in the environment which minimizes risks of environmental pollution. Furthermore, micronutrients improve crop health, which reduces the need for agrochemicals (pesticides, herbicides, fungicides, etc.). Accumulation in soils due to overuse may cause toxicity problems. The globally available mineral reserves of micronutrients are limited, which highlights the importance of nutrient recycling for long-term sustainable micronutrient availability for agricultural production.

There are many cost efficacy and effectiveness studies of other food-based approaches, and they are proven to work or not work in specific settings or countries. For instance, supplementation and fortification require sound medical and technical infrastructure in place which is not currently the case for many African countries which have predominantly rural populations that are difficult to reach. Similarly, dietary diversification also needs a high investment for implementation. Foods rich in bioavailable micronutrients tend to be expensive, unaffordable for poor people and require changes in dietary behaviour that are difficult to achieve. Regarding the cost-effectiveness of agronomic biofortification, there are few studies showing that foliar application could be cost-effective in sub-Saharan Africa. As financial analysis of agronomic biofortification was not a core part of this review, we cannot make any conclusive judgement on cost-effectiveness of agronomic biofortification.

Using agronomic biofortification in sub-Saharan Africa would require several technical as well as social-economic and infrastructural development steps. Firstly, accurate diagnostic tools should be developed and applied that give insight into the micronutrient availability as influenced by soil, climate and land use conditions. This would provide a basis for appropriate soil management and fertilizer use recommendations to farmers. Secondly, market and transport infrastructure need to be in place to give access to the necessary organic and/or mineral fertilizers and markets for the surplus produce. Finally, a number of other factors play a role in the effectiveness of the intervention, not all described here. These will be further explored during the workshop in April 2016.

Photo credit: Saskia Osendarp "Dietary diversification programme Ethiopia, Micronutrient Initiative"

Definitions

Micronutrient deficiency
Micronutrient deficiency is the lack of sufficient amounts of one or more micronutrients, which are elements required in plants and in the human body in very small amounts. In plants micronutrient deficiency is the lack of essential trace minerals whereas in humans, the term is used to cover both vitamin and mineral deficiencies. Most common micronutrient deficiencies in humans are iron, iodine, vitamin A, folate, zinc and selenium.

Bioavailability
"*The bioavailability of nutrients can be defined as its accessibility to normal metabolic and physiological process in the human body. Bioavailability influences a nutrient's beneficial effect at physiological levels of intake and also may affect the nature and severity of toxicity due to excessive intake*"
(*Hambidge, 2010*).

Biofortification
Biofortification is the process of increasing the content and/or bioavailability of essential nutrients in crops during plant growth through genetic and agronomic pathways.

Agronomic biofortification
Agronomic biofortification is the strategy to increase micronutrient content in the edible part of food crops through soil and/or foliar application of micronutrient-containing mineral fertilizer (*Fig. 1*).

Integrated Soil Fertility Management (ISFM)
"*A set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs and improved germplasm combined with the knowledge on how to adapt these practices to local conditions, aiming at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity [...]*"
(*Vanlauwe et al., 2010*).

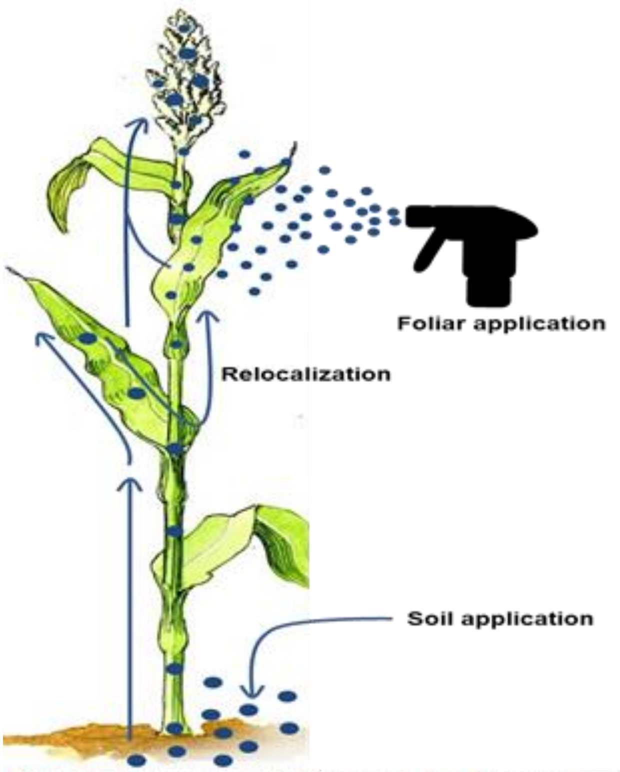

Figure 1. Agronomic biofortification is the strategy to increase micronutrient (blue circles) content in the edible part of food crops by soil and/ or foliar application of micronutrient-containing mineral fertilizer.

1 Introduction: Agronomic biofortification to alleviate micronutrient deficiencies

Micronutrient deficiency is a problem for crop production and for human nutrition. Soil micronutrient deficiencies limit crop productivity and nutritional quality, which together may affect human health (*Marschner, 2012; Alloway, 2009; Fig. 2*). Many African soils are affected by multiple nutrient deficiencies including the macronutrients N, P, K, secondary nutrients Se, Ca and Mg, as well as the micronutrients Zn, Fe, Cu, Mn and B (*Vanlauwe et al., 2015*). Soil micronutrient deficiencies are severe in sub-Saharan Africa, where 75% of the total arable land has serious soil fertility problems (*Toenniessen et al., 2008*). Insufficient micronutrient availability in soils in these regions not only causes low crop productivity, but also poor nutritional quality of the crops. Diets in sub-Saharan Africa (especially among the resource poor populations) are often low in diversity and dominated by staple crops such as maize, sorghum, millet, cassava, rice and sweet potato. These diets are poor in mineral micronutrients and vitamin content and consequently micronutrient deficiencies are widespread among these populations. The chronic lack of micronutrients can cause severe but often invisible health problems, especially among women and young children (*Kennedy et al., 2003; FAO, 2015; Black et al, 2013*).

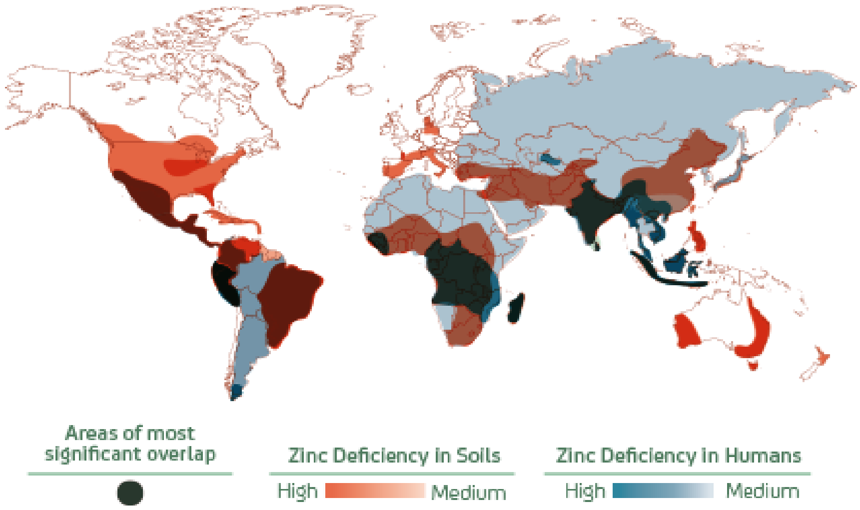

Figure 2. Significant overlap of Zn deficient soils and humans in sub-Saharan Africa, South Asia and Peru (figure from rootsforgrowth.com; source: IZA)

Worldwide over 2 billion people suffer from iron (Fe), zinc (Zn) and/or other (multiple) micronutrient deficiencies (*WHO, 2016; Black, 2003*). The problem is most severe in low- and middle income countries, especially in sub-Saharan Africa, where micronutrient deficiencies are responsible of 1.5-12% of the total Disability Adjusted Life Years (DALYs)[1] (*Muthayya et al., 2013*). This means that from a national perspective about 1 out of 10 years lived with a disability are due to insufficient micronutrient intake. The most alarming numbers are around iron deficiency anaemia, which affects over 50% of the female population in countries such as DR Congo, Ghana, Mali, Senegal, Togo and causes 115,000 maternal deaths per year (*IFPRI, 2015*). Likewise, almost half of the African population is selenium (Se) deficient, with up to 88% of the population being Se deficient in Malawi (*Melse-Boonstra et al., 2007*). Selenium is not an essential element for plant growth, but contributes to the human diet through uptake into crops from the soil.

Even mild to moderate deficiencies of micronutrients can lead to severe health problems. Iron deficiency is the prominent cause of anaemia which contributes to compromised physical productivity, cognitive impairment and adverse pregnancy outcomes. Likewise, Zn deficiency has been related to growth failure, decreased immunity leading to increased susceptibility to infection, morbidity and mortality due to diarrheal disease and the incidence of respiratory tract pneumonia (*Etcheverry et al., 2005*). Selenium has important antioxidant, anti-cancer and anti-viral properties and its deficiency makes human prone to thyroid dysfunction, cancer, severe viral disease and various inflammatory conditions (*Lyons et al., 2004*).

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[1] One DALY can be thought of as one lost year of “Healthy” life. The sum of these DALYs across the population, or the burden of disease, can be thought as a measurement of the gap between current health status and an ideal health situation where the entire population lives to an advanced age, free of disease and disability (http://www.who.int/healthinfo/global_burden_disease/metrics_daly/en/)

There are several approaches to alleviate micronutrient deficiencies among humans: dietary diversification, supplementation, modification of feeding habits, fortification and biofortification of food. Biofortification is the process of increasing the content and/or bioavailability of essential nutrients in crops during plant growth through genetic and agronomic pathways (*Fig. 3*).

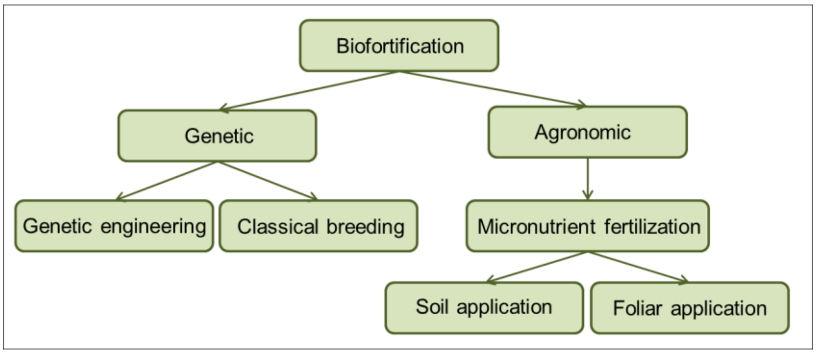

Figure 3. Pathways for biofortification.

Genetic biofortification involves either genetic engineering or classical breeding. Agronomic biofortification is achieved through micronutrient fertilizer application to the soil or application directly to the leaves of the crop (foliar application). Biofortification is mainly done on staple crops (like rice, wheat, maize, sorghum, millet, sweet potatoes and legumes), because they dominate diets worldwide and especially among groups vulnerable for micronutrient deficiencies. Agronomic biofortification is mainly studied with Zn and Se, for which it is assumed to be most effective (*Cakmak, 2014*). Besides Zn and Se, this paper also discusses agronomic biofortification with iron (Fe), because of the great importance for human health (*Welch and Graham, 1999*). Biofortification with vitamins is not possible through the agronomic pathway (because only minerals can be incorporated in fertilizers) and thus are not discussed in this paper.

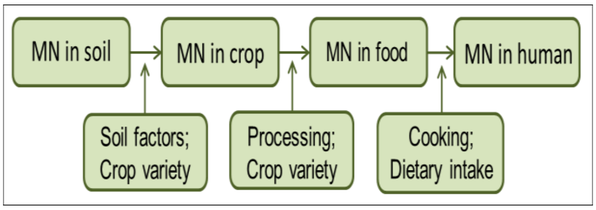

Figure 4. Schematic overview of micronutrient (MN) pathway from soil to humans and the factors that influence MN bioavailability to the next level. Based on Mayer et al. (2011).

Micronutrients follow a path from the soil through the crop and food into the human body (*Fig. 4*). Several critical factors determine the success of agronomic fortification to alleviate micronutrient deficiencies among humans. These factors depend on nutrient bioavailability at different stages: the presence and bioavailability of soil nutrients for plant uptake, nutrient allocation within the plant, re-translocation into the harvested food and availability of nutrients in prepared food for uptake in the human body. Bioavailability from soil to crop is influenced by many soil factors (i.e. pH, organic matter content, soil aeration and moisture and interaction with other elements) and the crop variety that, for example, defines the functioning of rooting systems. Bioavailability from crop to food is influenced by the crop variety (which defines the allocation and re-localization of micronutrients into edible parts of the crop) and processing of the harvestable part (i.e. milling and dehusking). Bioavailability from the food for the human body is influenced by cooking of food and dietary intake such as the amount of food consumed, diet composition and individual health status.

Opinions as to the effectiveness and feasibility of the different pathways towards biofortification differ among stakeholders. A generally accepted opinion is that classical breeding is a sustainable and relatively low-cost way to increase crop nutrient contents (*Velu et al. 2014*), while genetic engineering (GE) is not commonly used because development is costly and takes much time, and implementation is difficult due to regulations governing GE crops (*Global Panel, 2015*). Agronomic biofortification is generally considered as a complementary strategy to classical breeding, as it stimulates optimal growth of the improved crop varieties. Micronutrient fertilization is suggested by *Dimpka and Bindraban (2015)* as an effective practice to improve yields, nutritional quality and health of crops, which should have a positive impact on human nutrition and the environment.

The question remains, though what the actual potential of agronomic biofortification is to improve harvests, human health and the environment. Here we provide an overview of the currently available knowledge and developments on the impact of agronomic biofortification. This review addresses the impact of agronomic biofortification on: 1) yields and nutritional quality of crops, 2) micronutrient intake in human and impact on nutritional status and 3) the environment. Furthermore, a comparison is made between agronomic biofortification and other interventions to improve human health. At last, recommendations are made for successful implementation of agronomic biofortification in sub-Saharan Africa. The issue of cost-effectiveness and affordability of agronomic biofortification is not explored in detail.

Photo credit: CIMMYT on Flickr "Smallholder farmer prepares maize plot for planting with CIMMYT improved varieties, Embu, Kenya"

2 Impact of agronomic bio-fortification on yield and nutritional quality of crops

Soils in sub-Saharan Africa are highly diverse, ranging from some of the oldest soils in the world to relatively young volcanic soils in the Great Rift Valley that splits East and Southern Africa and alluvial soils along rivers. Many African soils suffer from multiple micronutrient deficiencies, due both to their inherent soil properties and to continuous cropping without nutrient replenishment. Current fertilization programmes in African countries, primarily focus on NPK fertilizers, but many soils are non-responsive to NPK due to (multiple) micronutrient deficiencies (*Vanlauwe et al., 2015*). Soil amendment with small amounts of (multiple) micronutrients has been suggested as a sustainable strategy to increase yields and nutritional quality of crops (*Vanlauwe et al., 2015; Voortman and Bindraban, 2015; Manzeke et al., 2012*).

Effectiveness is restricted to certain crops and fertilizer blends

Nutrient bioavailability from the soil to the plant is influenced by soil properties and soil management practices. Even when the soil contains sufficient amounts of micronutrients, soil properties can affect their bioavailability for plant uptake. For example, bioavailability of soil Zn to plants is limited by high soil pH, high calcium carbonate (CaCO3) concentrations, low soil organic matter contents, low soil moisture and interaction with other trace elements, especially Fe, Cu and Ni (*Alloway, 2009*). Some plants can modify the rhizosphere by the excretion of H+ ions or organic acids that enhance micronutrient availability and uptake (*Marschner, 2012*). Interactions between elements also influence the bioavailability for root uptake. Soil phosphorus, for example, can either stimulate root growth and Zn uptake while at the same time it can precipitate already small concentrations of Zn to form insoluble Zn phosphate and trigger Zn deficiency. There are many soil management strategies to influence soil properties and stimulate the bioavailability of soil nutrients for crop uptake. The application of organic amendments to the soil can increase the bioavailability and uptake of nutrients from mineral fertilizers, and pH can be altered through soil liming. Most crops have symbioses with arbuscular mycorrhizal fungi which increase uptake of nutrients that are poorly soluble in soil, such as P and Zn. The mycorrhiza forms an extensive fungal network acting as an extension of the root system and increasing the volume of soil explored for nutrient uptake.

When nutrients are taken up by the plant, the localization within the plant depends on multiple metabolic interactions that differ among plant species and varieties. The responses also firstly depend on specific plant-micronutrient interactions and on the fertilizer blend, as interactions between nutrients that are combined within the blend can have positive as well as neutral or even negative effects on yields and nutrient use efficiencies (*Rietra et al., 2015*). Furthermore, nutrients are distributed over different plant organs and can be re-localized when parts require higher concentrations during certain development stages, such as increased transport to grains as they fill. Whether the micronutrients are actually (re-) located in the part of the plant which is consumed depends on the crop (variety). In rice for example, Zn is localized in protein bodies in the outer layer of the grains, which is removed during processing (dehusking, milling) leaving little Zn in the consumed rice (*Duffner et al., 2014*). Other crops like wheat allocate Zn in the consumed part of the grain (endosperm) that remains even after removal of the seed coat and aleurone layer during the process of bread making – thus wheat is more suitable for agronomic biofortification (*Ajiboye et al., 2015*). For effective pass-through of micronutrients to humans, it is essential that targeted micronutrients end up in the edible parts of the crop. The main technique to influence this process is breeding for varieties that accumulate targeted micronutrients into these edible parts. Thus, for effective agronomic biofortification it is important to strategically choose crop (varieties) and approaches to crop and soil nutrient management that have the potential to alleviate micronutrient deficiencies.

Impact of agronomic bio-fortification on yield and nutritional quality

Agronomic biofortification has so far been most effective with Zn and Se (*Cakmak, 2014*). One of the most celebrated cases is from Finland, where the addition of Se to NPK fertilizers increased crop Se contents and the Se status of the whole population (*Alfthan et al., 2015*). A study from Malawi also showed the effect of Se fertilization to maize: yields remained unaffected but grain Se concentrations increased linearly with increased Se application rates (*Chilimba et al., 2012*). However, the effect of Se fertilization is not always observed: Se-enriched fertilizer (soil as well as foliar) in Australia by *Lyons et al. (2005)* did not affect wheat yields nor Se concentrations in the grain.

Most current research and development programmes focus on Zn, as this is a widespread yield-limiting factor and one of the most prevalent deficiencies in humans. Evidence is accumulating that Zn fertilization can increase both yield and nutritional quality of crops. Most research has been done in Turkey, where Zn fertilization of various cereals (maize, sorghum, barley, wheat) and dicotyledonous (soybean, safflower, pea, common bean, canola, common vetch) crops showed increased yields and grain Zn concentrations (*Cakmak et al., 2010*). *Yilmaz et al. (1997)* observed increased wheat yields and wheat grain Zn concentrations, which increased threefold with both soil and foliar Zn application. Field studies in India showed that the use of Zn-enriched urea on rice increased yields and grain Zn concentrations up to three times (*Cakmak, 2009*). A review of experiments from 10 African countries on the impact of Zn-enriched fertilizers, showed that soil Zn application increased the Zn concentration in maize, rice and wheat grains by respectively 23%, 7% and 19 % and by 30%, 25% and 63 % through foliar application (*Joy et al., 2015*). Teff yields in Ethiopia increased with mineral Zn fertilization (*Haileselassie et al., 2011*). However, studies in Africa are scarce and the fact that the impact largely depends on specific crops, nutrient and soil conditions, makes it difficult to make general statements on the potential impact of agronomic biofortification. In general it is known that, Zn fertilization reduces P uptake and the accumulation of phytate in grains, what increases the Zn bioavailability in humans (*Hussain et al., 2013a*). Another agronomic benefit is that seedlings from seeds with high Zn concentration have better growth performance and resilience against environmental stress, so positive impacts on productivity may be seen in the next cropping generation.

Iron is the second most studied element, but agronomic biofortification is more difficult than with Zn, because Fe is precipitated into insoluble forms in the soil which inhibits root uptake. As an example, a greenhouse experiment that compared Zn and Fe application on wheat showed enhanced grain Zn concentrations, while Fe concentrations were not effectively improved (*Cakmak et al., 2010*). Food fortification and supplementation have been the most commonly used strategies to alleviate Fe deficiencies among humans, although some argue that biofortification has more potential in the long-term because it is more cost-effective and practical (*Garcia-Banuelos et al., 2014*). The most effective agronomic practices for the Fe enrichment of crops are through litter fertilization or foliar application of mineral Fe. Foliar application has already showed to increase Fe concentrations in wheat grain and rice grain (*Shahzad et al., 2014*). However, some studies also showed no response of plant upon foliar Fe application, especially under treatment with inorganic and chelated Fe fertilizers (*Gracia-Banuelos et al., 2014*). The case from Finland, where Se-enriched NPK fertilizer application alleviated Se deficiency among the entire population, is one of the very few examples that directly and significantly showed the impact of agronomic biofortification to increase human health status.

Impact of different fertilization techniques

Effectiveness of mineral fertilizer application on crop performance is influenced by the fertilizer type and application method. Foliar fertilization with micronutrients often stimulates more nutrient uptake and efficient allocation in the edible plant parts than soil fertilization, especially with cereals and leafy vegetables (*Lawson et al., 2015*). The downside is that foliar fertilizers can easily be washed off by rain and are often more expensive and difficult to apply. Micronutrients that can best be foliar applied are Fe and Mn whereas Mo and Ni are not absorbed through the leaves; Zn, B, Cl and Cu can be applied by both techniques (*Dimpka and Bindraban, 2015*). Zn fertilization seems to be more effective though the foliar pathway as this avoids possible problems of immobilization of Zn in the soil. Evaluation of 17 studies on the effect of soil and/or foliar Zn fertilization on rice by *Phattarakul et al. (2012)*, showed that Zn fertilization in general had little effect on rice grain yield (average only 5% increase), but that it did increase grain Zn concentrations, especially under foliar application. Grain Zn concentrations of brown rice increased on average with 25% by foliar, 32% by foliar+soil and only 2.4% of the soil Zn application. A study by *Abijibove et al. (2015)* showed the potential of foliar Zn application on wheat to increase grain Zn contents. At the same time, the contents of other micronutrients (Fe, Cu and Mn) were increased, which indicates that improved plant Zn nutrition has the potential to increase overall plant nutritional status. The combination of soil and foliar application is the most effective method for many biofortification pathways (*Cakmak et al., 2010; Fig. 5*). However, despite the proven effectiveness of foliar fertilization, the technique is often rejected as a sustainable strategy to alleviate micronutrient deficiencies among resource poor populations in Africa, because it is costly (*Garcia-Banuelos e al., 2014*). Seed priming and seed coating with fertilizers is another strategy to apply micronutrients in precise amounts and location, but increased nutritious values of grains are rarely found (*Duffner et al., 2014*).

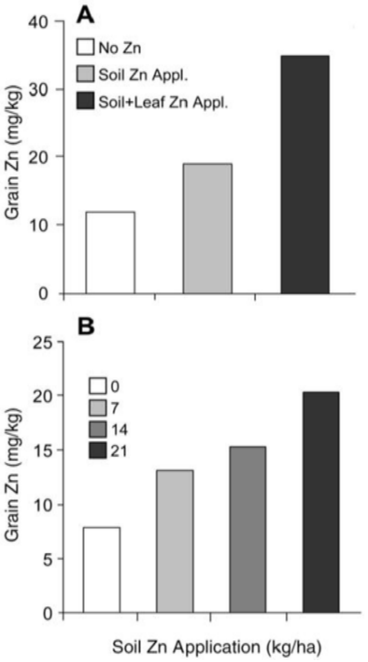

Figure 5. Wheat grain Zn concentrations after different fertilization techniques (A) and application rates of ZnSO4 (B); from a study on soils highly deficient in Zn in Central Turkey (Cakmak, 2010).

Increased positive effect in combination with NPK fertilization

Interactions of micronutrients with macronutrients can influence the effectiveness of agronomic biofortification. Good N and P status of plants has a positive influence on root development, shoot transport and re-localization of nutrients from vegetative tissue to the seeds (*Prasad et al., 2014; Cakmak et al., 2010*). This results in increased micronutrient uptake and concentrations in the edible parts of the crop. This has been shown in experiments with wheat, where high N application increased Zn and Fe concentrations in the grain endosperm (the edible part of the grain) (*Kutman et al., 2011; Shi et al., 2010*). Wheat fertilization with Zn-enriched N & P fertilizer has also been effective to increase wheat grain yields and grain Zn concentrations (*Cakmak, 2004*). In a study on the effect of macro- and micronutrient blending by *Rao et al. (2012)*, it was observed that productivity of soybean and finger millet and nutrient uptake (N, P, Zn, B, S) was increased significantly by fertilization with blends of mineral NPK plus Zn, B and S. On the other hand, P fertilization can also decrease micronutrient concentrations due to a dilution effect when plants grow prolifically. Proper N and P management is important for the (increased) effectiveness of micronutrient fertilization and indicates the importance of a more integrated soil fertility management approach, as explained further below.

Impact of integrated soil fertility management (ISFM)

Good soil conditions that enhance micronutrient availability for crop uptake are essential for the success of agronomic biofortification. Not only N and P increase the effectiveness of micronutrient fertilization, but also other soil chemical, physical and biological characteristics are essential to optimize nutrient use efficiency. A commonly suggested strategy to optimize soil conditions is Integrated Soil Fertility Management (ISFM), that is defined as “a set of soil fertility management practices that necessarily include the use of mineral fertilizer, organic inputs and improved germplasm” (*Vanlauwe et al., 2010*). The combination of mineral fertilizers and organic inputs is beneficial, because they have complementary functions and enhance each other’s effectiveness. Organic resources (plant residues and animal manure) help to sustain soil organic matter with multiple benefits in terms of enhanced soil structure, cation exchange capacity and water holding capacity (*van Noordwijk et al., 1997*). Furthermore, where organic inputs provide more slow but constant nutrient release, mineral fertilizers offer flexibility in the proper timing, placing and application rate to synchronize nutrient availability with crop demand (*Giller, 2002*). Fertilization with organic matter alone has the potential to increase soil micronutrient content and availability (*Thilakarathna and Raizada, 2015; Traore, 2006*). Animal manures, for example, are a good source of many secondary micronutrients (*Zingore et al., 2008*). Long-term application of organic matter to the soil not only increases total Zn content of the soil but also the proportion of labile Zn, which is the readily available form for plant uptake (*Santos et al., 2010*). However, organic inputs alone are often insufficient t to maintain nutrient balances in resource poor farming systems, because of the limited availability of nutrient-rich organic matter (e.g., manures and compost) and overall lack of nutrients in the system. The combined application of organic inputs and mineral micronutrient fertilizers has the potential to alleviate overall micronutrient shortage in these farming systems. Besides, agronomic efficiency of mineral fertilizers is often increased when applied in combination with organic matter, as was described in the case of Zn biofortification in rice by *Duffner et al (2014)*. Green manures (cover crops that serve as mulch or soil amendment) are also effective to enhance nutrient bioavailability, as was shown in a study on basmati rice in India, where the combined fertilization with green manure and mineral Zn improved yields and grain Zn nutritional quality (*Pooniya and Shivay, 2013*). The combination of mineral and organic fertilizers with improved germplasm enhances optimal nutrient use efficiency, when the variety is selected for characteristics of improved nutrient uptake and localization in the consumed parts of the crop.

3 Impact on bioavailability of micronutrients and human health using enriched fertilizers

The bioavailability of essential minerals depends on the form and amount of the mineral intake as well as the presence or absence of elements promoting or inhibiting their absorption in the gastrointestinal tract (*Frossard et al., 2000; Sandström, 2001*). Enhancers like ascorbic acid can increase the (Fe) bioavailability through various mechanisms. Phytic acid and polyphenols are the major inhibitors of micronutrient absorption (mainly Fe and Zn) in staple foods because they form unabsorbable complexes with dietary minerals. Phytate is formed during maturation of the plant seed and in dormant seeds (*Kumar et al., 2010*). Therefore, phytate is the prime concern in dietary intake of micronutrients, although *Kumar et al., (2010)* concluded that phytates also have beneficial effects on health. The phytate-to-mineral (PA/Zn or PA/Fe) molar ratio has widely been used to measure the bioavailability of minerals in human diet (*Johns & Eyzaguirre, 2007; Wang et al., 2015*). Dietary phytates have shown protection against various cancers, heart-related disease, diabetes and renal stones (*Kumar et al., 2010*). Therefore, *White (2009)* noted that while we increase the bioavailability of Fe and Zn in diet by decreasing phytates/polyphenols, it might also decrease the beneficial effects of these compounds on human health (*White & Broadley, 2009*). *Kumar et al. (2010)* also indicated that research on the dosage of phytates that might have a positive or a negative impact for human health is limited. So, it is important to consider trade-offs of decreasing phytate concentration in plants.

Table 1. Effectors of Bioavailability

Inhibitors	
Cereals	Phytic acid (Polyphenols)
Legumes	Phytic acid, protein (Polyphenols)
Tea, coffee, red wine and vegetables	Polyphenols
Enhancers	
Fruits	Ascorbic acid other organic acids
Vegetables	Ascorbic acid
Meat	Muscle tissues

Source: Gibson (2007)

Bioavailability of Fe

Fe is present in mainly two forms: haem-Fe in animal source food such as meat and blood, and non-haem-Fe in plants, eggs and milk. A third and a fourth type are ferritin and the so called contamination iron. Some 35 % of the haem-Fe is readily absorbed in human body whereas only 5-10 % of non-haem-Fe is absorbed in the human body depending on the iron-status of the human being. Studies on the bioavailability of ferritin and contamination iron showed conflicting results but it is generally assumed that absorption is rather poor (*Lukac et al, 2009; Hallberg et al, 1983*). Many staple foods such as wheat have high concentrations of polyphenols and phytic acid in their grain, reducing the bioavailability of minerals in the human body. Absorption of iron is enhanced by ascorbic acid from fruits and vegetables (*Hallberg et al, 1986*) and some digested peptides from muscle tissues while phytic acid and polyphenols such as tannin act as dose-dependent inhibitors of Fe absorption (*Gibson, 2007*). Phytic acid to iron molar ratio is an important determinant and it is assumed that a molar ratio of below 0.4:1 is preferable for iron absorption (*Hurell et al 1992*).

Bioavailability of Zn

Phytic acid also acts as an inhibitor for absorption of Zn in the human body. Studies have shown that foods containing high amounts of phytic acid have low Zn bioavailability, because phytic acids bind with Zn and form unabsorbable complexes (*Cakmak et al., 1999; Clemens, 2014*). Phytic acid to zinc molar ratio is an important determinant of level of bioavailability and ratios of < 5, 5-15 and >15 are generally considered to represent diets of relatively high (50%), moderate (30%) and low (15%) absorption levels (*Hotz and Brown, 2004*). Relative to the intake, absorption of 15-30% by the human gut system is associated with an increased risk of Zn deficiency (*Clemens, 2014*). Therefore, low bioavailability of zinc is one of the major factors for the occurrence of zinc deficiency (*Frossard et al., 2000*). Most studies have focused on the increase of the yield of wheat grain rather than bioavailability of the minerals in grains for human consumption. *Hussain et al. (2013b)* found that the soil Zn application not only increased the Zn concentration in the crop, but also reduced the phytate concentration.

Bioavailability of Se

The bioavailability and impact of selenium also depend on the amount and chemical form of Se supplied and availability in food. Selenomethionine (SeMet) and selenocysteine (SeCys) are the most bioavailable forms of selenium for human body (*Ip, 1998; White and Broadley, 2009*). Selenocysteine is part of glutathione peroxidase enzyme (GSHPx) that is a functional measure of selenium status in animals. It has been suggested that the amount of Se that is required to maintain maximal GSHPx activity may be used as the criteria for human nutrition requirement of selenium. Se bioavailability also depends not only on the form, but also on the source and Se status in the human body (plasma Se, whole blood Se or GSHPx activity). In addition, it depends on other dietary factors of human food e.g. lipids and metals that can inhibit the bioavailability by forming complexes with Se (*Navarro-Alarcon & Cabrera-Vique, 2008; Finley, 2006*).

A study assessed the impact of Se fertilization on leek with sodium selenite and sodium selenate along with the bioaccessibility[2] of Se. Approximately 60 % of the Se was absorbed in the stomach and 80 % in the intestine (*Lavu et al., 2012*). Other research has also shown that 70 % to 95 % of the Se is absorbed, depending on Se status of subject (*Finley, 2006; Melse-Boonstra et al., 2007*). A study in China by *Wang et al. (2013)*, found that foliar application of selenite improved seedling growth and grain yield. In vitro digestion assays suggested that organic Se compounds, including SeMet (54 % of total Se) and SeCys (21 % of total Se) were readily absorbed in the gastrointestinal tract.

Interactions between elements that affect bioavailability

A major concern in bioavailability of minerals from soil or foliar enriched fertilizers is the interactions among these minerals. *House et al. (1989)* found that absorption of Se is decreased with increased intake of Zn. Se deficiency may be induced with high dietary intake of Zn in chicken (*House & Welch, 1989*). Others have shown an inverse interaction between Zn and Fe: interactions were positive at low concentrations and negative at high concentrations of both of these nutrients (*Prasad et al., 2014*). Nutrient interactions between Fe and Zn may be another reason, in addition to the effects of phytates and polyphenols, that actual concentration of micronutrients in the grain do not always closely reflect their bioavailability (*Yang et al., 2007*).

Impact on nutritional and health status

There are few studies on the effect of agronomic biofortification on human nutrition (*White and Broadly, 2009*). Some cases have clearly shown evidence for a positive effect of micronutrient fertilization on improving human health status. Research from Finland showed the evidence of increased Se content via agronomic fortification of Se and stated that supplementation of fertilizers with Se is a safe and effective means to increase the Se intake of animals and humans (*Alfthan et al., 2015; Varo et al., 1998; Aro et al. 1988*). *Chilimba et al. (2012)* calculated that application of 5 g Se per ha would increase dietary Se intake by 26-37 µg per person per day considering the current maize consumption patterns in Malawi. A study from India also highlighted the possibility of reducing disease burden with a focus on agronomic fortification of cereals with Zn (*Cakmak, 2009*).

Joy et al (2015) reviewed the cost-effectiveness of Zn fertilizers in reducing disease burden due to dietary Zn deficiency with focus on an agronomic bio-fortification approach to address Zn deficiency in sub-Saharan Africa. The study focused on countries receiving national subsidies for granular Zn fertilizers i.e. Burkina Faso, Ethiopia, Ghana, Kenya, Malawi, Nigeria, Senegal, Tanzania and Zambia. The results showed that DALY's lost due to Zn deficiency were reduced by <1 % in Burkina Faso and 10 % in Malawi with a 3 % increase in the mean amount of absorbable Zn in the diet. Similarly, while looking at the impact of both subsidized and non-subsidized Zn-enriched fertilizer the DALY's lost was reduced from 3 % in Mali to 15 % in Malawi.

Another analysis on the foliar application of Zn-enriched fertilizer showed a 13-19 % reduction in DALY's lost due to Zn deficiency in Ethiopia (*Joy et al., 2015*). A study in Bangladesh on rice production with Zn-enriched fertilizer showed that Zn concentration increased in rice grain .The paper also estimated that almost 66 % of dietary Zn in children came from rice intake and claimed that increasing Zn content of soil by 0.8 ppm could increase Zn in unpolished rice by 11 % via Zn fertilizers and increase intake in children (*Mayer et al., 2011*). *Navarro-Alarcon and Cabrera-Vique (2008)* suggested this would also work with Se, which is volatile and soluble. Few studies have been conducted on this issue. The loss and retention of micronutrients has to be considered in the food chain approach along with bioavailability to determine impacts on human health.

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[2] "Bioaccessibility has been defined as the fraction of a compound that is released from its matrix in the gastrointestinal tract and thus becomes available for intestinal absorption (ie, enters the blood stream)" *(Fernández-García et al., 2009)*

4 Impact of agronomic biofortification on environment

Agronomic biofortification can have a positive impact on the sustainability of agriculture. Micronutrients are not susceptible to leaching or loss as gases from the soil, because they are strongly bound in the soil. The downside is that elements accumulate over time and cause toxicity if large amounts are applied repeatedly – most micronutrients are also classed as heavy metals. To optimize nutrient use efficiency and minimize risks for toxicity, fertilization practices should include precise application strategies. The so-called 4R strategy (a term widely used in the fertilizer industry) aims to optimize precise application by fertilization of the “Right source and Right amount at the Right place and Right time”. Techniques that can be used for this are micro-dose application and seed coating with the accurate blend of locally needed nutrients. When micronutrient demand and supply are synchronized, there should be no serious negative environmental effects within the agricultural ecosystem. In fact, crop health improves when micronutrient deficiencies in the crop are alleviated. The addition of micronutrients has shown to increase root development and with that NPK uptake efficiency and water use efficiency. The improved general crop health also increases resilience against pests and diseases, what may reduce the need for pesticides and herbicides. However, mineral elements are mined for the production of micronutrient fertilizer, that causes depletion of natural resources and environmental pollution. Not only the mining but also the fertilizer production process and global transportation system rely on high energy inputs and are responsible for significant amounts of greenhouse gases. Global availability of micronutrients could become a problem in the future, as most natural resources have less than 50 years left to meet the demands of agricultural production. *Dimpka and Bindraban (2015)* calculated that there is Fe left for 82 years, but only enough Zn for 21 years (*Table 2*). These natural limits emphasize the importance of nutrient recycling and the necessity to minimize overuse.

Table 2. Global resources of micronutrients for mineral fertilizers
(based on data from Dimpka and Bindraban, 2015).

Element	Global reserves (2014; in metric tons)	Global annual production (average over 1998-2012; in metric tons)	Availability (years)
Boron	210,000	4,502	47
Chlorine	No data	No data	No data*
Copper	690,000	15,133	46
Iron	$170{,}000*10^9$	$2{,}069*10^9$	82
Manganese	570,000	11,580	49
Molybdenum	11,000,000	201,833	54
Nickel	74,000,000	1,665,000	44
Zinc	230,000	10,815	21

**Highly abundant in nature*

5 Comparison between different intervention approaches for improving micronutrient status in humans

Different pathways to alleviate micronutrient deficiencies among human

Nutrition interventions differ in terms of cost, time and impact. Besides bio-fortification, nutrition interventions: dietary diversification, supplementation and food fortification are implemented to improve the micronutrient status among humans (*HarvestPlus, 2010*). Micronutrient supplementation is carried out by adding a micronutrient supplement (in the form of a capsule, tablet, etc.) to the diet to solve insufficient intake of that micronutrient directly. Dietary diversification is the increased consumption of micronutrient rich foods from different food groups, i.e. fruits, green leafy vegetables and meat that may be available but under-utilized by the deficient population. Food fortification represents adding a micronutrient to specific food items during processing in order to increase the micronutrient concentration of these food items (*Ma et al., 2008*). Agronomic biofortification, as explained already, is a strategy to increase the micronutrient content of the edible part of food crops. It is often considered as a short-term solution to increase micronutrient availability and mainly to complement another approach i.e genetic biofortification (breeding) which is generally seen as a more sustainable approach (*Garcia-Banuelos et al., 2014; Velu et al., 2014*). *Cakmak (2010)* argues that breeding is the only agricultural intervention to improve nutritional contents of staple crops in low-income countries, because fertilizers are not accessible or affordable for resource poor farmers. HarvestPlus, the biofortification program of CGIAR, states that dietary diversification is the most sustainable solution, but is often unaffordable for the resource poor, who are at greatest risk of deficiencies. *Bouis and Welch (2010)* argue that agronomic biofortification is the best approach to reach rural populations, which comprise a majority of the undernourished, because supplementation and diet diversification programs work best in centralized urban areas.

Comparison of effectiveness of different approaches

A backdrop of supplementation and food fortification is also that medical backup and central processing, respectively are continuously required *(HarvestPlus, 2010)*. *Slingerland et al. (2006)* reported that in West Africa these other approaches have only moderate chances of success due to the lack of an enabling environment. For example, dietary diversification aims to improve the main daily diet. On the other hand, these countries' diet is dominated by staple cereals or tuber/root crops for energy supply and pulses for protein which makes the minerals less bioavailable. At the same time, food items rich in bioavailable iron or vitamin C rich vegetables are expensive and show seasonal fluctuation in availability. Likewise, iron and vitamin A supplementation in tablets was successful only in countries with well organized health systems (*Stein, 1998*), continuous funding and proper adherence and compliance. In addition, research has shown that overdosing of Fe through supplementation increases the risk of malaria and other infectious diseases (*Clemens, 2014; Nubé & Voortman, 2011*). Regarding the supplementation of Zn, there is strong evidence that it improves the health status of children suffering from diarrhoea, but information on cost-effectiveness is inconclusive as large scale supplementation intervention like in Nepal showed no positive impact of Zn supplementation. Therefore, countries with poor health infrastructure and low purchasing capacity for processed foods, supplementation was not considered as the best approach (*Slingerland et al., 2006*). Likewise, fortification of foods with Zn in developing countries also lacks experience on methodology and approach. Whilst, dietary diversification for improvement of Zn intake could be a long term solution the possibility of interaction with Fe and protein, decreasing the bioavailability is a major problem (*Shrimpton & Darnton-Hill, 2002*).

Agronomic biofortification of Zn has been proven to improve the rice and wheat grain concentration of Zn, but it requires sophisticated infrastructure and comes with high costs (*Shahzad et al., 2014; Clemens, 2014*). There is little evidence of an association between the soil/crop concentration of Zn and human Zn deficiencies (*Nube & Voortman, 2011*).

Supplementation of high-Se wheat bread has shown evidence of positive impact on the health of individuals in New Zealand and Finland (*Thomson et al., 1985*). In China, the main strategy to cope with Se deficiency is Se fortification of table salt with Se. After the successful intervention of agronomic biofortification of Se in Finland, use of Se-enriched fertilizer is increasingly recommended for other countries. Unlike other micronutrients, for Se there is sufficient evidence of the positive impact of agronomic biofortification on health of the population. Therefore, it could be a feasible approach in addressing human Se-deficiencies (*Nube & Voortman, 2011*).

White and Broadley (2009) and *Yang et al. (2007)* concluded that biofortification based on either breeding or the application of mineral fertilization has a huge potential to improve the micronutrient status of the rural population. Yet they did not quantify the differential effects compared with other interventions (*White & Broadley, 2009*). Agronomic biofortification needs less behavioral change compared with other nutrition interventions and has a greater spatial reach (*Groote et al., 2016*). However, these papers also highlighted barriers for biofortification with mineral fertilization. The existing spatial variations in soil micronutrients that quickly get fixed in plants in unavailable forms, inefficient transportation of the micronutrients to the edible parts of plants and variation in terms of micronutrient absorption from soil in crops depending on the climatic, geographical condition are some of the issues mentioned (*Yang et al., 2007; Rengel et al., 1999*).

Financial comparison different approaches

There are great variations around the world not only in the biological aspects of agronomic biofortification but also in the economic variations. This affects the cost-effectiveness of various agronomic approaches in different geo-chemical and socio-economic settings. Therefore, pre-assessment of cost-effectiveness of micronutrient interventions in a specific country or region is necessary. *Ma et al. (2007)* estimated the cost and cost-effectiveness of different intervention strategies to cope with iron and zinc deficiency in China. For iron deficiency, the cost per capita per year for dietary diversification was highest ($1148) and genetic biofortification ($0.01) was lowest. The cost-effectiveness per DALY for supplementation was highest ($179) and lowest for food fortification ($66). Unfortunately, cost-effectiveness per DALY of agronomic biofortification was not determined. Similar for zinc intervention, dietary diversification showed the highest costs per capita per year ($1148) and genetic biofortification showed the lowest costs ($0.01), whereas cost-effectiveness per DALY was largest for supplementation ($399) and least for dietary diversification ($103). Another study by *Edejer et al. (2005)* on cost effectiveness of different nutrition interventions in South Asia and sub-Saharan Africa showed that food supplementation was the most costly and food fortification the least costly. Regarding the cost effectiveness of agronomic fortification of Zn. *Joy et al (2015)* compared the study with World Bank benchmark[3] and concluded that the only cost effective scenarios are foliar application of Zn in Burkina Faso, Ethiopia, Kenya, Malawi, Nigeria, Senegal and Zambia (*Joy et al., 2015*).

From above mentioned studies it can be concluded that food fortification is the best approach in terms of cost-effectiveness, but many challenges remain to reach the resource poor. Also improvement of dietary diversity is difficult for this group, because micronutrient-rich foods tend to be unaffordable for poor people. *Ma et al. (2007)* concluded that supplementation and food fortification could be a short term approach to decrease micronutrient deficiencies while genetic biofortification might be the most feasible, cost-effective and sustainable solution for rural population in the long term.

Photo credit: Adam Cohn on Flickr "Crane Hauling Fertilizer"

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[3] The World Bank. 1993 and WHO benchmarks for interpreting the cost per DALYs :A public health intervention with a cost per DALY of less than US$260 is "very cost-effective" (*Lividini & Fiedler*, *2015)*.

6 Potential and constraints of using agronomic biofortification in sub-Saharan Africa

Mineral micronutrient fertilizer use is currently limited in African countries due to general issues of cost and supply, the lack of information on micronutrient problems, a reliable fertilizer recommendation system, and the availability of micronutrient fertilizers. The lack of proper transport systems causes high prices, while investments are not always profitable when market accessibility to reach rural farmers or storage capacity are limited (*Sanchez and Swaminathan, 2005*). Especially in these regions with limited access to micronutrient-containing fertilizers, integrated soil fertility management practices are the most realistic approach to alleviate micronutrient deficiencies (*Cakmak and Hoffland, 2012*). There are many low-cost, locally available and environmentally sustainable technologies that smallholder farmers can use to create fertile soil conditions using an integrated approach (*Kerr et al., 2012*). An example is micro-dosing: a strategy of fertilizer application in small quantities and close to the seed or plant. The precise targeting for the roots minimizes nutrient losses as well as fertilizer costs (*Thilakarathna and Raizada, 2015*).

Nutrient management can be a challenge for farmers (especially small holders) when they face obstacles like limited availability of organic and mineral resources, high investment costs, extra labour requirements and environmental stress from drought, extreme rainfall, pests and crop diseases (*Giller, 2002*). To overcome challenges concerning logistics to successfully implement agronomic biofortification, a whole supply chain approach is required (*Slingerland, 2007*). Development of the bio-physical, economic, social and political environment is necessary to facilitate proper technologies, allocation of resources and food processing systems. In this regard, *Kempen et al. (2015)* engaged in initial analyses of spatial patterns of limiting soil micronutrients along with crop responses to micronutrient-containing fertilizers, to identify where and what combination of nutrients need to be applied to obtain a certain yield. This information can guide agri-business and policymakers to target their interventions. A key issue is the commercialization of smallholder agriculture to create markets for the extra production, because otherwise investments in (extra) mineral fertilizer are not economically feasible (*Giller, 2002*). Furthermore, knowledge and tools should be accessible and affordable for farmers in rural African regions. Soil kits have been developed, so farmers can simply test the chemical composition of their soils, but these tests are not accurate for micronutrients and inefficient on a larger scale. The development of a sensitive and accurate soil test for micronutrients is a key issue to gain insight into the local soil status and micronutrient requirements, but extensive research has failed to identify such tests.

For widescale implementation, the scientific world generally has more trust in models that can supply nutrient management recommendations on the basis of soil, climate and land-use characteristics. These models should generate insight in soil micronutrient availability on a regional scale, so policy makers and stakeholders along the fertilizers supply chain can implement targeted interventions to make necessary resources available and provide realistic fertilizer recommendations for farmers. Along with recommendations for mineral fertilizers, ISFM recommendations could be provided to ensure highest effectiveness and nutrient use efficiency. The African Soil Health Consortium (ASHC) works towards this goal (http://africasoilhealth.cabi.org). Next, guidance should be provided to include new fertilizer products and management practices into local socio-cultural environments in order to enhance adoption (*Slingerland et al., 2006*). The *Global Panel (2015)* suggests using the public sector (like institutional feeding programme) and active social marketing to promote biofortification practices among targeted population groups. Further education programs should focus on food processing and consumption that stimulates micronutrient bioavailability for the human body.

Further research

In a workshop early April 2016, various Dutch stakeholders and a few international guests will discuss the findings summarised in this paper and will be invited to share their ideas and recommendations for further research. The current paper already highlights a few areas where further research may be necessary.

For actual impact on the alleviation of micronutrient deficiencies in soils and crops, it is important to connect scientific knowledge to practical experiences in various countries and continents in applying ISFM and fertilizer management. It would be beneficial to have more studies that cover the full pathway(s) of micronutrient bioavailability from the moment of agronomic interventions towards the human nutritional status, in order to evaluate the actual effectiveness of agronomic biofortification to alleviate micronutrient deficiencies among human populations. For this it is important to use staple crops that are widely consumed in sub-Saharan Africa. In addition, when studying this pathway(s), it would be worth exploring the relative effectiveness of agronomic biofortification as compared to other micronutrient management interventions along the chain. A scientifically challenging topic would be to further explore molecular mechanisms that control micronutrient (re-) localization and accumulation in the edible parts of crops (*Cakmak et al., 2010*).

At the same time, further value chain dynamics and economic aspects of these pathways merit further research. The current paper identified several sources that suggest agronomic biofortification may not be economically feasible option for resource poor farmers. To better understand the pathway(s) mentioned above, socio-economic, political, as well as logistical constraints and opportunities should receive equal attention, in order to develop micronutrient management strategies that are truly effective and sustainable. Developing business cases that work for actors across the value chain (farmers, traders, international companies) is an important route to explore.

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