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The Links between Fertilizer and Nutrition in South Asia and Africa

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The following literature review explores the links between the use of macro- and micronutrient fertilizers and human nutrition. The review focuses on the academic literature covering the effects of fertilizers on plant and human nutrition in areas with nutrient deficient soils, with a particular emphasis on South Asia and Sub-Saharan Africa. Additionally, the review identifies a few of the primary institutions involved in fertilizer research.

This literature review is carried out in light of the history of the Green Revolution, a worldwide transformation of agriculture that began in Mexico in the 1940s emphasizing improved plant varieties (especially for staple crops), as well as agricultural research, extension, and infrastructure development. Scholars generally recognize three primary problems stemmimg from the Green Revolution with regard to human nutrition:

- the dramatic shift to high yielding cereals over pulses (which in turn led to lower consumption of nutrient-rich pulses in certain areas), and
- within plant breeding efforts, the prioritization of increasing crop yields over maintaining or increasing nutritional value of crops; and
- the heavy use of nitrogen (N) fertilizer

The shift to high yielding cereals over pulses during the Green Revolution was dramatic and this trend continues. In South Asia, for example, the past 30 years have seen a 200% increase in rice production and 400% increase in wheat production. This has been paralleled by decreased per capita production of traditional, micronutrient-rich crops (i.e. legumes, pulses) and a shift in dietary preferences. Diet changes have coincided with time trends in the increase of iron deficiency, most dramatically in South Asia (Welch, 2002).

Plant breeding during the Green Revolution and beyond may also have contributed to human nutrition problems. These breeding efforts have primarily focused on increasing crop yield and disease resistance, and have produced modern varieties of wheat and rice that have lower concentrations of iron and zinc than traditional varieties (Frossard et al., 2000).

Finally, the heavy use of nitrogen fertilizers may have contributed to declining nutritive value of crops. The use of nitrogen fertilizer has in many cases eliminated the need for crop rotations, and the subsequent shift to mono cropping, along with the stimulation of nitrogen uptake, has led to soil nutrient depletion. The excessive use of nitrogen fertilizer is also partially responsible for decreasing the concentration of vitamin C, soluble sugar, soluble solids, magnesium and calcium in some leafy vegetables (Wang, Li, & Malhi, 2008). Decreasing concentrations of some micronutrients through Green Revolution cropping systems and a parallel shift away from micronutrient rich crops have in turn contributed to human micronutrient deficiencies, also referred to as "hidden hunger," which is a significant nutrition issue in Sub-Saharan Africa and South Asia (Welch, 2002).

One question raised in response to hidden hunger is whether improved fertilizers, and better fertilizer use, could enhance human nutrition. This paper reviews the current literature linking fertilizer and human nutrition in several sections. The first section focuses on literature concerning the plant macronutrients, nitrogen (N), phosphorous (P), and potassium (K) and the research connections made to human nutrition. The second section focuses on micronutrient fertilizers with specific subsections on nutrition and fertilizer literature for zinc (Zn), iron (Fe) and other micronutrient deficiencies. The third section highlights current fertilizer compositions used to address these nutrient deficiencies, specifically focusing on micronutrient and fortified macronutrient fertilizers. The fourth section reviews cautionary literature that might apply to fertilizer-based interventions, including fertilizer application rates, cautions about using fortified macronutrient fertilizers in Sub-Saharan Africa, and the comparative costs and benefits of this strategy versus other possible interventions. The fifth section profiles a current example of multi-nutrient fertilizers used in East Africa and provides information about institutions conducting fertilizer research. Finally, the last section explains the methodology for the review and contains the bibliography.

There are many intervening steps between fertilizer use and human nutrition, each involving relatively complex biological processes that are influenced by many determinants. For fertilizer to impact human health, nutrients need to be available to plants in forms that can be taken up. They also need to be stored by the plant in the tissues that become human food, preserved throughout harvest, storage and cooking, consumed by humans in sufficient quantities to have a health impact, and be provided in a manner that is absorbed and used by the human body. As one example of the complexity involved, interactions between macronutrients and micronutrients can have a significant effect on the bioavailability of micronutrients, and yet this is still one of the least understood aspects of plant nutrition. The methods of applying micronutrient fertilizers are also still somewhat experimental and more research is needed to better understand how micronutrients react with macronutrient fertilizers and how to improve their longevity in the soil and plant availability. This review summarizes some of the conclusions that have been reported thus far; however, this is a research area that requires more study (Alloway, 2008).

1. Macronutrient Fertilizers: Nitrogen, Phosphorous, and Potassium

The three plant macronutrients nitrogen (N), phosphorous (P), and potassium (K) are essential to plant health. In modern, high-production agricultural systems nutrients are generally removed from the soil system when crops are harvested and over time, nutrient levels become depleted unless they are intentionally added. Macronutrient fertilizers are therefore a critical component of the worldwide agricultural industry today. Research indicates that use of macronutrient fertilizers increases crop yields as well as nutritional quality of the major staple cereal crops (Graham et al., 2005).

Historically, the introduction and increased use of macronutrient fertilizers was an instrumental part of the Green Revolution gains in productivity. However, productivity gains were not realized at the same level in Africa as in much of South Asia or the rest of world (Kelly, Jayne, & Crawford, 2005; Graham et al., 2005). African soils are naturally poor in nutrients that can be absorbed by crops, and even in cases when fertilizer is used, it may be less effective because variability of rainfall makes the uptake of nutrients less efficient. These problems are coupled with issues of lower farmer fertilizer demand and improper usage, issues that are outside the scope of this paper, but which are often cited and associated with high fertilizer cost and a lack of extension programs (Kelly, Jayne, & Crawford, 2005).

A review of the major staple crops finds a well-developed linkage between the use of NPK fertilizers and the nutritional value of harvested foods. Combined NPK fertilizers are mixed in varying ratios. The optimal nutrient ratio differs depending on whether the aim is to optimize plant nutrition or human nutritional value, and depending on the soil deficiencies, as well as the demands of the crop being grown. In most regions in the world, nitrogen fertilizers are used in optimum or excessive amounts for plant nutrition, while potassium and phosphate fertilizers are not always applied in sufficient amounts. This has an effect on nutrient uptake, as well as the size and quality of crop yield (Aulakh & Malhi, 2005).

It is also important to recognize that there are other characteristics of the soil that govern the chemical form of minerals, and thus their availability to plants. These include soil pH, redox conditions, cation exchange capacity, the activity of microorganisms, soil structure, and water content. Among these, pH is generally recognized to be the most significant, because it affects both the solubility of soil minerals present and the ability of plant roots to absorb nutrients. The response of each plant nutrient to pH is unique, but all nutrients are generally available in the pH range of 5.5 to 6.5. When minerals exist in highly soluble forms (such as in acidic soils, with low pH values), the nutrients may be subject to leaching, which occurs when dissolved ions, especially nitrate, is washed out of the agricultural system with drainage water (Taiz & Zeiger, 2006).

Agricultural soils, meanwhile, generally vary from pH 4.0 to 9.0, though adjusting the pH of soils is possible. Lime can be used to make soils more alkaline, with treatments lasting up to several years. Acidifying soil is also possible but may require frequent treatments, which can be cost-prohibitive.

In both acid and alkaline cases, adding organic matter can help to buffer the soil pH and improve nutrient retention.

However, given that pH and other soil conditions are favorable, applying fertilizers in the correct ratio can improve nutritional quality of the crops. For example, adequate nitrogen supply is vital for plants to synthesize protein because nitrogen is an essential component of amino acids, the building blocks for proteins. Sufficient supply of nitrogen, naturally occurring or supplied through fertilizer, is associated with increased concentration of protein and with improved nutritional and commercial quality of wheat (Wang, Li, & Malhi, 2008).

The timing of fertilizer applications has also been shown to be important for the nutritional quality of wheat; increased nitrogen early in the growing season stimulates vegetative growth and increases crop yield, which can actually dilute protein concentration. Application of nitrogen at late growth stages, on the other hand, tends to have less influence on yields and more influence on grain protein concentrations (Wang, Li, & Malhi, 2008). In particular, nitrogen additions at anthesis (when flowers are open and functional) have been shown to have a strong influence on protein concentrations (Ottmana, Doergeb, & Martin, 2000, and Wuest & Cassman 1992, as cited in Wang, Li, & Malhi, 2008).

Alternately, phosphorus fertilizer has not been shown to influence protein concentration in wheat and actually has proven in some instances to depress protein concentration when used without nitrogen fertilizer. A study in India found that the use of phosphorus fertilizer increased the crop yield of grain but decreased protein concentration as a result of the dilution effect (Buerkert, Haake, Ruckwied, & Marschner, 1997). The dilution effect occurs when application of a macronutrient fertilizer (such as phosphorus or nitrogen) causes a crop to grow more vigorously and thus reduces the percentages of protein or nutrients within plant tissue despite increased total absorption of each element.

Finally, potassium is closely related to nitrogen assimilation by plants. Nevertheless, potassium fertilizer showed no effects on protein concentration of winter wheat in field conditions in Canada and Italy despite having a positive impact on grain proteins in the growth chamber (Campbell et al., 1996, and Barraclough & Haynes, 1996, as cited in Wang, Li, & Malhi, 2008).

In other staple crops besides wheat, protein content can also be improved through correct fertilizer use. Maize is generally considered one of best sources of human energy because of its high starch content, but its low level of protein can be problematic. Nitrogen fertilizer was shown to increase the concentration of protein in maize (Tsai, 1992). The level of nitrogen fertilizer needed to enhance protein concentration is higher than the amount needed for maximum yield. Therefore, there is often no incentive for farmers, particularly very poor farmers, to use the necessary amounts of nitrogen on maize to optimize protein levels. Application of phosphorus fertilizers also improves yields of maize, but does not improve protein concentrations and can sometimes lower them through the dilution effect (Wang, Li, & Malhi, 2008).

Legumes are considered a high protein crop, and their amino acid profiles complement the profiles of grain in terms of human nutrition. Legumes have less need for nitrogen fertilizer because of their ability to fix atmospheric nitrogen. However, nitrogen fertilization early in the plant's life ("starter" nitrogen) has been shown to increase yields, and nitrogen has also had a positive impact on yields in cases where biological nitrogen fixation is low (Saimbhi & Grewal, 1986, as cited in Aulakh & Malhi, 2005). Studies have also shown that nitrogen stresses can cause lowered seed yields and protein concentrations (Wang, Li, & Malhi, 2008).

The application of macronutrient fertilizers can also impact the concentrations of other minerals and vitamins in plant tissues. In leafy vegetables, it was found that the over-application of nitrogen had a negative effect on vitamin C, soluble sugar, magnesium and calcium, while NPK application had a positive effect on zinc for some vegetables such as cucumber (Wang, Li, & Malhi, 2008).

2. Micronutrient Fertilizers

While significant attention has historically been paid to macronutrient fertilizers, this has been somewhat less true of micronutrient fertilizers, especially in cases where soil deficiencies are not so severe as to impact plant health. This section covers two micronutrients that are particularly important for human health, zinc and iron. It also covers other micronutrients and the potential link between fertilization and human nutrition.

Zinc

Zinc (Zn) deficiency is described as the ultimate "hidden hunger" in human populations because it is so widespread (Graham et al., 2005). It is estimated that 2.6 – 3 billion people today have some level of zinc deficiency with heavy concentrations in South Asia, Southeast Asia, and Africa. Zinc deficiency is characterized by a loss in muscle mass, which occurs as the body attempts to release zinc from muscles to fortify the blood and vital organs. Additional effects include slowed physical growth and impaired immuno-competence, reproductive function, and neuro-behavioral development (Hotz & Brown, 2004).

In the developed world, humans normally meet most of their needs for zinc through eating animal products. In the developing world, most people get zinc from cereals and legumes, because their diet contains little meat. However, these plant foods are normally high in phytic acid, which is a potent inhibitor of zinc absorption in people (Frossard et al., 2000).

Zinc deficiency can affect both the yield and the nutritional quality of the major staple crops, including wheat, rice, and sorghum (Alloway, 2004). In some cases, yields can be reduced as much as 40%. Zinc is vitally important to plant health as it is involved in a wide variety of plant biochemical pathways. A major reason for zinc deficiency is the heavy use of phosphorus fertilizer, a practice that is cited as a product of the Green Revolution (Graham et al., 2005). A recent study of phosphorus fertilizer application in India found that the use of phosphorus fertilizer increased grain yields but decreased zinc in the food by 6% to 11% as a result of the dilution effect (Buerkert, Haake, Ruckwied, & Marschner, 1997).

Zinc deficiency affects a variety of soils and is a particular problem in South Asia, especially India. African soils have also been found to be zinc deficient, particularly in West Africa (Alloway, 2004). In addition, even if zinc is present in soils, it may not necessarily be present in a form that makes it available to plants. Among the many soil properties that govern the chemical form of minerals and thus their availability to plants (including soil pH, redox conditions, cation exchange capacity, the activity of microorganisms, soil structure, and water content), pH is highly important for zinc, as for many other nutrients. In the pH range from 5.5 to 7.0, an increase of one pH unit causes a 30- to 45-fold decrease in aqueous Zn^{2+} concentration, the form readily available to plants (Frossard et al., 2000).

In cases where zinc is deficient in soils, the application of zinc fertilizers (generally a zinc compound fertilizer) can be very effective in addressing the deficiency and a single application can last for several years (Graham, et al., 2005). For basic reference, table 1a refers to the relative sensitivity of each crop as compared to their response to zinc fertilizer application (adapted from Alloway, 2004). Common zinc fertilizers and application methods will be covered more thoroughly in the fertilizer composition section (Section 3). However, it is important to note that increasing the concentration of zinc in plant tissue does not necessarily increase the amount of zinc bioavailable to humans, particularly if phytate-to-zinc ratios are not significantly altered (Welch, 1993, as cited in Frossard et al., 2000).

Table 1a. Relative response of zinc-deficient crops to zinc fertilizers, indicated by increased plant issue concentration (adapted from Alloway, 2004)

Crop	*Response*
Canola	Medium
Corn	High
Oats	Low
Potato	Medium
Rice	High
Sorghum	High
Wheat	Low

Iron

Nearly a third of the world's population is affected by anemia, generally caused by iron deficiency. Severe anemia is particularly common among pregnant women and young children in South Asia and Sub-Saharan Africa, primarily due to their increased need for iron. A woman who is anemic during pregnancy is at greater risk of death during the prenatal period, and the mother's anemia adversely affects the child's development, health and hematological status (Viteri, 1994). Human iron deficiency can be caused by consumption of foods grown in iron-deficient soils, consumption of food crops that naturally have low levels of iron, and deficiencies of other vitamins and minerals, including zinc, vitamin A, beta-carotene, iodine, selenium, folate, and B-12 (Graham et al., 2005).

People who consume iron may still experience anemia if the iron is not absorbed by the body. While iron in the heme form (present in animal products) is well absorbed in almost all cases, the absorption of non-heme iron (present in both animal and plant products) is strongly influenced by other dietary components that bind iron in the intestinal lumen. Phytic acid (from cereal grains and legumes) and polyphenol compounds (from tea, coffee, and other beverages) both inhibit absorption of iron, while ascorbic acid (from fruits and vegetables and animal muscle tissues) enhances iron absorption (Frossard et al., 2000). Iron deficiency in humans can also have other causes besides micronutrient deficient soils and food, including parasites or pathogens (Graham et al., 2005). In these cases, increasing dietary intake of iron may not do much to address the problem.

Iron deficiency can affect plants as well as people, and iron is critical for successful photosynthesis, as well as other plant functions. However, as with zinc, some chemical forms that iron takes in soil are available to plants, while others are not, and soil pH has a particularly strong influence. Within the pH range from 5.5 to 7.0, an increase of one pH unit causes a 100-fold decrease in aqueous Fe^{2+} concentration, and a 1000-fold decrease in aqueous Fe^{3+}concentration. Well-aerated soils tend to have much lower concentrations of free Fe^{2+} and Fe^{3+}, and plant uptake of iron is also influenced by root architecture and plant uptake mechanisms (Frossard et al., 2000).

Addressing iron deficiencies in soils through fertilizers is more complicated than for other nutrient deficiencies. Direct spraying of liquid iron fertilizers on soil, the most common technique used, is generally ineffective because the iron is quickly oxidized and made insoluble. The most effective current technique is a foliar application method with fortified macronutrient fertilizers. These treatments are widely used in developed countries and their use is increasing in developing countries. For basic reference, table 1b refers to crop response to iron fertilizer application (adapted from Alloway, 2004). These iron fertilizers, along with iron fortified NPK fertilizers, are covered in the fertilizer composition section (Section 3). As with zinc, increasing the concentration of iron in plant tissue may not be sufficient to address human nutrition issues, as the amount of iron bioavailable to humans is also affected by the presence of inhibitory and enhancing compounds, as well as food storage, processing, and preparation methods (Slingerland, Traore, Kayode, & Mitchikpe, 2005).

Table 1b. Relative response of iron deficicient crops to iron fertilizers, indicated by increased plant tissue concentration (adapted from Alloway, 2004)

Crop	*Response*
Canola	-
Corn	Medium
Oats	Medium
Potato	-
Rice	-
Sorghum	High
Wheat	Low

Other Micronutrients

Several other plant micronutrients have an impact on human health and can be deficient in soils. They include manganese (Mn), boron (B), copper (Cu), iodine (I), sulfur (Su), and calcium (Ca). People who have deficiencies of these nutrients can have reproductive issues, stunting, and significant developmental disabilities (Rosado, 1999). Micronutrient deficiencies, especially iron and zinc, are the highest in South Asia, primarily due to a lack of micronutrient-rich foods and a high infection rate. While iron and zinc are the most well known catalysts of hidden hunger, a variety of insufficient micronutrients are responsible for serious health concerns, especially in developing countries (Graham et al., 2005).

Recognition of the importance of addressing all micronutrients has increased over the years for a few primary reasons. High cropping yields have increased the dilution effect and there are now insufficient soil supplies of many micronutrients to meet plant nutrition demands (Roy, Finck, Blain, & Tandon, 2006). In addition to the human nutrients mentioned above, molybdenum (Mo) is necessary to plant health and is sometimes deficient in soils.

As with other nutrients, other soil properties are important. Soil pH is the most important, and for all micronutrients except molybdenum, higher soil pH leads to lower availability. For molybdenum, higher soil pH increases availability. Other soil properties that influence availability to plants include organic soil matter content (especially important for copper), redox conditions (especially for manganese), soil texture, and soil moisture (Shuman, 1998).

Currently, much of the nutrition research in progress for multi-nutrient fertilizers aims to understand the interactions between different nutrients and find the best nutrient combinations (see Fang et al., 2008; Jin et al., 2008; Aulakh & Malhi, 2005). Table 1c refers to crop response to the application of the other major micronutrients (adapted from Alloway, 2004). Some common techniques for including these micronutrients in fertilizers are described in the following section (Section 3).

Table 1c. Relative response of micronutrient-deficient crops to micronutrient fertilizers, indicated by increased plant tissue concentration (adapted from Alloway, 2004)

Crop	*Copper*	*Boron*	*Manganese*
Canola	High	High	Medium
Corn	Medium	Low	Medium
Oats	High	Low	High
Potato	Low	Low	High
Rice	High	Low	Low
Sorghum	Medium	Low	High
Wheat	High	Low	High

3. Fertilizer Composition

The type of fertilizer needed to correct deficient soils and enhance human nutrition depends on the type of soil deficiency and the needs of the crop being grown. Fertilizers can be effective in increasing crop yields and food nutritional content, but only when combined with adequate agronomic practices such as crop rotations and soil moisture management. Factors such as soil pH and the timing of nutrient release in relation to plant growth are also important for fertilizer to have the desired impact on plant growth and nutrient levels. This section covers some of the common fertilizers that are used to enhance nutrition, including multi-nutrient fertilizers, and specialized fertilizers used to address iron and zinc deficiencies.

Multi-Nutrient and Specialty Fertilizers

Multi-nutrient fertilizers, also sometimes referred to as fortified or complete fertilizers, are used as a tool for addressing soil deficiencies. Fortified fertilizers are NPK fertilizers, usually with one or two other trace micronutrient elements added in order to make the fertilizer more widely applicable in different deficient soils. Complete fertilizers are NPK fertilizers with many additional trace elements added. Complete fertilizers, which contain N, P, K, magnesium (Mg), and sulfur (S) as well as manganese (Mn), copper (Cu), and boron (B) can be used broadly for soils that are deficient in multiple nutrients, but they are prohibitively expensive for poor farmers. Some examples of fortified fertilizers include zincated urea, DAP (generally 11% nitrogen, 55 % P_2O_5) complex fortified with 0.5% zinc, and NPK complex fortified with 0.5% zinc or 0.3% boron (Roy, Finck, Blain, & Tandon, 2006). A 1999 study of NPK fertilizers fortified with calcium, iron, and zinc in India found that the fertilizers significantly improved the concentration of zinc, iron and magnesium in ambat, chukka, and spinach (Reddy & Bhatt, 2000). Nonetheless, the effect of multi-nutrient fertilizers is a subject continuously cited as needing additional study and evaluation to determine effectiveness in different soil conditions (Wang, Li, & Malhi, 2008).

The most common fertilizer combinations used to address iron deficiency are ferrous sulfate and ferrous ammonium sulfate, the latter a three-nutrient fertilizer with nitrogen, sulfur, and iron. Iron-fortified macronutrient fertilizers can be particularly effective in Africa and South Asia where iron deficiencies are the highest and soil requires heavy use of macronutrient and micronutrient fertilizer (Wang, Li, & Malhi, 2008). Foliar techniques for treating iron deficiency have proven to be the most effective, but are generally cited as being overly expensive and technical for sustained use in developing countries and have not been widely used. A 2006 study found that the foliar application of boron and iron complex increased iron (18.9%) concentration in seed and other nutritive values (such as zinc) in rice (Jin, Minyan, Lianghuan, Jiangguo & Chunhai, 2008). For highly acidic soils, iron chelates (organic substances that hold micronutrients in a form better absorbed by plants) are the most common iron-containing fertilizers used (Roy, Finck, Blain, & Tandon, 2006).

In the case of zinc, phosphatic fertilizers, referred to as diammonium phosphate (DAP) or monoammonium phosphate (MAP), have been used successfully. Nitro phosphorous fertilizers with zinc also have been found to be effective (Alloway, 2004). In dry and sandy areas, such as parts of Africa, conventional zinc sprays often fail to move through the soil to the deeper roots; however, this problem can be addressed by injecting liquid zinc fertilizer 40 cm underneath the topsoil (Alloway, 2004). Applications to the soil range from 4.5 to 34 kg zinc ha^{-1} in the form of zinc sulfate, normally broadcast or sprayed on the seedbed (Alloway, 2004). For increased crop concentration of zinc iron in rice, a study found that the primary variables influencing increased concentration were selenium and zinc. The study found the combination of 0.9kg ha^{-1} Zn, 0.015kg ha^{-1} Se, and 0.9 kg ha^{-1} in foliar fertilization was optimal for enhancing these nutrients in rice (Fang et al., 2008).

4. Cautionary Literature

While a combination of nutrients is important for correcting nutrient deficiencies, the method and rate of application can sometimes adversely affect the nutritional quality. Additionally, the benefit of utilizing fertilizer techniques versus traditional nutrition fortification and newer strategies such as plant breeding is something being discussed by social scientists. This section highlights literature on excessive use of certain kinds of fertilizer and an argument against using fortified macronutrient fertilizer in Sub-Saharan Africa. The section also discusses the cost and benefits of fertilizer use versus traditional fortification strategies and plant breeding, although rigorous comparisons of costs and benefits of a fertilizer strategy have not been found.

Fertilizer Application Rates

The optimal rate of fertilizer application can change depending on the soil conditions and crop. Applying fertilizer to optimize plant growth is fairly common, while applying fertilizer to optimize human health is less well understood. Toxicity levels must be monitored, particularly in the application of micronutrient fertilizers such as iron, zinc and calcium, which can become toxic to crops if applied excessively, beyond the amounts that are needed for plant nutrition (Frossard et al., 2000). In some cases applying micronutrients and macronutrients above the levels required for maximum yield provides nutritional benefits; in other cases no additional benefit is derived from excessive applications (i.e. the micronutrient concentration does not improve). For example, the nutritional quality of wheat is enhanced when zinc and selenium are applied at excessive rates. However, applying excessive amounts to address iron deficiency has little effect on the nutrient quality of staple seeds and grains (Wang, Li, & Malhi, 2008).

Applying large amounts of fertilizers can also have negative effects on the environment. Crop plants typically use less than half of the fertilizer applied (Loomis & Conner 1992, as cited in Taiz & Zeiger 2006), and the remaining minerals may leach into and contaminate surface water or groundwater, become attached to soil particles, or contribute to air pollution. These added nutrients can alter ecosystems and negatively impact drinking water quality (Taiz & Zeiger 2006). These problems can be exacerbated when fertilizers are applied in excess of amounts that can be readily taken up by plants.

The balance between the levels of different nutrients can also impact the nutritional quality of crops. One example is that excessive use of nitrogen fertilizer adversely affects the level of vitamin C in some vegetable crops such as lettuce and kale. However, increasing potassium fertilizer in these same crops generally raises vitamin C levels. This balance has also been found in citrus fruits such as oranges, lemons, and apples (Welch & Graham, 2002). In another example of the potential complexity of these types of interactions between nutrients, excessive application of phosphorous can lead to iron deficiency in plant tissue. It is suggested that this occurs for two reasons. First, the application of phosphorous seems to inhibit the growth of mycorrhizal fungi on the roots of plants. These fungi, which inhabit the roots of up to 80% of plants, normally enhance the plant uptake of both phosphorous and zinc (as well as other nutrients), in exchange for energy from the plant, but when phosphorous is readily available, the relationship may be interrupted. Second, higher growth rates increase the plant requirements for zinc (Frossard et al., 2000).

Finally, there is a literature that argues against the idea of using macro-fortified fertilizers entirely, specifically in Sub-Saharan Africa. The Centre for Food Studies at Ryerson University cautions that the combination of large amounts of macronutrient fertilizers and micronutrients might cause an antagonistic effect between the minerals and trace elements, which would inhibit uptake of macronutrients by plants. Additionally, they argue that the soils of this region is so depleted that these combinations might have little effect on micronutrient rehabilitation. The Centre therefore recommends the direct application of micronutrient fertilizers as the preferred method to correct deficiencies (Nube & Vortman, 2006).

Costs and Benefits of Fertilization Compared to Other Strategies

Fertilizers are considered a relatively new strategy for tackling human nutrition issues in developing countries. The most common strategies for addressing micronutrient malnutrition, and the most widely accepted, are supplementation with pharmaceuticals, food fortification, and dietary diversification (Frossard et al., 2000). These strategies have some drawbacks; for example, supplementation is a very expensive strategy, primarily due to the high cost of delivering the medication. Fortification may be relatively cost effective, but can be ineffective with populations who consume few processed foods. Diet diversification might be impossible in developing countries for economic and social reasons (such as some societies disliking milk or not being able to support livestock). However, the costs and benefits of fertilizer use have not been well studied, and it is unclear whether fertilizers offer a more suitable, or cost-effective, method for addressing human nutrition issues than other methods.

In addition, there are several other agricultural strategies that have the potential to increase the amounts of macro- and micronutrients in edible crops, including plant breeding and gene techniques. The relative benefits and drawbacks of these strategies, compared to fertilizers, are also not well understood. The CGIAR has launched a project to increase the density of iron and zinc in edible plant parts through breeding, based on the fact that modern varieties of wheat and rice have a lower concentration of iron and zinc than their traditional counterparts. CGIAR has realized some positive gains with the initiative (Potrykus, 2003, as cited in Slingerland et al., 2005). If iron and zinc in these varieties is well absorbed and utilized by humans, this could be a relatively inexpensive way of increasing the availability of these micronutrients (Frossard et al., 2000).

Some exploratory studies have shown promising results. For example, tests of 49 native Andean potato varieties showed significant genotypic variation in iron and zinc levels, and significantly different nutrient uptake responses to varying environments (Burgos et al., 2007). Breeding could also potentially be used to increase ascorbic acid content or decrease phytic content in crops to enhance iron uptake by humans (Frossard et al., 2000; Kayode et al., 2005). Additionally, the benefits could be significant because once the mineral rich crops are developed; there will be few extra costs in introducing them into current agricultural systems (White & Broadley, 2005). However, in at least some cases, the difference in micronutrient content between varieties may not be high enough to benefit the health of populations suffering from malnutrition. For example, in a feeding trial of Filipino women consuming either a high iron cultivar of rice or a local variety for 9 months, only a modest increase in total body iron, and no increase in hemoglobin was seen (Haas et al., 2005).

Genetic engineering could potentially be used in multiple ways, including manipulating genes that regulate iron and zinc uptake ability of plant roots, and lowering the amount of phytin in edible parts of plants (given that phytin inhibits the absorption of zinc and iron in humans) (Frossard et al., 2000; Zimmerman & Hurrell, 2007). However, as with plant breeding, these strategies rely on well-organized and developed seed systems to be able to reach poor rural populations (Ndjeunga, 1997, as cited in Slingerland, Traore, Kayode, & Mitchikpe, 2006).

It is also possible that fertilizers need to be used in combination with other strategies if they are to impact human health. Given the many constraints present in many parts of Sub-Saharan Africa (including low household purchasing power, lack of elementary logistics, lack of central food processing, and high heterogeneity in production and consumption conditions), a collaborative team involving researchers from Wageningen University in the Netherlands and institutes in Benin and Burkina Faso suggested that an approach focusing on the staple food chain may be more effective. Based on current economic, ecological, and social conditions, interventions were designed for villages in Benin and Burkina Faso to address iron deficiency, focusing on sorghum. Interventions included phosphorous fertilization and soil organic amendments (with organic amendments used to supply additional micronutrients to plants). By itself, this led to increased yields but also increased levels of phytic acid, inhibiting iron uptake. Project partners aim to offset this drawback by incorporating strategies aimed at other points in the food chain: breeding for high iron and moderate phytic acid contents and improving food processing methods to remove phytic acid (Slingerland et al., 2005). Such interdisciplinary approaches may have more chance of success, but they are unlikely to be easily scalable, so cost-effectiveness may be an issue.

5. Current Fertilizer Project Examples

The Farmers Inputs Promotions Africa (FIPS- Africa), a joint venture between the John D. Rockefeller Foundation, USAID, and the World Bank, is a comprehensive intervention that aims to provide an increased supply of proper agricultural inputs through private-public partnerships (such as fertilizer companies and governments), along with farmer education. A key component of this program was the development of a two-part multi-nutrient fertilizer called Mavuno. The first part contains a formulation of nitrogen, phosphorus, potassium, sulfur, calcium, magnesium, and traces of boron, zinc, and molybdenum. The second part is a top-dressing fertilizer supplemented with nitrogen. This fertilizer is sold primarily in Kenya through a local distributor at a cost of $.40 to $.50 per kilogram.

A similar multi-nutrient fertilizer is sold in Kenya called Chapa Simba. A thorough evaluation of this formulation has yet to be carried out, but initial results have shown positive increases in yields and increased farmer demand for the fertilizer (FIPS-Africa Toolkit, 2003).

In addition to these products produced specifically for the African context, there are various companies that produce multi-nutrient fertilizers in the United States, as well as in Europe, Africa, and South Asia. The companies have a wide variety of NPK and micronutrient products. No specific literature was found on companies that have been particularly effective or involved in agricultural interventions.

There are several research institutions currently involved in fertilizer research. These organizations are shown, along with a brief description, in the following chart:

Research Institution Chart

This chart has selected organizations based on the affiliations of several of the authors cited in this report. Additionally, an internet search was conducted for organizations that are involved in fertilizer research.

Organization	**Location, Primary Researchers**	**Brief Description**
National Fertilizer Development Centre (NFDC)	Headquartered and programs in Pakistan, *www.nfdc.gov.pk/*	NFDC is a multidisciplinary research and development organization at the federal level that integrates disciplines such as economic planning, pricing and subsidies, privatization and deregulation, production and imports, marketing and credit, agronomy and soil science, research, extension and training.
The International Plant Nutrition Institute (IPNI)	Headquartered in the US, programs in China, India, Southeast Asia, Northern Latin America, Brazil, Americas, *www.ipni.net*	The International Plant Nutrition Institute (IPNI) is a not-for-profit, science-based organization with a focus on agronomic education and research support.
International Center for Soil Fertility and Agricultural Development (IFDC)	Headquartered in the United States, programs in South Asia and Africa, *www.ifdc.org*	IFDC conducts projects covering agribusiness, engineering, technology development, management information systems, and plant nutrient management. Does not conduct significant research but is heavily involved in technology transfer in developing countries. Recent success in Africa with multi-nutrient fertilizers.
International Crops Research Institute for Semi Arid Crops (ICRISAT)	Headquartered in India, projects exclusively in Africa and South Asia, *www.icristat.org*	Institute based in India that does upstream scientific research on agricultural issues in developing countries. Their focus is a wide variety of biotech, plant breeding, watershed, and fertilizer studies.
The Fertilizer	Trade organization for the	Holds conferences and sponsors research on fertilizer issues. Several of the organizations on this list are

Institute	industry (US based), *www.tfi.org*	members of the institute.
Cornell University, Department of Crop and Soil Sciences	Several of the nutrient scientists, including RM Welch, conduct soil and nutrient research in African and South Asia, *www.cnn.cornell.edu*	The school focuses on two main research themes: agricultural sustainability and crop biology. Many of their research projects focus on soil and environmental issues in developing regions.
Centre For World Food Studies, University of Vrije University Amsterdam	M Nube, R.L. Vortman are based in this Centre, research on developed and developing countries, *www.onderzoekinformatie.nl/en/oi/no?organisatie/ORG1236787/*	Variety of research projects including one focused on addressing micronutrient deficient soils and creating both higher yields and better nutritional quality.
Swiss Federal Institute of Technology (ETHZ), Institute of Plant Science	Emmanuel Frossard and Feliz Machler are based in this center. ETHZ is a science and technology university in Switzerland, *www.ethz.ch*	Their plant science group, led by Professor Frossard, explores connections between human nutrition and increasing the content of micronutrients through agriculture. The department is also involved in plant breeding science.
Wageningen University in the Netherlands	MA Slingerland is based out of this university. Resaearch areas are worldwide, *www.wageningenuniversiteit.nl/UK*	Well-regarded research institution that has a primary focus on plant and animal breeding. Also, they have a heavy focus on the chain management of food policy, including packaging and storing.
University of Minnesota, Department of Soil, Water, and Climate	Research both domestically and throughout the world. Several internationally focused faculty members, *http://www.soils.umn.edu/*	The department does primary research in the areas of precision agriculture, biological nitrogen fixation and biochemical cycling. They also carry out research in the areas of nutrient management, pesticide transport and transformation of soils, land use planning and policy decisions.
University of Adelaide, School of Agriculture	RD Graham is associated with this university, researches agricultural issues in Australia and internationally, *www.agwine.adelaide.edu.au/*	The School's research interests include agronomy, animal science, integrated pest management, horticulture, viticulture, oenology, wine business, plant biotechnology, and crop improvement.
Oklahoma	Haiin Zang is based at the school.	Recently received a grant from the Fertilizer Institute

State University, College of Agricultural Sciences and Natural Resources	School focuses on domestic and international research projects, *www.casnar.com*	for an endowed chair with a focus on fertilizer science issues. School is currently involved in plant breeding and has an interdisciplinary program in international agriculture.

6. Conclusion

As our understanding of the impacts of hidden hunger on human nutrition grows, understanding the link between fertilizer use and human nutrition becomes increasingly important. Some nutrient deficiencies, such as zinc, can be effectively addressed through fertilizer use while others, such as iron deficiency, are more difficult to address. Promising breakthroughs with fortified and complete fertilizers present the opportunity to correct multiple deficiencies.

Current fertilizer products exist that, when applied with the proper agronomic methods, can have a significant effect on nutrition in the developing world. However, it is important to recognize that there are many factors in the developing world that have the potential to inhibit the benefits of fertilizer for human nutrition. Two significant factors are poor farmers' difficulty in procuring the correct product and the relative sophistication required to apply fertilizers at the correct amounts and time to achieve desired results. In addition, researchers have not focused on fertilizer and nutrition studies until recently, particularly micronutrient fertilizer studies, and few studies specifically study the impacts of fertilizer on human nutrition. More research needs to be done to understand the most effective combinations and techniques, and to understand whether these methods truly increase the amount of nutrients bioavailable to humans.

7. Methodology and Bibliography

The literature review was conducted using both Web of Science and Google Scholar. NGO and governmental websites were also searched, including IFPRI, FAO, World Bank, and USDA. A number of keywords were searched, including, but not limited to:

- Fertilizer and NPK Fertilizer
- Nutrition
- Micronutrients and Iron and Zinc
- South Asia, Africa (countries such as India, Pakistan, Nepal, Bangladesh, Kenya, etc.)
- Human Health
- Specialty/Micronutrient Fertilizers
- Biofortification

The review focused mainly, though not exclusively, on literature published since 2000, and we did not list or review individual studies reviewed in literature review articles. A draft of this review was sent to an outside reviewer, Laura McCann, Associate Professor in the Department of Agricultural Economics at the Univiersity of Missouri, who reviewed it for conceptual accuracy and additional sources and concepts.

Bibliography and Brief Summary of Articles Reviewed

Articles are organized in the table below first by year (with most recent first), and then by last name of the first author.

Citation	**Subject**
Alloway, B.J. (2008). *Micronutrients and Crop Production: An Introduction.* Netherlands: Springer.	Book/Theoretical. Reviews the eight trace elements crucial for plant nutrition and discusses methods (fertilization, agronomic, etc.) for correcting deficiencies in soil and crops, as well as acute symptoms for the diagnosis of deficiencies.
Fang Y, Wang L, Xin Z, Zhao L, An X, & Hu Q. (2008). Effect of Foliar Application of Zinc, Selenium, and Iron Fertilizers on Nutrients Concentration and Yield of Rice Grain in China. *Journal of Agricultural and Food Chemistry,* Vol. 56, pp. 2079-2084.	Primary study. Study on the foliar application of micronutrients. Results indicated that Zn, Se were the main variables influencing the Zn, Se, and Fe contents of rice. Provides optimal ratio for increased concentration of these nutrients.
Jiang W, Struik P.C., Van Keulen H, Zhao M, Jin L.N., & Stomph T.J. (2008). Does increased zinc uptake enhance grain zinc mass concentration in rice? *Annals of Applied Biology,* Vol. 153, pp. 135-147.	Primary study. Study on the effects of zinc uptake in rice. Concludes that uptake increases with application rates but, from a human nutrition perspective, breeding may have more potential.
Skwierawska M, Zawartka L & Zawadzki B. (2008). The effect of different rates and forms of applied sulphur on nutrient composition of planted crops. *Plant Soil and Environment,* Vol. 54, (5), pp. 179-189.	Primary study in Northeast Poland. A three-year study on the application of sulphur rates. The most effective rates in terms of composition and yield were the low and medium applications, with the high application depressing yield and potassium levels.
Zhang J, Wang M, Lianghuan W, Jiangguo W., & Chunhai S. (2008). Impacts of Combination of Foliar Iron Biofortification and Nutritional Quality of Rice Grain. *Journal of Plant Nutrition,* Vol. 31, pp. 1599-1611.	Primary study. The study concluded that foliar application of iron and boron increased the nutritive values of polished rice. Fe and B biofortification significantly raised levels of Fe, Zn, protein, and amino acids.

Aires A, Rosa E, Carvalho R, Haneklaus S, & Schnug E. (2007). Influence of Nitrogen and Sulfur Fertilization on the Mineral Composition of Broccoli Sprouts. *Journal of Plant Nutrition,* Vol. 30, pp. 1035-1046.	Primary study. Studied the effects of N and S application to broccoli on their mineral contents. Results indicated that N and S applications increased biomass production in the early growth stage and N and S significantly influenced the uptake of all elements.
Burgos G, Amoros W, Morote M, Stangouilis J & Bonierable M. (2007). Iron and Zinc Concentration of Native Andean Potato Cultivars from a Human Nutrition Perspective. *Journal of the Science of Food and Agriculture,* Vol. 87 (4), pp. 668-675.	Primary study. Study found a significant variation in genotypes for 49 native Andean potato varieties, indicating that the variation could be exploited in breeding programs to increase Fe and Zn levels in the crops.
Nemeth T, Mathe-Gaspar G, Radimszky L & Gyori Z. (2007), Effect of nitrogen fertilizer on the nitrogen, sulphur and carbon contents of canola (Brassica napus L.) grown on a calcareous chernozem soil, *Cereal Research Communications,* Vol. 35, (2), pp. 837-840.	Abstract/Article not available through the UW library system but it appears it could be of interest. Can find if requested.
Wang ZH, Li SX, & Malhi S. (2007). Effects of fertilization and other agronomic measures on nutritional quality of crops. *Journal of the Science of Food and Agriculture,* Iss. 88, pp 7-23.	Primary study. Discusses the effects of fertilization on nutritional quality of cereal and protein crops. Analyses the excessive use of the N fertilizer and its effect on nutrition.
Zimmermann M.B. & Hurrell R.F. (2007). Nutritional Iron Deficiency. *Lancet,* Vol. 370, pp. 511-520.	Review/theoretical. Overview of the physiology behind iron-absorption and methods to fortify iron such as supplementation and fortification. Also discusses the promise of plant breeding for improved iron nutritional quality.
Akinrinde E.A. (2006) Strategies for Improving Crops Use Efficiencies of Fertilizer Nutrients in Sustainable Agricultural Systems. *Pakistan Journal of Nutrition,* Iss. 5 (2), pp. 185-193.	Theoretical. Discusses techniques used to address acid infertility including organic and liming strategies. Describes appropriate nutrient techniques for acid soils.
Nube M, & Voortman R.L. (2006). Simultaneously addressing micronutrient deficiencies in soils, crops, animal and human nutrition: opportunities for higher yields and better health. *Centre for World Food Studies. Staff*	Theoretical. Relevant sections include the use of micronutrient fertilizers in Africa and techniques to address deficient soils in Sub-Saharan Africa.

Working Paper. September 2006, pp. 1-48.	
Polycarpe A.P., Linnemann A.R., Hounhouigan J.D., Martinus J.R., & Martinus A.J. (2006). Genetic and Environmental Impact on Iron, Zinc, and Phytate in Food Sorghum Grown in Benin. *Journal of Agriculture and Food Chemistry,* Vol. 54 (1), pp. 256-262.	Primary study. Genotype clusters were evaluated for their Fe, Zn, and phytate concentrations to assess the impact of genetic and environmental effects on the composition of the grains and to identify farmers' varieties with high potential Fe and Zn availability.
Roy R.N., Finck A, Blain G.J., & Tandon H.L.S. (2006). Plant Nutrition for Food Security. *Food and Agriculture Organization of the United Nations: Food and Nutrition Bulletin,* Iss. 16, pp. 1-357.	Theoretical. Overview of the different fertilizers used for deficiencies of each plant nutrient and the common products and techniques used throughout the world, guide to NPK fertilizers.
Slingerland M.A., Traore K, Kayode A.P.P. & Mitchikpe C.E.S. (2006). Fighting Fe deficiency malnutrition in West Africa: an interdisciplinary programme on a food chain approach, *NJAS Wagenheim Journal of Life Sciences,* Vol. 53, Iss. 3-4, pp. 253-279.	Primary study. Preliminary results of a group of interventions aimed at addressing iron deficiencies in Benin and Burkino Faso. Application of P fertilizer and organic amendments raised sorghum (staple crop) yields, but also increased phytic acid content. Strategies that will complement fertilizer use and create the desired human health impact have been designed and are being implemented.
Taiz, L., & Zeiger, E. (2006). *Plant Physiology, Fourth Edition.* Sunderland, MA: Sinauer Associates, Inc., Publishers.	Plant physiology text.
Aulakh M.S., & Malhi S. S. (2005). Interactions of nitrogen with other nutrients and water: effect on crop yield and quality, nutrient use efficiency, carbon sequestration, and environmental pollution. *Advances in Agronomy,* Vol. 86, pp. 341-409.	Review article. Fairly technical article, but very in depth, looking at the interactions between nitrogen and other nutrients. Focuses on the situations of limited-resource farmers (and developing world), and on environmental issues resulting from over-application of fertilizers.
Haas J.D., Beard J.L., Murray-Kolb L.E., Del Mundo A.M., Felix A. & Gregorio G.B. (2005). Iron Biofortified Rice Improves the Iron Stores of Nonanemic Filipino Women. *The Journal of Nutrition,* Vol. 135, pp. 2823-2830.	Primary Study. Filipino women were used to study the effects of high-iron rice on iron status. The most significant effects were found in non-anemic women and iron store in women were influenced by the biofortified rice.
Johnson S.E., Lauren J.G., Welch, R.M., &	Primary study. Study that evaluates the effect of

Duxbury, J.M. (2005). A Comparison of the Effects of Micronutrient Seed Priming and Soil Fertilization on the Mineral Nutrition of Chickpea, Lentil, Rice, and Wheat in Nepal. *Expl Agriculture,* Vol. 41, pp. 427-448.	micronutrient treatments on yield and plant micronutrient concentration. Results show that the effect varies depending on nutrient.
Kelly V, Jayne T, & Crawford E. (2005). Farmers Demand for Fertilizer in Sub-Saharan Africa. *Michigan State University,Working Draft,* pp. 1-33.	Economic analysis. Analysis of the different fertilizers used for each crop and how each crop responds. Also provides an overview of farmer input obstacles.
White P.J. & Broadley M.R. (2005). Biofortifying Crops with Essential Mineral Elements. *Trends in Plant Science,* Vol. 10, no. 12.	Theoretical. Traditional strategies to deliver minerals to susceptible populations have drawbacks, paper discusses method to mineral concentrations in crops through biofortification.
Alloway B.J. (2004). *Zinc in soils and crop nutrition.* Brussels: IZA. Publications. International Zinc Association.	Theoretical. Analysis of different zinc fertilizers and the importance of matching the proper fertilizer type with the soil and crop requirements.
Hotz C & Brown K.H. (2004). Assessment of the risk of zinc deficiency in populations and options for its control. *Food Nutrition Bulletin,* Vol. 25, pp. 94–204.	Theoretical. Discusses the medical effects of human zinc deficiency, proper methods of assessment in populations, and strategies to combat deficiency, including nutritional fortification and agricultural methods.
Welch, R.M., (2002), Micronutrients, Agriculture and Nutrition: Linkages for Improved Health and Well Being. *USDA, Plant, Soil and Nutrition Laboratory.* http://www.css.cornell.edu/foodsystems/micros&agriman1ref.html.	Theoretical. Wide ranging overview of the common strategies for linking agriculture and nutrition; including fortification, supplementation, plant breeding, and fertilizer. Review concentrates on a new, multiple strategy, food system.
Welch R.M. & Graham R.D. (2002). Breeding Crops for Enhance Micronutrient Content. *Plant and Soil,* Vol. 245 (1), pp. 205-214.	Theoretical. Discusses the linkages between nutrition and agriculture and some of the effects of the Green Revolution on human health.
Frossard E., Bucher M., Machler F., Mozafar A., & Hurrell R. (2000). Potential for Increasing the Content and Bioavailability of Fe, Zn and Ca in Plants for Human Nutrition. *Journal of the Science of Food and Agriculture*, Iss.	Theoretical. Reviews the possibility and limits for increasing the content and bioavailability of micronutrients in the edible parts of staple crops, such as cereals, pulses, roots, etc. Advocates for plant breeding as the most effective strategy, but also details foliar techniques that are effective for

80, pp. 861-879.	Fe fortification.
Reddy N.S. & Bhatt G. (2000). Contents of minerals in green leafy vegetables cultivated in soil fortified with different chemical fertilizers. *Plant Foods for Human Nutrition,* Iss. 56, pp. 1-6.	Primary Study. Controlled study of the effects of fortified fertilizers on selected leafy vegetables in India. Study showed positive results, with especially significant gains in iron.
Rosado, Jorge L. (1999). Separate and Joint Effects of Micronutrient Deficiencies on Linear Growth. *The Journal of Nutrition,* Iss. 129, pp. 531-533.	Theoretical. Discusses the impacts of micronutrient deficiencies on human growth.
Welch R.D. & Graham R.M. (1999).A New Paradigm for World Agriculture, Meeting Human Needs: Productive, Sustainable, Nutritious. *Field Crop Research,* Vol. 60, (2), pp. 1-10.	Theoretical. Discussion of the new "green revolution" that will include biofortified crops and increased consideration of plant nutritional content to combat hidden hunger.
Rengel Z., Batten G.D., & Crowley D.E. (1998). Agronomic approaches for improving the micronutrient density in edible portions of field crops. *Field Crops Research,* Iss. 60, pp. 27-40.	Theoretical. Discusses fertilization techniques that could maximize micronutrient density. Advocates for soil application for zinc and copper, foliar application for iron, and adding iodine fertilizers to irrigation water.
Shuman L.M. (1998). Micronutrient Fertilizers. In Z. Rangel (Ed.), *Nutrient Use in Crop Production.* (pp 165-196). New York: Food Products Press.	Only portions were available for review. Review article within longer comprehensive book about nutrient use in crop production.
Buerkert A., Haake C., Ruckwied M., & Marschner H. (1997). Phosphorous application affects the nutritional quality of millet grain in Sahel. *Field Crops Research,* Iss. 57, pp. 223-235.	Primary study. Study which shows the large increases of millet grain yield with the application of mineral P fertilizers on acid sandy soils in South Africa may detrimentally affect the nutritional quality of the grain.
Viteri F.E. (1994). The consequences of iron deficiency in pregnancy. *Advance Expert Medical Biology,* Iss. 352, pp. 127-139.	Theoretical. Reviews the human health impacts of iron-deficiency for women in developing countries.
Tsai C.Y., Dweikat I., Huber D.M. & Warren, H.L. (1992). Interrelationship of nitrogen nutrition with maize (*Zea mays*) grain yield, nitrogen use efficiency and grain quality. *Journal*	Primary study. Analyzes the need for different levels of fertilizer use for hybrid and traditional forms of maize.

of the Science of Food and Agriculture, Vol. 58 (1), pp. 1-8.	
FIPs Africa – stat sheet, background can be found at: http://www.worldbank.org/afr/fertilizer_tk/documentspdf/FIPS_SmallPacks_Demos.pdf	Informational. Overview of the FIPs program with descriptions on fertilizer strategy and initial increases in fertilizer, demand and yields for the project. No explicit connections with human health were measured.