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FARMING FOR NUTRITIOUS FOODS: AGRICULTURAL TECHNOLOGIES FOR IMPROVED HUMAN HEALTH

Ross M. WELCH
Cornell University, USA

USDA-ARS, U.S. Plant, Soil and Nutrition Laboratory, Tower Road,
Cornell University, Ithaca, NY USA 14853
Email: rmw1@cornell.edu

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Paper by Ross M. Welch
USDA-ARS, U.S. Plant, Soil and Nutrition Laboratory
Cornell University

Human existence requires that at least 42 nutrients (e.g., water, energy sources, vitamins, minerals, trace elements, essential amino acids, and essential fatty acids) be ingested in adequate quantities to sustain life. During fetal development, infancy and childhood, sufficient nutrient supplies are particularly important because of the high demand for nutrients during rapid growth periods. If population groups (i.e., food insecure households) consume less than adequate levels of these nutrients for extended periods, health declines, diseases increase, societies suffer, national development efforts ebb and civil unrest may ensue. Many nations in the Global South are dependent on failing food systems that cannot provide adequate nutrient output to meet the basic nutritional demands of all their citizens (especially resource-poor families), during all seasons, and are now reaping the dire consequences associated with these failures (ACC/SCN, 1992; ACC/SCN, 1997; ACC/SCN, 2000; Combs, Jr. et al., 1996; Combs, Jr. and Welch, 1998; Welch et al. 1997; Welch, 1998).

Importantly, the primary source of all dietary nutrients is derived from agricultural products produced on farms. During the past four decades, improvements in agricultural technologies were able to meet the food-energy demands of a greatly expanding global human population (Schneeman, 2001; Trewavas, 2002). This “green revolution” success story was primarily the result of increases in cereal crop production (i.e., rice, wheat and maize). Unfortunately, cereal grains (as normally eaten) provide mostly carbohydrates (i.e., energy/calories), a small amount of protein and little else; they do not deliver enough micronutrients to meet human nutritional requirements (Welch et al., 1997; Welch, 2001). While saving the world from widespread starvation and massive famine (a very laudable accomplishment), food system modifications resulting from altered cropping systems to more intensive cultivation of cereal crops, with less diversity in available food crops, have led to increased micronutrient malnutrition among the poorest of the poor in many nations (Tontisirin et al., 2002; Underwood and Smitasiri, 1999; Welch et al., 1997). Incredibly, there are over three billon people (i.e., half the world's population) now suffering from one or more micronutrient deficiencies globally. Clearly, it is imperative that the world's agricultural communities begin to address this growing crisis in human health resulting from dysfunctional food systems hampered by unwise agricultural policies and practices (Fresco, 2000).

In many countries, increasing morbidity and mortality rates resulting form diet-related chronic diseases (e.g., cancer, heart disease, stroke, diabetes, osteoporosis, etc.) are a growing concern to the nutrition and health communities (Bowen and Beresford, 2002; Frazao, 1996; Solomons, 2000). Consumer interest in functional foods and in dietary factors perceived as contributing to healthiness is increasing rapidly in many developed nations (McInerney, 2002). Nutrition transitions to western style diets from more nutritionally balanced traditional diets are also of growing concern to many healthcare practitioners in many rapidly developing countries (Sobal, 1999). These concerns also point to the need for agriculture to commit to an explicit goal of improving human health. How can agriculture contribute to improving the nutritional health of an increasingly malnourished world population?

Improving the nutritional quality of food crops and the nutrient output of agriculture systems

Numerous approaches can be used by agriculture to improving the nutritional quality of food crops and the nutrient output of agricultural systems. However, this requires that agricultural researchers understand: 1) the importance of such action to human health and society, 2) how they might contribute, and 3) what nutrients are of greatest concern to the nutrition and health communities. Further, government policies must reflect support for such action, consumers must understand the importance of a diverse and balanced diet to their health, productivity, and well being, and farmers must be shown that participation would be profitable. Increasing consumer knowledge about the impact of poor nutrition on livelihood, educational attainment, employment opportunities, and health should provide a stimulus to increase the demand for better nutritional quality and diversity of foods (McInerney, 2002). Increased consumer demand for improved products and for more diversity of products available in the marketplace would motivate farmers to produce more nutritious and diverse agricultural products.

Some of the ways that agriculture can contribute to reducing malnutrition globally are discussed below. What is currently lacking, however, is the resolve of the agricultural community, the nutrition community, public health officials, private industry, and government policy makers to use agriculture as a primary tool to alleviate malnutrition. Hopefully, through communications, such as this, it will become abundantly clear to the world's leaders that agriculture holds the paramount means by which sustainable solutions to malnutrition can be found. Unless profitable ways are established that will allow agriculture to provide enough food for healthy diets consistently to all, and unless consumers are informed of the consequences of poor diets on their health and livelihoods, developing nations will continue to be plagued with "hidden hunger" with all of its unacceptable ramifications, and developed nations will continue to be burdened with increasing chronic disease rates.

Farming practices

Today, current agricultural practices are almost always directed at maximizing production while minimizing costs. Recently, preserving the environment is becoming a more important objective of agriculture (i.e. "sustainable" agricultural goals) worldwide (Cakmak, 2002; Tilman et al., 2002). Unfortunately, maximizing nutrient output of farming systems has never been a purport of either agriculture or of public policy. Yet, scientific knowledge is available that could greatly improve the nutrient output of farming systems, and the available nutrient content of the food crops produced. The debilitating effects of malnutrition on people and societies and its current magnitude in developing nations certainly testifies to the need to do so. The following discussion briefly presents some examples of how some cultural and agronomic practices could be used to enhance the nutrient output garnered from farms.

Fertilizers and soil amendments

Both macronutrient fertilizers containing N, P, K, and S, and certain micronutrient fertilizers (e.g., Zn, Ni, I and Se) can have significant effects on the accumulation of nutrients in edible plant products (Allaway, 1986; Grunes and Allaway, 1985; Welch, 2001). Other micronutrient fertilizers have very little if any effect on the amount of the micronutrient accumulated in edible seeds and grains when they are applied to soils or when used as foliar sprays (Welch, 1986). This is especially true for those micronutrient elements with limited phloem sap mobility such as Fe, B, V and Cr. Some examples of the effects of fertilizer practices on the micronutrient concentrations in edible plant parts are given below. For more detailed information concerning the effects of fertilization practices on micronutrient accumulation in plant foods refer to: Allaway, 1975; Grunes and Allaway, 1985; Karmas and Harris, 1988; Nagy and Wardowski, 1988; Salunkhe and Desai, 1988; Welch, 1997; Welch, 2001.

Excessive N fertilizers can adversely affect the accumulation of vitamin C in various vegetable crops such as lettuce (*Lactuca sativa* L.), beets (*Beta vulgaris cicla* L.), kale (*Brassica oleracea acephala* DC.), endive (*Cychorium endivia* L.), brussels-sprouts (*Brassica oleracea gemmifera* DC.) by as much as 26% (cited in Salunkhe and Desai, 1988). However, increasing the amount of K fertilizer supplied to these crops significantly increased their vitamin C content from about eight to 20% depending on the species. The concentration of β-carotene in carrot, [*Ducus carota* subsp. *carota sativus* (Hoffm.) Arcang.] roots increased at first harvest in response to increases in the N supplied from 113 mg 100 g^{-1} root in those plants supplied 0.3 g N per pot to 126 mg $100g^{-1}$ root dry weight (about 12% increase) for plants treated with 2.4 g N per pot (Habben, 1972 cited in Salunkhe and Desai, 1988). By the third harvest the increase in β-carotene level resulting from increasing N supply was only about 7%, but the late harvest resulted in an increase in the level of β-carotene even in the lowest N treatment from 113 mg 100 g^{-1} to 136 mg 100 g^{-1} demonstrating a large effect of harvest date on β-carotene content of carrot.

Macronutrient treatments can also influence the concentration of β-carotene and other micronutrients in carrots (Welch, 1997). Vereecke, in 1979 (cited in Salunkhe and Desai, 1988) reported results of studies concerning the effects of combined N, P, K and Mg fertilizers on β-carotene, Fe, Mn, Zn and Cu in carrot. Treatments containing N, P and Mg increased the accumulation of β-carotene by 42%. Adding K to the fertilizer treatments increased the β-carotene by 27% over control plants not receiving K. Removal of Mg from the combined fertilizers lowered the increase in β-carotene from 42% to 30%. Apparently, Mg was required for maximum β-carotene production in carrots furnished adequate N, P, and K.

Macronutrient fertilizers also affect the vitamin C concentration in fruits. As with vegetable crops, excessive N fertilization was reported to reduce vitamin C concentration in the fruits of several species including oranges, lemons, mandarins, cantaloupe, and apple. Also, higher rates of K fertilization are associated with greater concentration of vitamin C in fruits (Nagy and Wardowski, 1988). Apparently, the effects of Zn, Mg, Mn, and Cu fertilization on increasing vitamin C concentration in citrus fruits are limited to soils that are deficient in these elements. Supplying more of these elements then is required for optimum yield does not increase vitamin C level in the fruit further.

For certain essential micronutrient elements (e.g., Zn, Ni, I, and Se), increasing their supply to food crops can result in significant increases in their concentrations in edible plant products. For example, increasing the supply of Zn to pea plants (*Pisum sativum* L.) at levels in excess of that required for maximum yield has been shown to increase the concentration of bioavailable Zn in pea seeds (see Figure 1) (Peck et al., 1980; Welch, et al., 1974). Furthermore, increasing the supply of Zn and Se to wheat (*Triticum aestivum* L.) improved the amount of bioavailable Zn and Se in wheat grain (see Table 1) (House and Welch, 1989). Increasing Zn levels via Zn fertilization has also been shown for navy beans (*Phaseolus vulgaris* L.) as well as other crops (Moraghan 1994; Peck,et al., 1980; Welch et al., 1974). For iron, providing more to plants then required to sustain growth does little to further increase the Fe in edible seeds and grains (for example, see Welch and Van Campen, 1975). Interestingly, the micronutrient I, supplied in irrigation water, can greatly increase the levels of I in edible portions of food crops alleviating the debilitating disease, cretinism, as well as other I disorders in populations dependent on irrigated food crops grown on low-I soils (Cao, et al., 1994). In Finland, Se added to fertilizers and applied to soils increased the Se status of the entire Finnish population (Mäkelä et al., 1993).

The accumulation of micronutrient elements in seeds and grains is controlled by a number of processes including root-cell uptake, root-shoot transfer, and the ability of leaf tissues to load these nutrients into the vascular phloem elements which are ultimately responsible for delivering these nutrients to developing seeds and grains via the phloem sap (Welch, 1986). Phloem loading and unloading of these nutrients are tightly control by poorly understood haemostatic mechanisms in the plant and further research should be carried out to understand these processes if we are to significantly increase certain micronutrient elements, such as Fe, in staple seeds and grains (Welch, 1995).

Soil amendments are frequently used by farmers to adjust soil pH and to enhance the plant growth properties of soils. Using lime ($CaCO_3$) raises soil pH permitting acid-intolerant legume species to grow in soils that would otherwise be too acidic for their growth. It is also used to supply Ca to plants. However, adding lime depresses the uptake of Zn, Cu, Fe, and Co, and increases the uptake of Se and Mo by plants. A high soil-pH favors the oxidation of reduced forms of Se such as Se^{2-} and SeO_3^2 to the more soluble and plant-available SeO_4^{-2} anion. Gypsum ($CaSO_4$) and elemental S are used to decrease the pH of alkaline soils as well as to provide S for plant uptake and to ameliorate high-Na alkali soils. Using gypsum on alkaline soils could increase plant-available Fe, Mn, Zn, Cu, and Co by decreasing alkaline soil pH (Allaway, 1986; Sander et al., 1987).

The use of farm-yard manures and other forms of organic matter can also change plant-available micronutrients by changing both the physical and biological characteristics of the soil. In many circumstances these changes improve soil physical structure and water holding capacity resulting in more extensive root development and enhanced soil microflora and fauna activity, all of which can affect available micronutrient levels in soil to plants (Stevenson, 1991; Stevenson, 1994). However, very few controlled experiments have been done to determine which types of organic matter practices significantly enhance or depress the levels of micronutrients in edible portions of major food crops. More research should be carried out to understand the impact of various types of organic matter on crop nutritional quality.

Variety selection

Using micronutrient-dense staple food-crop varieties is one approach that could be used to increase the micronutrient output of farms (Combs, Jr., et al., 1996). Although there is substantial evidence in the literature that plant traits for micronutrient efficiency and high micronutrient content of edible parts do exist for various plant species (Gerloff and Gabelman, 1983; Graham, 1984), until recently there has been no systematic survey of staple plant food genomes for these types of traits. However, currently, there is such a global effort underway for surveying the world genomes of rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L. and *T. durum* Desf.), maize (*Zea mays* L.), beans (*Phaseolus vulgaris* L.), cassava (*Manihot esculenta* Crantz) and sweet potato (*Ipomoea batatas*, L.) for high micronutrient density traits (Graham et al., 2001). This project is currently known as the "Biofortification Challenge Program" (BCP) within the Consultative Group on International Agricultural Research (CGIAR) and is administered by two of the Future Harvest Centers, the International Food Policy Research Institute (IFPRI) in Washington, D. C. and the *Centro Internacional de Agricultura Tropical* (CIAT) in Cali, Columbia. The program also includes cooperators from several other CGIAR Centers including, *Centro Internacional de Mejoramiento de Maiz y Trigo* (CIMMYT) in Mexico, the International Rice Research Institute (IRRI) in the Philippines, and the International Institute for Tropical Agriculture (IITA) in Nigeria. Other CGIAR Centers in Peru, Syria and India are also involved (covering other staple food crops), as well as some collaborating institutions including the Department of Plant Sciences, Waite Campus, University of Adelaide in Australia, the USDA-ARS, U.S. Plant, Soil and Nutrition Laboratory at Cornell University, Ithaca, NY, the Department of Biochemistry and Molecular Biology at Michigan State University, East Lansing, MI, the USDA-ARS Children's Research Center in Houston, TX, and the Institute for Biology at the University of Freiburg, Germany.

The CBP directed at surveying the staple plant food genomes for micronutrient efficiencies and accumulation ability is based on the premise that increasing the concentrations of micronutrients in staple plant foods through traditional plant breeding techniques would be the most efficient and cost-effective means to target micronutrients to people most at risk of developing micronutrient malnutrition, i.e., poor women, infants and children. Historically, most interventions that employ micronutrient supplements or micronutrient food fortification programs have proved not to be sustainable and usually do not effectively reach all of the most at-risk people. Furthermore, these types of interventions are relatively expensive and require sophisticated infrastructures for their creation, management and maintenance to assure compliance (Yip, 1997). The cost of breeding plants with traits that result in significant accumulations of micronutrients in edible portions of staple foods would be a one time cost. Once achieved, these traits can be passed on in breeding programs for future varietal generations and transferred globally to all nations with relatively little additional effort or expense (Bouis, 1999). Thus, this approach to improved micronutrient nutrition is sustainable and cost effective (Graham, et al., 2001).

Currently, the CGIAR-sponsored BCP focuses on three micronutrients, Fe, Zn and provitamin A carotenoids in staple plant foods because these plant foods feed most of the world's poor and because deficiencies of these micronutrients are known to affect vast numbers of people in developing countries. This plant breeding approach could be expanded to include other nutritionally limiting micronutrients such as I, Se, Cu, vitamin E, vitamin C, folic acid, and other limiting essential trace elements and vitamins given the resources.

Recent results of the current effort to identify micronutrient-dense genotypes are encouraging. For example, Figure 2 presents the results of an experiment in which 24 genotypes of beans (*Phaseolus vulgaris* L.), selected by CIAT for their variability in seed-Fe concentrations, were grown in radiolabeled (i.e., ^{59}Fe) nutrient solutions and subsequently fed to Fe-depleted rats to determine the bioavailability of Fe in the beans. The mature beans harvested varied in Fe concentrations from about 50 $\mu g\ g^{-1}$ to 160 $\mu g\ g^{-1}$ dry weight depending on the genotype. Thus, there was about a threefold range in Fe concentration in the genotypes studied, which demonstrates that beans can be substantially enriched in seed-Fe via genetic selection. There was a positive relationship between the Fe concentration in the beans and Fe bioavailability to rats fed the beans.

This data supports the contention that increasing the concentration of Fe in bean seeds could be of value in supplying more bioavailable Fe to humans even though beans can contain high levels of certain antinutrients such as phytic acid and tannins (polyphenols) that are known to reduce dietary Fe bioavailability under certain circumstances (see discussion on antinutrients below) (Fairweather-Tait and Hurrell, 1996; McDonald et al., 1996).

There is also a large variation in the concentration of grain-Fe and -Zn in different populations of wheat. As shown in Table 2, different wheat species and genotypes within this species can vary greatly in grain-Fe and grian-Zn concentrations (i.e., ranging from 24 to 93 μg g^{-1} for Fe and 27 to 143 μg g^{-1} for Zn). Thus, it seems feasible for wheat breeders to select for high-Fe and high-Zn density traits in breeding programs. However, further research is needed to determine if the edible portions of high-Fe and high-Zn dense wheat grain still retain enriched levels of Fe and Zn after milling and processing, and if enriched levels of Fe and Zn in wheat grain are bioavailable to target human populations.

For further information on the genetic variation in some micronutrients in staple foods refer to the following references: B□nziger and Long, 2000; Cakmak, 2002; Chavez et al., 2000; Graham et al., 1998; Graham et al., 1999; Kalayci et al., 1999.

Crop management

Using certain legume crops in rotation with cereal crops can result in substantial increases in the concentration of Zn in cereal grain in areas where soil-Zn is currently limiting wheat production [see the thesis of Holloway (1997)]. The selection of crops to avoid micronutrient deficiencies in animals has long been practice (Mertz, 1987; Underwood, 1971). For instance, in large areas of the United States, soils contain too little Co to meet grazing animal requirements when the livestock are dependent on grasses for feed. However, mixing legumes (that accumulate significantly more Co then grasses) with grasses in pastures is an effective way to supply adequate levels of Co to the grazing animals (Allaway, 1986). Such practices as using pulses in cereal rotations could contribute substantially to increasing the micronutrient output of farming systems in developing countries. This is not only because it would increase the amount of certain micronutrient metals in cereal grains following pulses, but also it would increase the dietary supply of the more micronutrient-rich pulses for local, regional and national markets lowering the cost to consumers and potentially increasing the consumption of these important micronutrient sources to people at risk of developing micronutrient deficiencies.

Increasing the use of indigenous and traditional food crops with high nutritive value

Within many developing nations certain indigenous food crops are being displaced and lost as important nutritional components of traditional diets. For instance, in Africa during the last few centuries traditional grains, such as African rice (*Oryza glaberrima* Steudel), Fonio (*Digitaria exilis* Stapf and *D. iburua* Stapf), Tef (*Eragrostis tef* Trotter), pearl millet (*Pennisetum glaucum R. Br.*) and sorghum (*Sorghum bicolor* Moench), have been superseded by high yielding cereals (e.g., rice and wheat) introduced and promoted by agricultural experts from developed nations. The production of many of these traditional crops has decreased even further because of importation of and subsidies paid for millions of tons of wheat, rice and maize that are sold at lower prices. Many traditional crops are much richer sources of micronutrients then the introduced cereal crops that are displacing them (National Research Council, 1996).

Increasing the supply of fruits and vegetables to people in many nations would also help reduce the numbers of people afflicted with micronutrient malnutrition. The Asian Vegetable Research and Development Center in Taiwan has recommended that people eat 73 kg of vegetables per person per year to satisfy their micronutrient requirements. Figure 3 shows the average per capita vegetable supplies of several nations in Asia. With the exception of China, South Korea and Taiwan, none of these countries depicted in Figure 3 produce enough fruits and vegetables to meet this recommendation.

Designing cropping systems to meet human needs

Cropping systems can be designed to maximize nutrient output to meet human needs. An example of such an approach was published by McIntyre et al. (2001). They modeled a maize-based and a banana-based cropping systems in Uganda to provide sufficient quantity to meet household nutritional requirements. Figure 4 depicts some of their results. Clearly, the banana-based system does not provide enough vitamin A, Zn and Ca, and the grain-based system does not provide enough Zn and Ca to meet human needs. The Fe values were calculated using the established USA's National Research Council's RDA value of 15 mg Fe d^{-1}. If one uses the recommended nutrient intake (RNI) value for Fe developed by FAO/WHO of 59 mg Fe d^{-1} to calculate Fe needs, neither system would supply enough Fe to meet nutritional requirements of the people dependent on these cropping systems. These authors explored how these systems could be modified, using locally available resources, to meet human nutritional requirements. They concluded that adequate nutrition, given the same resource base, would require the incorporation of several common but underutilized species into the cropping systems.

Designing cropping systems for maximum nutrient output to improve nutrition and health should become an integral part of agriculture's goals and government policies. Additionally, ways must be found to increase diet diversity among food-insecure people. This would substantially reduce the risk of micronutrient malnutrition to the most at-risk people. Furthermore, any increase in the production of more micronutrient-rich foods (micronutrient-dense food crops, livestock, dairy or fish) could contribute greatly to finding sustainable solutions to micronutrient malnutrition.

Given these axioms, selecting cropping systems not only for their production potential, but also for their ability to supply needed dietary sources of bioavailable nutrients and health promoting factors should become a goal of all nations if we are to meet the laudable objectives of better health and prosperity for all.

Molecular alterations of plant genes to improve nutrient supplies

Modern molecular biological techniques can be used to genetically alter food crops to increase their nutritional and health-promoting qualities (Chassy et al., 2003; DellaPenna, 2001; Huang et al., 2002; Knauf and Facciotti, 1995; Schachtman and Barker, 1999; Thompson, 2002). However, this requires detailed knowledge of various physiological and biochemical processes in plants (DellaPenna, 2001; Grusak and DellaPenna, 1999). Several homoeostatic plant processes must be altered to allow for increased accumulation of nutrients in edible plant products.

For micronutrients elements these processes include increased uptake, increased translocation form roots to shoots, increased remobilization from shoots to reproductive organs, and increased deposition in edible portions of food crops. For vitamins, increased biosynthesis and accumulation of these micronutrients must be expressed in edible organs of the plant in forms that are not degraded by processing and cooking. All of these potential genetic modifications must be done without negatively affecting crop yields, crop quality, food safety, or consumer acceptability. Finally, the micronutrients must be in forms that are bioavailable to the people that eat the plant foods in meals that contain numerous other interacting dietary components (Graham, et al., 2001).

Increasing efficiency of micronutrient uptake

The mechanisms by which plants accumulate micronutrient elements and vitamins are under genetic regulation that is influenced by environmental factors. Unfortunately, plant breeders normally have not taken advantage of micronutrient element efficiency traits to enhance the ability of major food crops to absorb micronutrient elements form micronutrient-poor soils. Commonly, breeders have used their most productive soils to breed high yielding, disease and stress resistant crops. These fertile soils contain ample available sources of micronutrient elements for crops. Because breeders normally use highly fertile soils for their selections, they may have inadvertently lost micronutrient-element efficiency traits during their genetic selection for high yielding traits because there were no selection pressures to preserve such traits in the breeding process. However, there is ample evidence to show that these traits do exist in plant genomes and that they can be selected for in breeding programs. Graham and his colleagues have published extensively on this subject for various micronutrients (e.g., Zn, Mn and Cu) and for several cereal crops including wheat, oats and barely (Graham, 1984; Graham, 1988a; Graham, 1988b; Graham et al., 1992; Graham and Welch, 1996; Rengel and Graham, 1995a; Rengel and Graham, 1995b). Selecting for the ability to accumulate more micronutrient elements from nutrient-poor soils is the first step in breeding for micronutrient dense staple food crops.

Increasing translocation, re-mobilization and deposition of micronutrients

The second step in increasing the density of micronutrient in staple foods involves altering the genes that control the translocation of root-accumulated micronutrient elements to shoots. Here also there is sufficient evidence to suggest that this can be done by genetic selection, but more research is required to more fully delineate the processes and genes involved (Welch, 1986; Welch, 1995).

Once more micronutrients are accumulated in plant shoots, they must be re-translocated out of leaves to reproductive organs before they can be deposited in developing seeds and grains. Re-translocation requires the loading of micronutrient elements from source tissues into vascular phloem elements and the phloem sap, long distance transport within the phloem sap, and unloading of micronutrient elements out of the phloem sap and into sink sites within reproductive organs. The mechanisms that control these processes in plants are not known with any certainty. Further research is needed to determine what these mechanisms are and what genes are responsible for their construction and their regulation.

Knowing how micronutrients are stored and in what forms they are occurring in edible seeds and grains are also important constituents (see discussion below) of increasing the bioavailable content of micronutrients in edible plant parts. Here also, very little is known about this aspect of micronutrients in plants and much more research should be directed at increasing our knowledge in this area (Welch, 1986; Welch, 1999).

Improving the bioavailability of micronutrients in plant foods

Increasing the concentrations of micronutrients in edible plant foods is only the first step in making these foods richer sources of micronutrients for humans. This is because not all of the micronutrients in plant foods are bioavailable to humans that eat these foods. Plant foods can contain substances (i.e., antinutrients) that interfere with the absorption or utilization of these nutrients in humans (Welch and Graham, 1999).

Plant breeders could breed for genotypes that contain lower concentrations of antinutrients or molecular biologists could alter plant genes in ways that reduce or even eliminate antinutrients from plant foods. However, doing this is not without risk and should be done with caution because many antinutrients are major plant metabolites that may play important roles in plant metabolism and in plant resistance to crop pests or pathogens. Additionally, some of the antinutrients may play important beneficial roles in human diets by acting as anticarcinogens or by promoting health in other ways such as in decreasing the risk of heart disease or diabetes. Thus, plant breeders and molecular biologists should be aware of the possible negative consequences of changing antinutrients in major plant foods before they attempt to alter food crops in this fashion (Graham et al., 2001).

Other substances (see Graham et al., 2001 for detailed discussion of this topic) can promote the bioavailability of micronutrients in plant foods to humans even in the presence of antinutrients from those foods. Many of these compounds are normal plant metabolites and only small changes in their concentration may have significant effects on the bioavailability of micronutrients. Therefore, it is highly recommended that plant breeders and molecular biologists closely scrutinize the strategy of increasing promoter substances in food crops when attempting to improve food crops as sources of micronutrients for people.

Increasing the accumulation of vitamins in edible parts of food crops

Currently, much of the research on increasing vitamins in food crops has been directed at the provitamin A carotenoids in vegetable crops (Camara et al., 1992; Sandmann, 2001; Schuch et al., 1996; Simon, 1992). In the past some research was also performed to determine the variability of ascorbic acid (vitamin C) in various fruits and vegetables and the environmental factors that influence ascorbic acid concentrations in fruits such as tomato (Salunkhe and Deshpande, 1991). Unfortunately, our knowledge of the biosynthetic and regulatory processes that control the accumulation of most vitamins in food crops is extremely limited and much more research is needed to be preformed before significant progress can be made in genetically altering staple food crops as sources of vitamins for humans.

However, current molecular biological techniques are available that would allow for rapid genetic alterations of plant foods in ways that would increase vitamins in these foods once the biosynthetic pathways and their regulation are understood (DellaPenna, 2001; New York Academy of Sciences, 1996).

Established biochemical approaches to delineating vitamin biosynthesis and metabolism in plants have depended on the purification of enzymes and determinations of their activity *in vitro*. These approaches are being displaced by molecular genetic techniques using mutants of model plants (such as *Arabidopsis thaliana*) and the expression of plant genes in heterologous systems. These model plant systems are currently being used to understand vitamin metabolism in plants, i.e., *Arabidopsis* mutants, to screen for altered expression of carotenoids. This has enabled the cloning of genes for various biosynthetic enzymes, and also has demonstrated the extent to which provitamin A carotenoids can be altered within the plant, without impaired growth and function of the plant. A second approach includes using genes identified in non plant organisms, such as yeast or bacteria, to identify homologous genes in plants for vitamin biosynthetic pathways of interest. Once the plant genes have been cloned, their expression can be manipulated to determine the consequences to plant growth and the extent to which various vitamins can be increased (Comai, 1993; DellaPenna, 2001; Phillips, 1993; Watson, 1995).

Conclusion

This review has discussed various ways in which agricultural technologies can contribute to improving human health in sustainable ways. Importantly, to solve the massive problem of malnutrition facing the world today requires an understanding of the major causes creating the problem. Certainly (as discussed in this review), if agricultural systems do not provide enough nutrients to meet human needs continuously, malnutrition will persist especially among the world's poor. Major changes in how agriculturalist, nutritionists and policy makers view the problem and their roles in attacking malnutrition must occur if we are to find sustainable solutions to this growing quandary. The ultimate goals of the agriculture, nutrition, and health communities must be viewed as fundamentally linked to each other, and programs must reflect this vision. Sustainable means to these aspirations are necessary in order to provide humans with a foreseeable future that will reflect happier and healthier lives for all. This goal cannot be met unless people are well nourished, healthy, more vigorous and productive in every way, not only for enhanced labor productivity, but also for mental creativity, social accordance, and civic life. Therefore, it is imperative that close linkages be forged between the agriculture, nutrition, and health arenas (Combs, Jr. and Welch, 1998).

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Table 1: Effects of increasing Zn and Se supplies to wheat (*Triticum aestivum* L.) grown in radio-labeled (^{65}Zn and ^{75}Se) nutrient solutions on the concentration of Zn and Se in mature wheat grain and bioavailable amounts of Zn and Se in the grain when fed to Zn-deficient rats in a single meal (data from House and Welch, 1989).

Zn Supplied	**Se Supplied**	**Zn in Grain**	**Se in Grain**	**Bioavailable Zn**	**Bioavailable Se**
--------(μM)---------		------(μg g^{-1}, dry wt.)-----		----(μg absorbed from meal)----	
1.0	0.3	8.8	0.6	5.9	0.41
1.0	1.5	9.3	3.8	5.5	2.03
5.0	0.3	33.0	0.6	18.7	0.42
5.0	1.5	36.1	4.3	15.4	1.91

Table 2: Variation in Fe and Zn concentrations in mature wheat grain of diverse populations from various world regions (unpublished data furnished by Robin Graham and CIMMYT, 1997).

Region	**Population**	**Fe (SD)**[*]	**Range**	**Zn (SD)**	**Range**
		(μg g^{-1}, dry weight)			
Turkey	133 landraces (1993)	51(3.5)	43-62	33 (5.6)	19-48
Mexico	1000 diverse germplasm entries				
	50 *Triticum dicoccon* (1992)	62 (17)	24-93	80 (26)	27-135
	30 *Triticum tauschii* (1995)	76 (10)	59-99	50 (7)	38-69
	47 *Triticum dicoccoides* (1992)	42 (6)	27-93	68 (27)	27-143
Various	Breeder's lines				
	154 *Triticum aestivum* (1995)	42 (6)	33-73	40 (8)	27-85
	230 *Triticum durum* (1995)	37 (3.5)	30-47	47 (6)	34-63
	239 *Triticosecale rimpaui* (1995)	33 (3)	27-57	46 (6)	33-66

[*] SD = standard deviation

Figure Legends

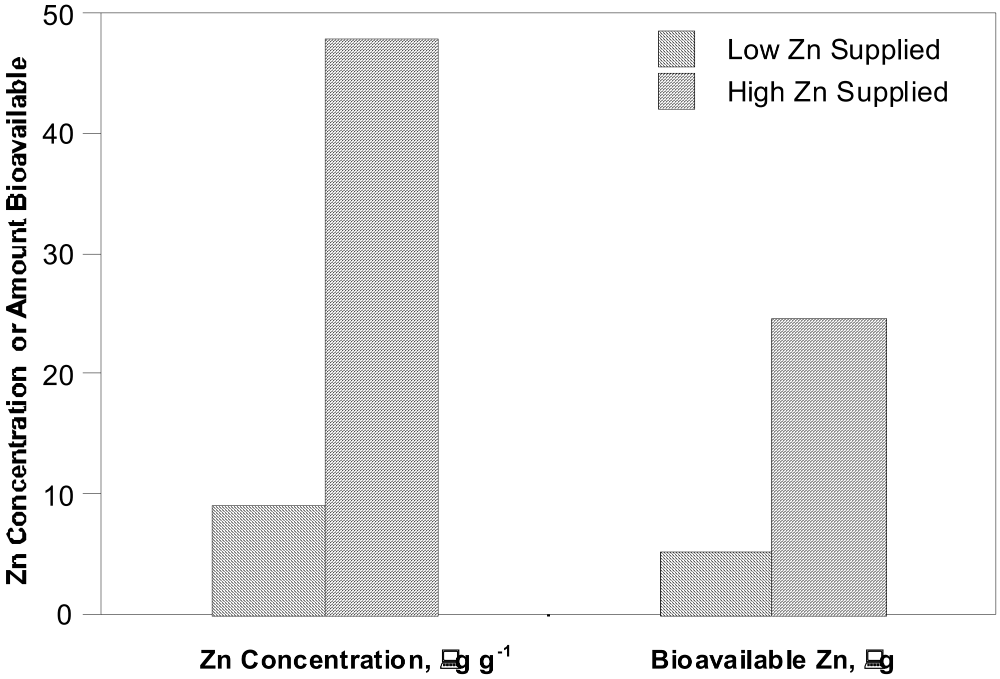
Figure 1. Effects of increasing Zn supply to pea (*Pisum sativum* L.) plants grown in ^{65}Zn radiolabeled nutrient solutions on Zn concentration and bioavailable Zn in mature pea seeds fed in single meals to Zn-depleted rats (data from Welch et al., 1974).

Figure 2. Relationship between bean-Fe concentrations in 24 bean genotypes and Fe absorbed form beans fed in single meals to marginally Fe-depleted rats. R^2 is the correlation coefficient squared.

Figure 3. Asian nations' vegetable supplies (three year average, 1986-1988). The recommended per person supply of vegetables is 73 kg year^{-1} to meet micronutrient requirements (modified from unpublished figure developed by Ali et al., Asian Vegetable Research and Development Center, 1994).

Figure 4. Output of nutrients (i.e., energy, protein, vitamin A, Zn, Fe and Ca) for two Ugandan food systems (banana-based and grain-based) relative to the recommended daily allowance (RDA) expressed as a percent of required nutrient intake (i.e., percent of RDA). Values were calculated on a consumption unit basis (data from McIntyre et al., 2001).

Figure 1



Zn Concentration or Amount Bioavailable
0
10
20
30
40
50
Low Zn Supplied
High Zn Supplied
Zn Concentration, µg g-1
Bioavailable Zn, µg

Figure 2

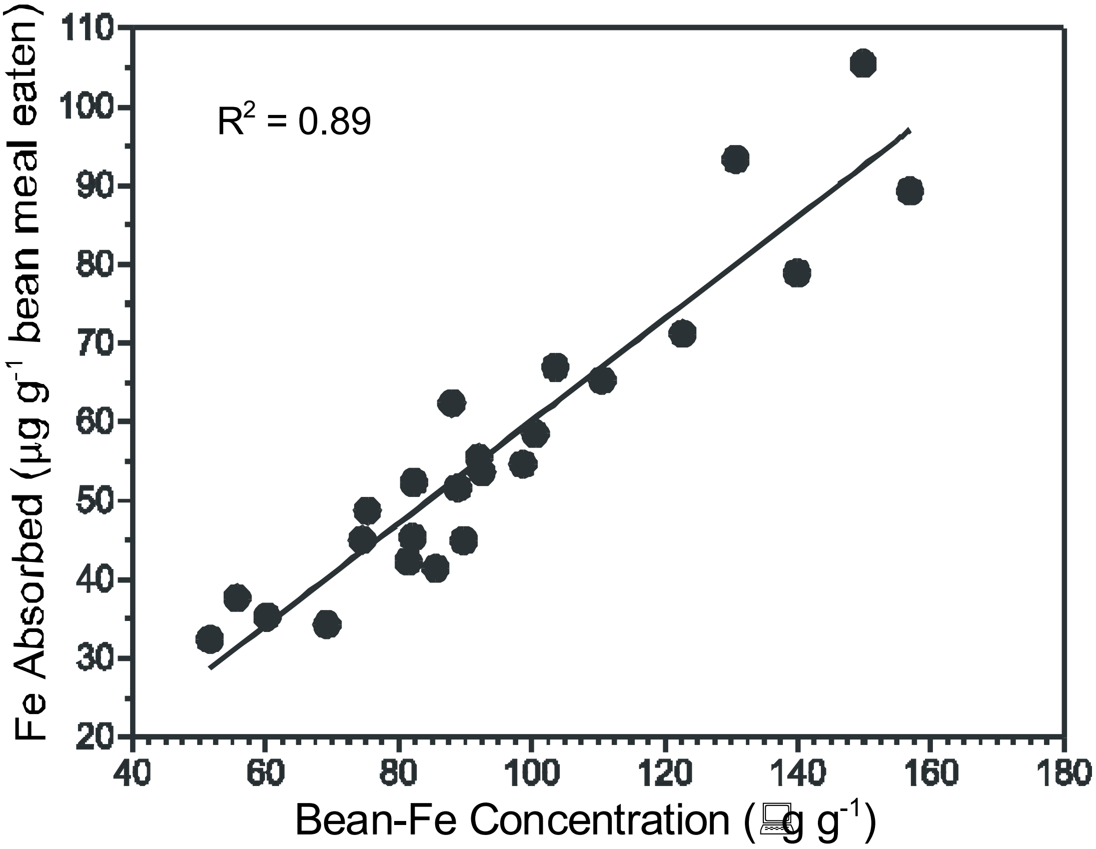

R² = 0.89
Fe Absorbed (µg g-1 bean meal eaten)
Bean-Fe Concentration (µg g-1)
20
30
40
50
60
70
80
90
100
110
40
60
80
100
120
140
160
180

Figure 3

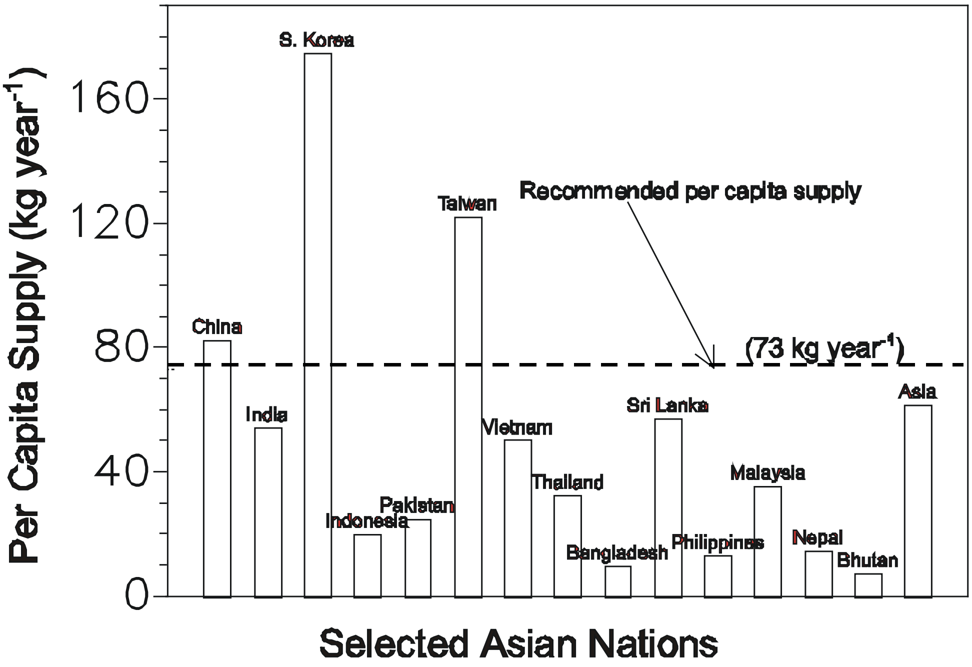
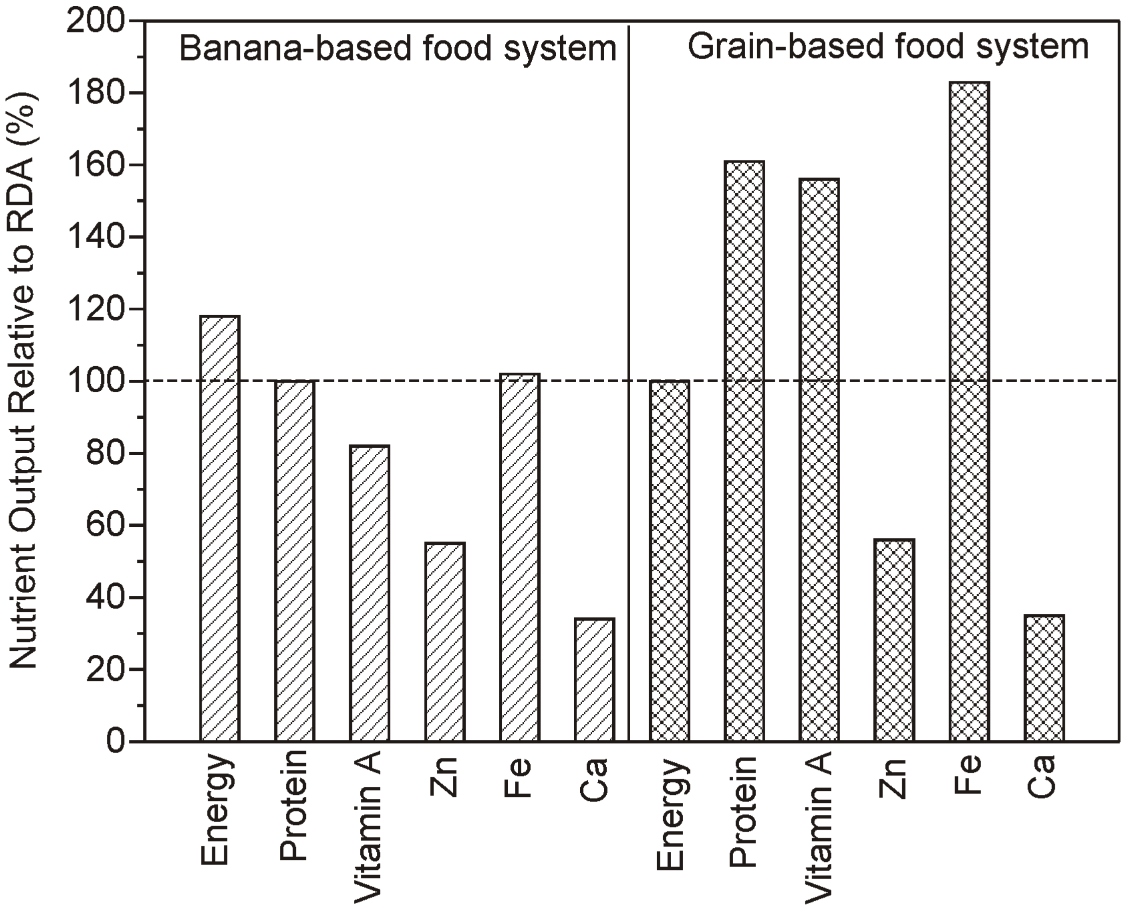

Per Capita Supply (kg year^{-1})
0
40
80
120
160
S. Korea
Taiwan
Recommended per capita supply
China
(73 kg year^{-1})
India
Vietnam
Sri Lanka
Asia
Thailand
Malaysia
Pakistan
Indonesia
Bangladesh
Philippines
Nepal
Bhutan
Selected Asian Nations

Figure 4


Banana-based food system
Grain-based food system
Nutrient Output Relative to RDA (%)
0
20
40
60
80
100
120
140
160
180
200
Energy
Protein
Vitamin A
Zn
Fe
Ca
Energy
Protein
Vitamin A
Zn
Fe
Ca