NUTRITIOUS SUBSISTENCE FOOD SYSTEMS

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Advances in Agronomy, Volume 92

0065-2113/07 $35.00
DOI: 10.1016/S0065-2113(04)92001-9

The major subsistence food systems of the world that feed resource-poor populations are identified and their capacity to supply essential nutrients in reasonable balance to the people dependent on them has been considered for some of these with a view to overcoming their nutrient limitations in sound agronomic and sustainable ways. The approach discusses possible cropping system improvements and alternatives in terms of crop combinations, external mineral supply, additional crops, and the potential for breeding staples in order to enhance their nutritional balance while maintaining or improving the sustainability and dietary, agronomic, and societal acceptability of the system. The conceptual framework calls for attention first to balancing crop nutrition that in nearly every case will also increase crop productivity, allowing sufficient staple to be produced on less land so that the remaining land can be devoted to more nutrient-dense and nutrient-balancing crops. Once this is achieved, the additional requirements of humans and animals (vitamins, selenium, and iodine) can be addressed. Case studies illustrate principles and strategies. This chapter is a proposal to widen the range of tools and strategies that could be adopted in the HarvestPlus Challenge Program to achieve its goals of eliminating micronutrient deficiencies in the food systems of resource-poor countries.

I. INTRODUCTION

Life cannot exist without continuous supplies in adequate amounts of all essential nutrients. If even one nutrient is limiting or missing from the nutrient medium or diet of an organism, the organism will suffer and ultimately die. Thus, nutrient supplies form the basis of all life on earth. Humans are no exception. Indeed, massive numbers of people are dying each year because of a lack of sufficient nutrients to thrive. The magnitude of this crisis in human health is appalling with annually over 50% of all deaths on earth associated with malnutrition (World Health Organization, 2003). In 2003 this amounted to about 30 million deaths mostly among the resource-poor people in developing countries (Muller and Krawinkel, 2005; World Health Organization, 2003). Incredibly, approximately one (i.e., 0.95) person dies of diet-related diseases every second. No other causes

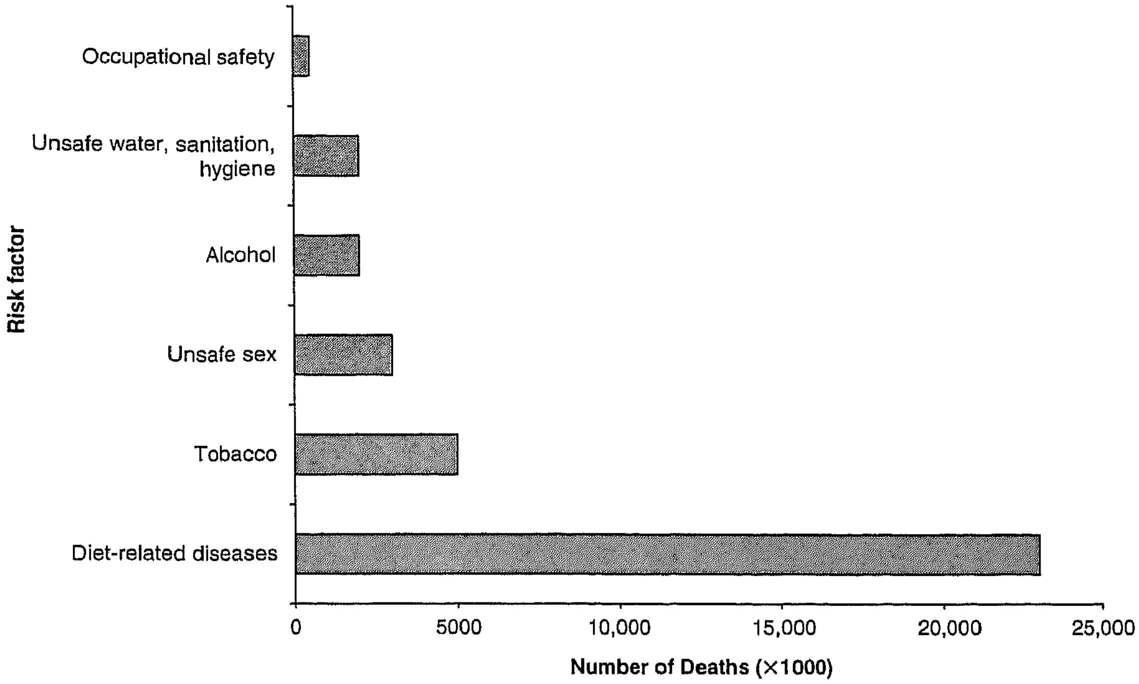

Figure 1 Global human deaths in 2002 related to various risk factors (data from the World Health Report, World Health Organization, 2002).

of death (Fig. 1) and related misery even come close. Importantly, these deaths are preventable if sustainable solutions to malnutrition are implemented.

Micronutrient malnutrition alone [e.g., iron (Fe), iodine (I), selenium (Se), zinc (Zn), and various vitamin deficiencies] afflicts over 3 billion people worldwide (Mason and Garcia, 1993). The consequences to human health, felicity, livelihoods, and national development are staggering, resulting in increased mortality and morbidity rates, decreased worker productivity and poverty. These circumstances are associated with and indeed begin with diminished cognitive ability and lower educational potential in children born to deficient mothers (Bhaskaram, 2002; World Health Organization, 2002). Dr. Bro Harlem Brundtland (Director General, World Health Organization, United Nations) declared at the World Economic Forum in 2000 that:

> Nutrition is a key element to any strategy to reduce the global burden of disease. Hunger, malnutrition, obesity and unsafe food all cause disease, and better nutrition will translate into large improvements in health among all of us, irrespective of our wealth and home country.
>
> (World Health Organization, 2002)

Further, the World Health Organization's 2002 World Health Report states that inadequate food and its poor nutritive value lead to a downward spiral of increased susceptibility to illness and loss of livelihood, ending in premature death. Micronutrient deficiencies continue to increase in many nations. For example, the global burden of Fe deficiency has risen from about 35% of the world's population in 1960 to over 50% in 2000 (World Health Organization, 2002) and the population during this time had almost doubled. Fe deficiency among poor women is increasing at an alarming rate in many developing countries. Current intervention programs (i.e., food fortification and supplementation programs) to alleviate the problem have not proven to be effective or sustainable in many countries (Darnton-Hill, 1999). Furthermore, globally these programs have been limited to addressing only Fe, I, and vitamin A deficiencies, often singly, with no global programs currently planned for addressing other limiting essential nutrients in the diets of the poor, not to mention the necessity of addressing all limiting nutrients together.

The US National Academy of Sciences held a workshop in 2003 titled "Exploring a vision: Integrating knowledge for food and health" where attendees recommended a new paradigm for agriculture, one that closely links agriculture to human health. At that meeting, Dr. Charles Muscoplat, Dean, College of Agriculture, Food, and Environmental Sciences, University of Minnesota stated:

It is time for the United States to shift to a new agricultural paradigm—one based on both what is good for the consumer and profitable for farmers.

The workshop recommended that new research was needed to address the gaps at the intersection of agriculture and food, food and people, and people and health (Fig. 2).

At the 57th World Health Assembly in 2004, malnutrition (both undernutrition and nutritional deficiencies) was acknowledged as a major cause of death and disease globally (World Health Organization, 2004). Noncommunicable diseases were recognized as being in crisis proportions in developed countries and rapidly increasing in developing nations. In 2001, chronic diseases (many diet related) accounted for almost 60% of the 56 million deaths annually and 47% of the global burden of disease. It was recommended that national food and agricultural policies be consistent with the protection and promotion of public health. Member States were asked to take healthy nutrition into account in their agricultural policies.

In 2004, leading economists from around the world met in Copenhagen, Denmark to rank the 10 most important global challenges that nations should invest in. From that meeting the Copenhagen Consensus was born which included the top 10 challenges facing the world today. Two of the top 10 challenges in the Copenhagen Consensus (numbered 2 and 5) included: malnutrition—providing micronutrients to meet human needs, and development of new agricultural technologies to address malnutrition (Copenhagen

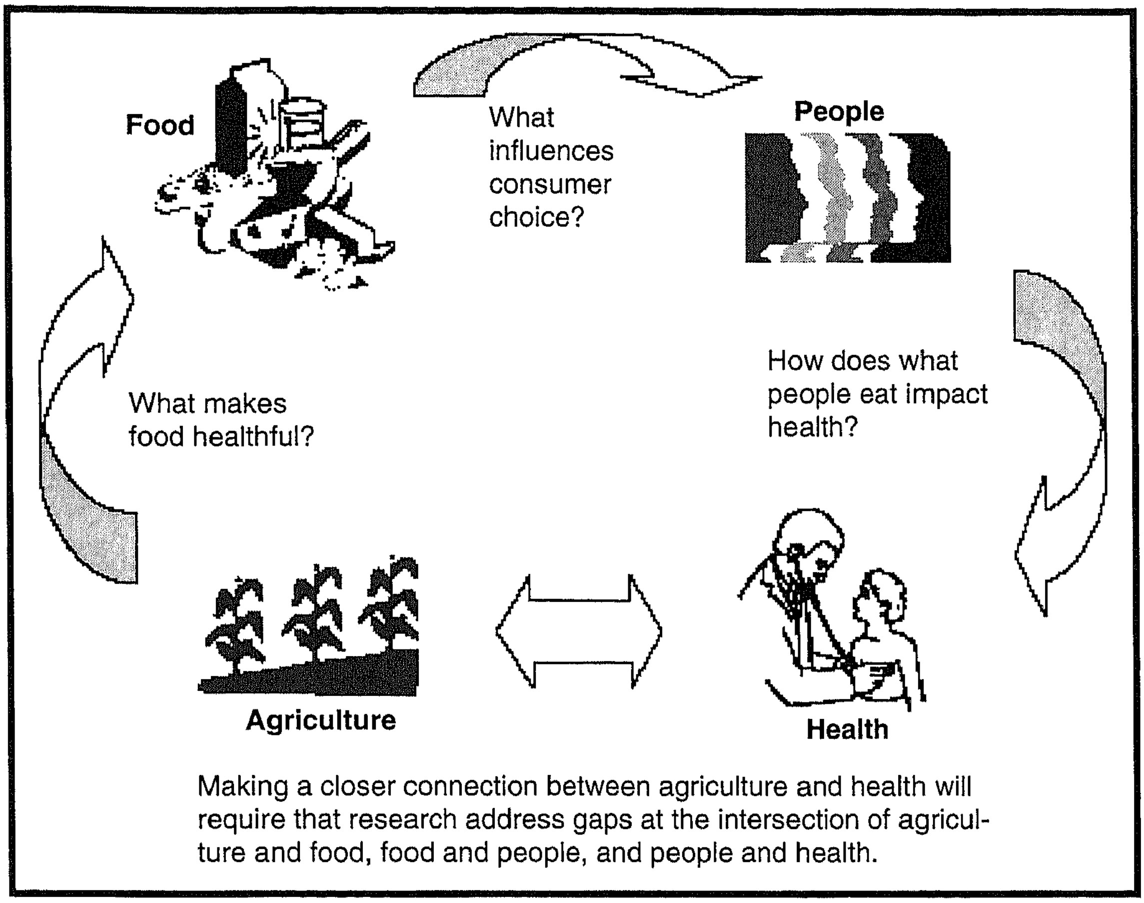

Figure 2 Table to farm: A new agriculture paradigm, linking agriculture to human health, modified from Rouse and Davis (2004).

Consensus, 2004). Thus, the world's most respected economists recognized the importance of linking agriculture to human health.

This global crisis in malnutrition is the result of dysfunctional food systems that cannot deliver enough essential nutrients to meet the requirements of all. Because agriculture is the primary source of all nutrients (excluding water and oxygen) for humans, agricultural systems must be contributing to this failure to meet nutritional needs (Welch *et al.*, 1997). How can agricultural systems be changed in ways that will result in enough nutrient output of farming systems to assure adequate nutrition for all? Importantly, if agricultural technologies are directed at improving the nutritional quality of food crops, they must encompass a holistic food system perspective to assure that the intervention will be sustainable, and adopted by farmers and consumers. Further, the agriculture sector must adopt a specific goal of improving human nutrition and health, and the nutrition and health sectors must adopt agricultural interventions as a primary tool to fight malnutrition (Welch and Graham, 1999).

II. FOOD SYSTEMS, DIET, AND DISEASE

Humans require at least 51 known nutrients (Fig. 3), in adequate amounts, consistently, to live healthy and productive lives. Unfortunately, global food systems are failing to provide adequate quantities of all of these essential nutrients to vast numbers of people. Advances in crop production, incurred during the Green Revolution, were dependent mostly on improvements in cereal cropping systems (rice, wheat, and maize) and resulted in greatly increased food supplies for the world, preventing mass starvation in many nations. However, cereals as normally eaten only supply needed carbohydrates for energy, a modest amount of protein but few other nutrients in required amounts. This change in agricultural production toward systems of cereal monoculture and away from more varied cropping systems appears to be contributing to micronutrient deficiencies by limiting food crop diversity (Welch, 2001a). This has had the unforeseen consequences of reducing available micronutrient supplies to resource-poor populations

The known 51 essential nutrients for sustaining human life*					
Air, Water and Energy (3)	**Protein (amino acids)** (9)	**Lipids-Fat (fatty acids)** (2)	**Macro-minerals** (7)	**Trace elements** (17)	**Vitamins** (13)
Oxygen	Histidine	Linoleic acid	Na	Fe	A
Water	Isoleucine	Linolenic acid	K	Zn	D
Carbohydrates	Leucine		Ca	Cu	E
	Lysine		Mg	Mn	K
	Methionine		S	I	C (Ascorbic acid)
	Phenylalanine		P	F	B_1 (Thiamine)
	Threonine		Cl	Se	B_2 (Riboflavin)
	Tryptophan			Si	B_3 (Niacin)
	Valine			Mo	B_5 (Pantothenic acid)
				Co (in B_{12})	B_6 (Pyroxidine)
				B**	B_7/H (Biotin)
				Ni**	B_9 (Folic acid, folacin)
				Cr**	B_{12} (Cobalamin)
				V**	
				As**	
				Li**	
				Sn**	

*Numerous other beneficial substances in food are also known to contribute to good health.

** Not generally recognized as essential but some supporting evidence published.

Figure 3 The known essential nutrients for sustaining human life, modified from Welch and Graham (2004).

formerly dependent on more diverse cropping systems which provided more traditional micronutrient-rich food crops such as pulses, fruits, and certain vegetables that are now in low supply and no longer affordable to this sector of society (Graham *et al.*, 2001; Tontisirin *et al.*, 2002).

Nutrition transitions in rapidly developing nations are also causing increased rates of chronic diseases (e.g., cancer, heart disease, diabetes, obesity, osteoporosis, and so on) where people are shifting from traditional diets to more calorie-rich diets derived from adopting developed nations' food systems (Clugston and Smith, 2002). There is an urgent need to tightly link the agricultural and food processing sectors to human health to find ways to reduce the burden of diet-related diseases in the world.

A. Farming for Health

There are numerous ways in which agriculture can contribute to improving human nutrition and health. Of high priority is increasing the output of micronutrients in staple food crops from farming systems to meet human needs, utilizing genetic variation within crop germplasm banks (biofortification), applying fertilizers, diversifying food systems, and increasing income (Graham *et al.*, 2001). Agriculture must be closely linked to human health if we are to find sustainable solutions to nutrient deficiencies afflicting the lives and health of massive numbers of people globally.

B. The Bioavailability Imperative

"You are not what you eat. You are what you eat and do not excrete." This is because not all of the nutrients consumed in meals can be absorbed and utilized in the body (i.e., not all nutrients in diet matrices are "bioavailable") because of various interactions that operate in the digestive system. Various antinutrients (substances, especially in staple plant foods, which inhibit the bioavailability of nutrients) can dramatically reduce the amount of a nutrient that is absorbable from a meal. However, other substances (promoters) can counteract the negative effects of antinutrients on nutrient bioavailability. Thus, it is imperative that agriculture not only increases the levels of nutrients in staple plant foods but also attend to the effects of antinutrients by enhancing content of promoters. In this chapter, there is not enough room to discuss the implications of bioavailability to improving the nutritional quality of plant foods. Various review articles are available for those interested in pursuing this aspect of the nutritional quality of staple plant foods (refer to Lopez and Martos, 2004; van het Hof *et al.*, 2000; Welch, 2002a,b).

III. AGRICULTURAL INTERVENTIONS TO DELIVER INDIVIDUAL LIMITING NUTRIENTS

There are several strategies that can be deployed in agriculture to increase the delivery of nutrients to people dependent on its production. Plant breeding is a highly favored strategy because appropriate new varieties are readily accepted by farmers. This has been well demonstrated by the large numbers of small producers who accepted and benefited from the new, high yielding varieties of the Green Revolution. On the whole, this approach requires the least change in behavior on the part of the subsistence farmer, so impact can be high. Of course, to be acceptable, these new, more nutritious varieties must satisfy the profit criteria that any other new variety must in order to be widely grown: high yield and acceptable cooking/eating quality.

Nutrient content also can be increased by use of fertilizers, both mineral and organic. Fertilizer use is common in Asia but much less so in Africa in spite of the fact that Africa's soils are often highly infertile. Fertilizers are relatively expensive and all other determinants of production must be reasonably well optimized for fertilizer use to be economic, and so resistance on the part of farmers is more common than with the use of new varieties. Nevertheless, for some nutrients commonly deficient in agricultural soils [nitrogen (N), phosphorus (P), potassium (K), sulfur (S), Zn], it is possible to boost nutrient content more by fertilizer use than through plant breeding. If this also increases yield, it is generally profitable for farmers to use fertilizer for the yield and profit advantage, and the superior nutrient content is a bonus without additional cost to the farmer. Other agronomic practices can also affect nutrient concentration in foodstuffs: gypsum, lime, green manures, minimum tillage, and intercropping. The remaining intervention of concern in this concept paper is to alter the cropping mix to create or recreate diet diversity in order to balance the nutrient supply to the diet by exploiting the differences in nutrient content of various crops. Diet diversity was lost during the Green Revolution with its emphasis on high yielding cereals. As the population continues to grow, although fortunately not at such high rates (Lutz *et al.*, 2001), it is quite difficult to turn the clock back to a time when diet diversity was much richer than now. However, we argue here that it is possible with the use of best-practice agronomy on the main staples to maximize yields, allowing the subsistence farmer the luxury of devoting less land to cereal production and more to secondary crops that diversify the diet and help to balance the nutrients delivered by the food system. Combining all three tools, breeding, fertilizers, and diversifying diets, is obviously complicated to implement with sustainability, economic viability, and societal acceptability, but their complementarities offer the best prospects of eliminating micronutrient deficiencies and reducing diet-related chronic diseases that threaten more than half of the world's people.

A. THE PLANT BREEDING STRATEGY

A plant breeding strategy is currently employed by the HarvestPlus Challenge Program to improve diets in resource-poor populations by enhancing micronutrient density (coined "biofortification") in major staple crops (Graham *et al.*, 2001). The HarvestPlus strategy focuses on enriching 6 major staples for Fe, Zn, and β-carotene density, and collecting preliminary genetic data on these traits for 10 other important staples. Enriched new varieties must have high yield and cooking quality to ensure they are widely grown. Genetic variation for each of these traits has been found in all crops investigated (Graham *et al.*, 1999) but with Fe and Zn that are nutrients not only for humans but for the crop too, a high genotype × environment interaction has been found that makes the breeding effort more complicated and breeding progress slower. For β-carotene that is synthesized by the plant and is not a nutrient taken from the soil (that varies from place to place), the breeding is much simpler; moreover, the yellow pigment in the edible parts is easy to see so that once the pigmentation has been confirmed to be due to β-carotene, selection in segregating populations can in large part be done rapidly by eye or simple color meter. Across a number of crops the inheritance of β-carotene or other carotenoids appears to be simple, frequently due to one or two genes in any given cross. On the other hand, for Fe or Zn in seeds or grains, several uptake, translocation, and grain-loading genes may be involved in each of these components of the pathway from soil to seed. Moreover, as mentioned already, the content and availability of these nutrients in each soil and the effects of climate and season all impinge on the final concentration measured in the seed.

We argue that a better strategy is to breed for more of certain plant-synthesized substances that promote the absorption by the gut of the Fe and Zn present in the grain, or to breed to decrease the inhibitors of absorption. Among the promoters are vitamins A and C, sulfur amino acids, and prebiotic nondigestible polysaccharides such as inulin and resistant starch. These prebiotics pass the small intestine undigested but get metabolized in the colon by ubiquitous strains of beneficial bacteria (e.g., bifidobacteria and lactobacilli) that are able to degrade these indigestible carbohydrates and through release of short chain fatty acids, and induced transporters in the mucosal cell membrane can enhance absorption of calcium (Ca), magnesium (Mg), Fe and Zn (Van Loo, 2004; Yeung *et al.*, 2005). Vitamin C, usually high in fresh root and tuber staples, is a strong promoter of absorption of Fe from seeds and grains. Vitamin A and β-carotene also enhance the utilization of Fe and Zn from bound forms in grains, as do sulfur amino acids under some conditions.

On the other hand, certain tannins and other polyphenols inhibit the absorption of Fe from staples. Low-polyphenol varieties have shown better bioavailability of Fe in tests (Glahn *et al.*, 2005), although health benefits in relation to chronic diseases may accrue from many of these so-called antinutrient polyphenolics (Hasler, 2002), so to breed for low content is debatable.

B. FERTILIZER STRATEGIES

The nutrient requirements of higher plants differ materially from those of humans shown in Fig. 3 because most higher plants require only certain minerals [N, P, K, Ca, Mg, S, Fe, boron (B), Zn, copper (Cu), manganese (Mn), molybdenum (Mo), nickel (Ni), chlorine (Cl), possibly cobalt (Co) and Se], water, oxygen, carbon dioxide, and solar radiation from which they can synthesize all organic compounds they need. On the other hand, animals and humans require even more minerals than are known to be needed by plants, and in addition, they require some 25 or more preformed organic compounds in amounts varying from large to very small (Fig. 3).

Plants are able to supply all the known essential minerals for human diets even though they may not necessarily require all of them for their own growth. In particular, plants contain Se, I, and Co (in column 5 of Fig. 3) and their concentrations may be enough to satisfy human requirements fully if the soils on which they grow are not too poor. However, probably half of all soils are deficient in one of these three ultra-micronutrients (daily requirements about 100 times less than those of Fe and Zn) and although plant production is not restricted, humans dependent on crops for most of their diet can be deficient. Well over 1 billion people live in areas of Se-deficient soils, and a similar number live in areas of I-deficient soils. These soils can be fertilized with Se or I as the case may be in order to prevent these deficiencies in humans, but crop production is unlikely to be increased because of the smaller requirements for these elements by plants, if they are required at all. In these cases, there is no incentive for the farmer to use Se and/or I fertilizers unless the consumers are willing to pay more for the enriched product. The alternative is for government to legislate for I and/or Se to be added to fertilizers, such as urea, phosphate, or compound fertilizers, which may be used in these deficient areas. The fertilizer strategy has a particular advantage in that the nutrient has to pass through the crop and/or grazing animal to enter the human diet and this will ensure that overdose through misuse or misunderstanding is highly unlikely. This approach has been used with spectacular success using I in far western China (Cao *et al.*, 1994) and Se in Finland (Makela *et al.*, 1993).

Cobalt fertilizer may need to be used in some subsistence food systems where soil-available Co is low because Co is a constituent of cobalamin, vitamin B12. The diets of many resource-poor people in developing countries is so low in animal products that vitamin B12 deficiency is becoming of increasing concern to nutritionists (Stabler and Allen, 2004). Vitamin B12 for humans comes mostly from animal tissues. It is synthesized by rumen bacteria in ruminants and by other bacteria in nature, but not by plant or animal cells. All other organic requirements of humans can be sourced from plant products, and if vegetarians eat some animal products such as milk-based foods or honey, they can obtain enough vitamin B12 for health, provided soils have sufficient Co in the first place.

In all probability, essential micronutrients remain to be discovered, but it is already clear that these would be needed in only minute amounts, probably in the order of the 2 μg day^{-1} requirement of vitamin B12, a requirement that may be satisfied by eating small amounts of diverse and exotic fresh vegetables, herbs, and spices. No strategy discussed in this chapter deals directly with these unknown requirements, but increasing diet diversity per se will be dealt with after the discussion of Zn.

C. Zn DEFICIENCY IS IMPORTANT

The most widespread known nutritional deficiency in humans worldwide is that of Fe, but it is particularly ineffective as a fertilizer because it is quickly oxidized and made insoluble in soil. Significantly, Fe deficiency in humans can be due to causes other than Fe-deficient soils and low-Fe food crops. It can also be caused by Zn, vitamin A, β-carotene, I, Se, folate, or vitamin B12 deficiencies, as well as by certain gut bacteria, intestinal worms, and other human parasites and pathogens. But of all of these, Zn deficiency is the most widespread problem (Hotz and Brown, 2004; Wuehler *et al.*, 2005).

Half of the world's soils are deficient in Zn (Sillanpaa, 1982, 1990) but Zn fertilizers are remarkably effective; a single application may last for several years. Zn deficiency occurs in most environments and soil types, inorganic reactions with S and P controlling its solubility, whereas in biological systems, its solubility is controlled by complexation with amino, sulfhydryl, phosphate esters and carboxylic compounds and related polymers. In turn, Zn determines the functionality of many macromolecules by conformational changes that are extremely important in biology. Zn-containing enzymes are involved with DNA synthesis and repair and RNA synthesis and editing, and transcription, translation, and feedback control of these systems. It further binds to over 900 human proteins (11 times more than does Fe) and more than 500 proteins in plants (Gladyshev *et al.*, 2004), largely determinant of function. It is not surprising therefore the symptoms of Zn deficiency are many and varied, depending on the genotype. The concentration of Zn in average rock and soil is perhaps 100 times less than that of Fe, yet Zn acquired from soil participates in almost all processes and pathways in living organisms. It can be deemed the most important metabolic promoter among the 51 essential nutrients. Because Zn interacts with such a vast number of proteins, symptoms of Zn deficiency in humans are many and overlapping, and consequently many different disease states are associated with its deficiency. Under Zn deficiency, humans lose muscle mass to release Zn for maintenance of the Zn concentration in blood and vital organs. So unlike Fe, Zn deficiency is not easily diagnosed by blood analysis. In these respects, it is not surprising that Zn deficiency has been exceedingly difficult to diagnose in humans and animals. Deficiency of Zn is the ultimate "hidden hunger." However, a survey by Hotz and Brown (2004) of Zn in global diets resulted in a map of putative Zn deficiency (dietary Zn deficiency), and these authors estimated 2.6–3 billion people at risk. A map from this seminal work (Fig. 4) shows a distribution of low-Zn diets that is heavily concentrated on South Asia, Southeast Asia, and Africa, and reasonably mimics, for data so inherently different in nature, the map of Zn-deficient soils (Alloway, 2004).

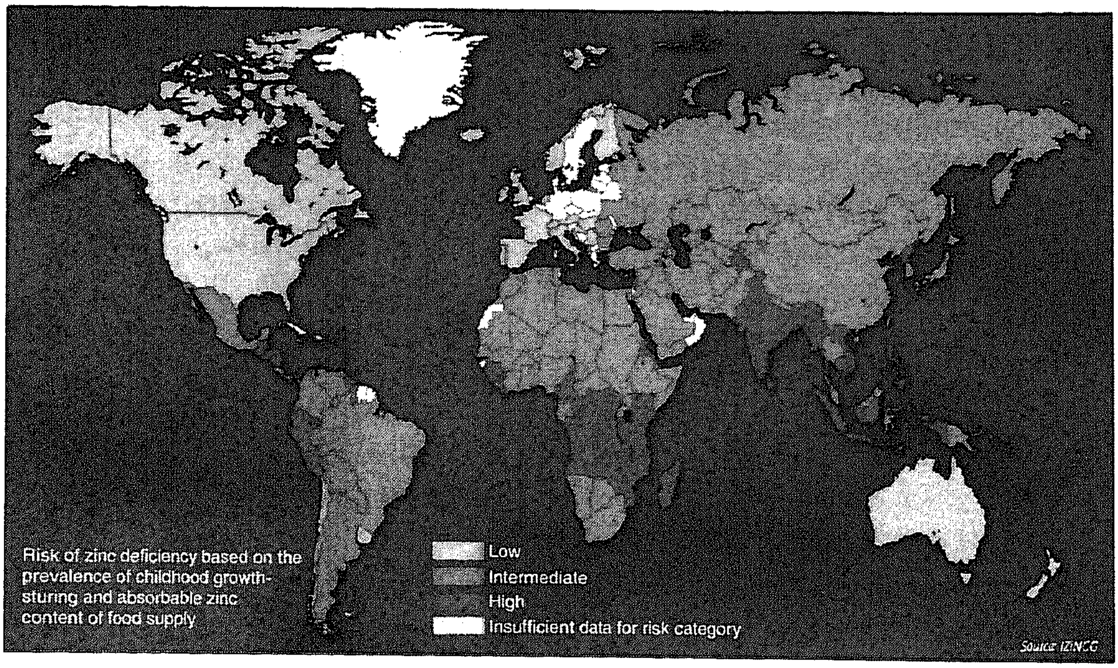

Figure 4 Global distribution of diets low in Zn (Hotz and Brown, 2004).

Among the changes in food/cropping systems brought about by the Green Revolution are the following:

- Loss of diet diversity toward more cereal-based diets lower in Zn
- Shift to higher pH soils and lower rainfall characteristic of cereal production
- Use of P fertilizers that tend to decrease Zn uptake
- Use of N fertilizers that tend to reduce Zn retranslocation from leaves to seeds

Each of these changes can decrease Zn in the diet, which may be viewed as an unexpected consequence of the Green Revolution. The rise of micronutrient deficiencies generally appears to be among covarying events of the Green Revolution and include, as well as Zn deficiency, Fe deficiency anemia and vitamin A deficiency in humans. We propose that the rise in Zn deficiency is fundamental and so a possible underlying causal factor in the other changes.

For all these reasons, addressing Zn deficiency is of the highest importance and excellent fertilizer strategies are available for almost any agroecosystem. Moreover, the widespread availability of the inductively coupled plasma (ICP) optical emission spectrometer makes certain the diagnosis of Zn-deficient crops and the safe use of Zn fertilizers (Graham, 2006).

D. DIET DIVERSIFICATION THROUGH FOOD SYSTEMS APPROACHES

The incidence of some micronutrient deficiencies can be dealt with by breeding more nutrient-dense crops (especially for Fe, Zn, and vitamin A deficiencies), whereas deficiencies of Zn, Se, and I can be best addressed by fertilizer strategies. Both these strategies are available to address Zn deficiency. However, for the two most important cereals, wheat and rice, and for beans, no genetic variation has been found in nature for β-carotene so for these crops currently conventional breeding programs are not an option, but food systems can be changed to introduce pro-vitamin A carotenoids into the diet from complementary foods. This is probably the single most important change that can be made to food systems by way of diet diversity.

The study that follows in Section IV.C is a special case of a dysfunctional food system in a poor area of Bangladesh where Ca is deficient in the diet especially for children. However, the general strategy can be used to address any dysfunctional food system, one that fails to deliver all essential nutrients in reasonable balance.

The approach is first to deal with the agronomy of the staple crop production. This position paper takes the view that low-input agriculture is unsustainable in the modern world because the population has increased beyond what can be sustained without modern inorganic fertilizers. Global ecologists have estimated that the sustainable human population of the planet is 2 billion (Evans, 1993, 1998), meaning in effect that more than 4 billion people could not survive without artificial fertilizers. If that is accepted, then even subsistence farmers need some fertilizer to compete effectively—to match the overall lower costs of production from the use of fertilizers, allowing farm families to pay for access to better education and health opportunities, as well as for diet diversification and better nutrition. Of course, this may require certain interventions by governments in facilitating access to credit and the manufacture/distribution of appropriate fertilizers, and the availability of experienced agronomists, although in many instances, all these services may be supplied by the private sector if the needs are properly identified. Therefore, we advocate first optimizing the nutrition of the existing staple crops.

When the crop is well nourished, the yield advantage should make production more profitable for the farmer. Moreover, dealing with micronutrient deficiencies as well as the basic NPK, lime, and S requirements means that many of the real or potential deficiencies in humans should be dealt with, but there are exceptions already mentioned: vitamins A and B12. Vitamin A can be dealt with by introducing a β-carotene-rich crop into the cropping system, which should be readily achievable because the increased productivity of the fertilized primary staple will allow some land to be freed for crop diversification. Field crops rich in β-carotene include selected varieties of pulses like cowpea, chickpea, the cereals maize and sorghum, root crops like cassava and orange-fleshed sweetpotato, and a variety of yellow, orange, and red vegetables and fruits. The other vitamin that is not addressed in the cropping system is vitamin B12, mentioned earlier, that needs to come from very small amounts of dairy, egg, or meat sources that ultimately depend on soil Co taken up by plants. It is necessary of course that the food system is developed with the community to ensure its sustainability, economic viability, and its acceptability in terms of foods provided and labor requirements.

IV. ANALYSIS OF SUBSISTENCE FOOD SYSTEMS

Food systems encompass activities related to production, acquisition, and utilization of foods that affect human nutrition and health (Bernstein, 2002). They comprise subsystems such as cropping systems (Christiansen, 1967; Pumisacho and Sherwood, 2002) and form part of wider livelihood systems (Ellis, 2000). Food systems strategies seek to address problems of food insecurity and malnutrition by understanding requirements for the production of and access to diverse foods to increase their supply, affordability, and their consumption.

Subsistence food systems evolve to optimize food production and quality in the face of limitations and variability in the environment, seed material, availability and affordability of inputs, and numbers of people dependent on them. In the last 40 years, there has been an acceleration of change in food systems following the population explosion of the human race that began after World War II. Under the threat of potential mass starvation, an international effort later dubbed the Green Revolution greatly increased production of cereals, especially rice, wheat, and maize, and in the two decades 1960–1980 restored the world to overall food sufficiency. Cereals now dominate food systems more than ever before. They have partly replaced legumes in food systems because of their greater yield, tolerance to biotic stresses, and wide adaptability: Fig. 8 shows that cereal production has increased at a faster rate and pulse production at a much slower rate than has population growth. In this chapter, the major food systems are identified by the dominant cereal component(s) and further by secondary staples.

Rice is the most important cereal; rice–based food systems feed over half of the human population, most notably in South, East, and Southeast Asia, but also provide a complementary staple throughout the world. Rice-based food systems include rice, rice–wheat, rice–pulse, and rice–fish systems that are discussed here. These days, rice is most commonly eaten after polishing, a process of abrading away the outer layers of the grain (after removing the hull or husk to convert "paddy" into "brown rice"). These outer layers, called the "bran," include the pericarp, seed coat, testa, and the nutrient-rich aleurone layer. In polishing, the aleurone and the germ, also rich in nutrients, are lost to the bran. The bran thus contains much of the Fe, Zn, Ca, vitamins, phytate, and some of the protein (Lauren *et al.*, 2001). Before the advent of electric milling machines in the villages, rice was processed for cooking by pounding or parboiling. Pounding is a milder process than modern milling and basically removes the pericarp and seed coat to allow faster water penetration during cooking, an important step as the cost of energy for cooking rice is significant for many resource-poor rice farmers. Pounding, by removing the tough seed coat and pericarp, also imparts a more refined taste. With the germ and aleurone largely intact, some farmers today still claim that pounded or brown rice is more sustaining and nutritious, essential for the hard work of growing the crop itself (Drs. Apichart Vanavichit and Girish Chandel, personal communication). In much of India and Bangladesh, brown rice is parboiled by steaming and redrying before milling. This brief hydration and redrying allows a milder milling so that more nutrients are retained in the rice while still achieving a product acceptable in appearance and eating quality. In India, 61% of rice is parboiled (Department of Agriculture and Cooperation, 2002), undoubtedly a positive factor in the nutrition of a largely vegetarian population.

Milling is a food processing issue of importance at least as great in terms of nutritional impact as other interventions discussed in this chapter. The Philippines has created a Foundation for Promotion of Eating Brown Rice (Cuyno, 2003) that has increased consumption of brown rice to about 10% of the total in a short time. Similar advocacy and education are needed for parboiled rice, wheat, yellow maize, and cassava and other staples processed into flour. Wheat is mostly milled before use. In subsistence food systems, this is done by stone grinding in which all the components of the grain, including the aleurone and germ, are retained in the cooked (wholemeal) products. Modern milling to white flour may be even more drastic than rice milling as pure endosperm (break flour) can be separated. On the other hand, sophisticated mills can now separate by various means all of the different layers of the wheat grain making possible flour of chosen nutritional composition, potentially a significant advance for nutrition.

Major wheat food systems include rice–wheat and wheat–pulse. The rice–wheat food system of South Asia and adjacent China covers 17 million ha and feeds in whole or in part about 1 billion people. Although wheat is necessarily grown on drained land (upland), most rice is wet (paddy) rice in which the land is flooded. This system allows rice to be grown in the wet season when the risk of flooding is high and wheat would fail, whereas wheat can be grown in the "dry," cooler season less conducive to high rice yields.

Maize is the most widely grown and productive cereal but more than half is used to feed animals, and so feeds humans indirectly. There are, however, important subsistence farming systems based on maize, notably in its origins of Central America and South America and in Africa. Maize is also an important crop in Asia where soils are too sandy and/or infertile for rice. Important maize-based subsistence food systems are: maize, maize–pulse (Africa), maize–bean, and maize–cassava (Mesoamerica).

Other important subsistence food systems are cassava, cassava–bean (Africa), potato, sweetpotato (Melanesia), and Andean potato-based mixed staple.

A selection of these major subsistence food systems has been described in this section, with the recognized agronomic and nutritional problems of the communities dependent on them. We describe examples of how the cropping system could be changed in potentially sustainable ways to deliver a more nutritionally balanced food system for improved health of the people dependent on the system.

We discuss several major food systems important in their own right because they feed billions of people, and others that are smaller in size but illustrate our concept of increasing nutrient output of food systems to improve human health. The principal concept held here is that a food system is only sustainable if it adequately supplies, year round, from internal or external sources, all the nutrients required for good health by the people who are dependent on the food system, including those who in subsistence systems are the drivers of the food system. An in-depth analysis of a system includes productivity, agronomic management practices, sustainability issues, and food composition values for the major crop components, as well as genetic and environmental variability and reliability of food composition data. Our aim is to identify strengths, weaknesses, and opportunities within a particular food system for enhancing its value to human nutrition and health of the dependent communities where problems are known to exist. The first system discussed is the large rice–wheat food system of South Asia and China.

A. The Rice–Wheat Food System

1. Introduction

Rice and wheat are the world's two most important food crops, contributing 45% of the digestible energy and 30% of total protein in the human diet (Evans, 1993). The rice–wheat cropping system is one of the most important in the developing world with approximately 17 Mha in South and East Asia. The distribution of this cropping system includes India, 10.5 Mha; Pakistan, 2.2 Mha; Nepal, 0.6 Mha; Bangladesh, 0.5 Mha; and China, 3.2 Mha (Dawe *et al.*, 2004; Timsina and Connor, 2001). This section will concentrate on the analysis of the rice–wheat cropping system in the Indo-Gangetic Plains (IGP).

Before the Green Revolution many of the wheat and particularly the rice varieties were photosensitive and/or of long duration resulting in difficulties in matching the planting dates of rice and wheat in a double cropping system. There was more crop diversity in the common mixed cropping systems where a number of crops were planted together like wheat with chickpea, mustard, lentil, flax, and others all in the same field. The intensification of the rice—wheat cropping system became feasible with the adoption of the shorter season, nonphotosensitive, higher yielding rice and wheat varieties, which, together with the development of new irrigation systems, increased fertilizer and pesticide use, resulted in the Green Revolution. Rice production in South Asia grew from 67 Mt in the early 1960s to 144 Mt in the early 1990s (Hobbs and Morris, 1996). During the same period, wheat production increased from 15 to 73 Mt. As productivity increased, farmers' incomes grew, staple food costs declined for low-income consumers, employment of landless laborers grew, and—indirectly—development of small rural industries was stimulated (Hobbs *et al.*, 1997). Although the benefits of the

Green Revolution are clear, India is now a country that has high levels of malnutrition despite large stocks of food grains.

2. Breeding Potential

Wheat screening has shown that the germplasm with the highest levels of Fe and Zn in the grain are the wild relatives, primitive wheats and landraces. There are reports of some entries with levels around 90–100 mg kg^{-1} of Zn (Cakmak, 2002; Monasterio and Graham, 2000). The HarvestPlus Challenge Program has adopted the target of increasing the concentrations of Zn in wheat grains by at least 10 mg kg^{-1}, and approximately 25 mg kg^{-1} for Fe in order to have measurable impact, assuming the percentage of bioavailable nutrient is similar (HarvestPlus website: www.harvestplus.org). Under the conditions of northwestern Mexico, Pakistan, and northwestern India, this means that the levels of Zn will have to be increased from the current 35 to a target 45 mg kg^{-1}, while for Fe it will have to be increased from 35 to 60 mg kg^{-1}. That the donor parents for high levels of Fe and Zn in the grain have levels above those required by human nutritionists suggests that breeding the required levels of Fe and Zn in the grain in modern varieties is an achievable goal even though there is significant environmental effect on Fe and Zn concentrations in wheat and numerous genes involved. The challenge is to be able to maintain the high levels of Fe and Zn present in the primitive and wild wheat, while keeping the high yields of the improved modern varieties. The adoption of biofortified varieties will not take place on the basis of micronutrient concentration in the grain, but rather in terms of their yield potential, disease resistance, and/or consumer acceptability.

There are reports of genetic variability for micronutrient concentration in brown rice with a range of 7.8–24.4 mg kg^{-1} in Fe and 15.9–58.5 mg kg^{-1} in Zn (Gregorio *et al.*, 2000). However, the overall mean values and variances found in polished rice seem to be much smaller, which suggests that using conventional breeding to increase levels of Fe and Zn in polished rice will be a bigger challenge than in wheat and may require a biotechnological approach. While most urban people in the IGP prefer to eat polished rice, there appears to be a trend developing for rural people to recognize and value the superior nutritional qualities of brown rice, pounded rice, or parboiled rice (less polished rice) that they consumed in earlier times Department of Agriculture and Cooperation (2003).

Screening for β-carotene in wheat and rice has not revealed any promising natural variability for this trait. All the yellow wheat samples analyzed so far present higher levels of lutein but not of β-carotene. The lack of natural variation for β-carotene in rice led to the development of genetically modified organism (GMO) rice varieties with high levels of β-carotene, which came to be known as "golden rice." The lack of variability observed for β-carotene in wheat so far suggests that a biotechnological approach similar to that used for rice may also be required in wheat.

A preliminary study found limited variability in Se and I concentrations in the grain of wheat and white rice (Lyons *et al.*, 2005a,b). This suggests that improvement for these nutrients through plant breeding would be slow, and probably impracticable where soils are low in these elements. On the other hand there are successful fortification initiatives to make I more available to the population using salt as a vehicle, and as these two elements are quite effective as fertilizers in increasing concentrations in grain, Se- and I-fortified fertilizers have the potential to be an even more sustainable strategy.

3. Agronomic Practices

Long term experiments on the rice–wheat rotation in South Asia and China have shown that there has been a significant decline in input productivity (Hobbs and Morris, 1996; Pingali *et al.*, 1997), resulting in farmers having to apply more inputs to obtain the same yields as previous harvests. This suggests that the sustainability of the rice–wheat cropping system should be reevaluated not only in terms of agronomic performance but also in terms of a food system that can provide the necessary nutrients to the target populations.

In India, it is estimated that 47% of the soils are Zn deficient (Katyal and Vlek, 1985). For example, a soil survey in India reported that out of 90,218 soil samples collected in the states of Bihar, Haryana, Punjab, Uttar Pradesh, and West Bengal, 51% of the soils were considered Zn deficient, 10% Fe deficient, 3% Mn deficient, and 2% Cu deficient. The state with the highest incidence of Zn and Fe deficiency was Haryana, while the lowest was West Bengal (Singh, 1999).

Zn deficiency is the main micronutrient problem reported in the soils of the IGP. This problem is more prevalent in rice than in wheat and this seems to be associated with two factors: (1) flooding of rice fields reduces Zn availability and (2) rice is more sensitive than wheat to Zn deficiency. However, problems of Zn deficiency have also been reported in wheat that can be corrected by soil applications of zink sulfate. Experiments in wheat have shown that soil, seed, and/or foliar application of Zn can be effective in increasing levels of Zn concentration in the grain (Cakmak, 2002). Moreover, high Zn seeds produce more vigorous seedlings in the next crop. Similarly, fertilizer studies have shown good responses in grain concentrations of

Se and I, indicating that crop fertilization is a viable strategy for Zn, Se, and I biofortification (Lyons *et al.*, 2005b).

Heavy rates of P fertilizer application to soils low in available Zn can induce Zn deficiency (Robson and Pitman, 1983). There are some indications of overfertilization with P (diammonium phosphate) in some areas of the IGP. In a survey of 105 soil samples, 60% contained levels of available P ranging from 35–120 kg ha^{-1}. This excess P application is likely to result in reduced accumulation of Zn in the grain of wheat and rice and a less favorable phytate to Zn ratio in the grain (Cakmak, 2002). Reports of Fe deficiency in the IGP rice–wheat system are restricted to rice in light-textured, high pH, and calcareous soils.

4. Nutritional Analysis of the Food System

The segment of the population with the most problems of micronutrient malnutrition is the poor, and within this group, especially children and women. According to Dixon *et al.* (2001) the typical poor family in the rice–wheat cropping areas has access, in addition to rice and wheat, to some vegetables and milk. While it is estimated that up to 50% of the milk production is consumed by the family (Hemme *et al.*, 2003), still, the production of vegetables and milk remain in short supply and not sufficient to cover all the nutritional needs of the family. There are also the landless poor in the rural areas and the urban poor that cannot grow their own crops and mostly buy them. The urban poor could also potentially benefit from biofortification of food staples.

Vitamin A deficiency is a serious problem in the rice–wheat area (Table I). This could be addressed by bringing into the food system a β-carotene-rich pulse crop, such as cowpea (summer) and chickpea (winter), or a cereal crop like high β-carotene yellow maize, or root crops like yellow/orange cassava and sweetpotato, and a variety of yellow, orange, green, and red vegetables and fruits. Cassava or sweetpotato in the IGP is found usually on the upper parts of the topography where rice is not grown and drainage is better. Many farmers in Bihar grow maize as a winter staple. In other areas maize is mainly grown as a fodder crop or for roasted sweet corn. All in all, there is sufficient potential to increase the β-carotene supply in this food system: promoting suitable yellow varieties and educating mothers and their families of its critical importance may be the needed drivers for change in this direction.

Another solution could be the adoption of golden rice, which is currently being tested in field trials. Golden rice is genetically engineered to contain β-carotene in the rice endosperm, which is later converted by the body into vitamin A; 70 g day^{-1} would provide the recommended daily allowance (RDA)

Table I
Fe, Zn, and Vitamin A Deficiency Estimates in India and Pakistan (Hotz and Brown, 2004; UNICEF and the Micronutrient Initiative, 2004)

Nutrient deficiency country	Number per year of child deaths	Children under 6 years (%)	Population at risk (%)
Fe deficiency anemia			
India	22,000	75	51[a]
Pakistan	–	56	59[a]
Vitamin A and Zn[b] deficiencies			
India	330,000	57	26[b]
Pakistan	56,000	35	11[b]

[a]Risk in women 15–49 years.
[b]Risk of inadequate Zn intake, entire population.

of vitamin A (Paine *et al.*, 2005). However, golden rice is yellow-orange in color and it is a GMO, so problems with adoption and acceptance must be overcome.

The prevalence of Fe deficiency anemia mainly in children and women is another important micronutrient malnutrition problem for the populations that live in the rice–wheat cropping system (Table I). The increase in anemia in the IGP during the Green Revolution has been attributed to the reduction in the consumption of legumes (Fig. 8). Although there is some consumption of legumes and vegetables, these are not sufficient. Legumes and green leafy vegetables need to play a more important role in the food system due to their content of Fe bioavailability promoters (Sections II and III).

A large proportion of the population in the rice–wheat area does not eat meat. This makes it more vulnerable to vitamin B12 deficiency, which needs to come from dairy, egg, or meat sources. However, recent increases in milk production in parts of India where the rice–wheat rotation is important promise to help reduce the problem with this vitamin, and also with I deficiency (Hemme *et al.*, 2003).

Protein content in legumes is significantly higher than in rice and wheat. In addition, there is an important difference in the amino acid composition of the protein. Wheat is deficient in the amino acid lysine, while rice has inadequate levels of lysine and threonine. In contrast, grain legumes are deficient in the S-containing amino acids, methionine, and cysteine. Combined consumption of cereals and grain legumes is common in South Asia, which results in almost complete essential amino acid balance and a nutritional improvement over cereal-based diets. Maximum protein nutrition is obtained when the grain legume content is about 10% in a wheat-legume diet, and about 20% in a diet with rice, maize, or barley (Lauren *et al.*, 2001) but these are levels that have not been adequately met since the Green Revolution (Fig. 8).

5. Diversification of the Rice–Wheat Rotation

In the analysis of the food system, the importance of diversifying the rice–wheat system to improve human nutrition was addressed. In this section, the agronomic feasibility of diversifying the system is discussed.

In the Trans-Gangetic Plain and in the western part of the Upper-Gangetic Plains, rice–wheat systems mostly include an indica-type monsoon rice and a spring wheat because there is generally insufficient time for a third crop. In the Punjab, covering parts of northern India and Pakistan, in addition to Haryana and parts of western Uttar Pradesh, Basmati rice is a popular cash crop. There, the rice crop is generally transplanted from May to July and harvested from late October to late November. Wheat is then grown from November/December and even into January to March in warmer areas and to May in cooler parts of Pakistan (Timsina and Connor, 2001). In this area, the best chance for diversification would be to replace part of either rice or wheat with a different crop. In the eastern part of Upper-Gangetic Plains, and in the Middle- and Lower-Gangetic Plains where temperatures are generally higher, monsoon rice is grown from June/July to October/November, and wheat from November/December to March/April. There, rice–wheat systems often include an additional crop [e.g., mungbean (*Vigna radiate*), cowpea (*V. unguiculata*), dhaincha (*Sesbania* spp.)], after wheat or before rice and less frequently, cowpea, mustard (*Brassica juncea*), and potato (*Solanum tuberosum*) after rice or before wheat (Timsina and Connor, 2001). Rice–potato is now one of the most common rotations in the IGP (Section IV.B).

In the northeast and eastern IGP, unpredictable heavy rains during sowing and emergence (ca. 20% of years) reduce establishment of legumes and cause ineffective root nodulation, while more frequent rains (ca. 80% of years) during reproductive growth cause abortion of flower buds, and pods, and reduce grain yield and quality. Thus, high rainfall and waterlogging appear to be a major constraint to the successful inclusion of legumes as premonsoonal crops in rice–wheat systems of the Middle- and Lower-Gangetic Plains. Therefore, new cultivars are required of legumes and other crops that can germinate, emerge, and establish under transient waterlogging, and are also able to complete grain filling and maintain grain quality under heavy rain. Planting legumes on raised beds should alleviate waterlogging problems (Timsina and Connor, 2001). There are reports of 15–47% increase in the yield of legumes when planted on raised beds compared to planting on the flat in the IGP (Connor *et al.*, 2003).

Inclusion of legume crops in the rice–wheat cropping system could potentially have a number of agronomic advantages, for example, biological N fixation if there is good nodulation, nutrient cycling from deeper soil layers, and breaking of weed and pest cycles.

In the mid and lower reaches of the IGP, there is usually a 60–70 day period between wheat harvesting and rice transplanting that could potentially be used for the inclusion of a third crop in the rice–wheat cropping system. The third crop could be an edible legume, (Ahlawat *et al.*, 1998; Dwivedi *et al.*, 2003), and development of short-duration summer varieties of crops like black gram, green gram, mungbean, and pigeon pea, with adequate insect and disease resistance, could potentially be used to diversify the rice–wheat cropping system, particularly when grown on a raised bed system. There is little information about the potential of fruits and vegetables for diversification in the rice–wheat system, but wider adoption of them should also be beneficial.

However the rice–wheat system is diversified, if it is to have a nutritional benefit to the rural communities, the additional food crop must be consumed and become a part of the normal diet, not merely marketed. On occasions, this may require some inputs into education of the health benefits and aspects of consumption.

B. Rice/Potato-Based Food Systems in the IGP

1. Introduction

Although rice–wheat is the dominant system in the IGP, there are many other important cropping systems practiced by farmers for sustainable livelihoods. The kharif (wet season) rice–potato–boro (summer season) rice is the emerging cropping system in Eastern IGP (Bangladesh and West Bengal, India). Since the early 1970s, potato production has increased more rapidly in the irrigated subtropical low lands of Asia than in any other part of the world. The most impressive example of the area expansion occurred in West Bengal, where land cultivated to potato expanded fivefold over the past 25 years (Bardhan Roy *et al.*, 1999).

2. Cropping Systems

The role of potato relative to wheat in the cropping systems is influenced by temperature that in turn depends on latitude and altitude. Irrigation within

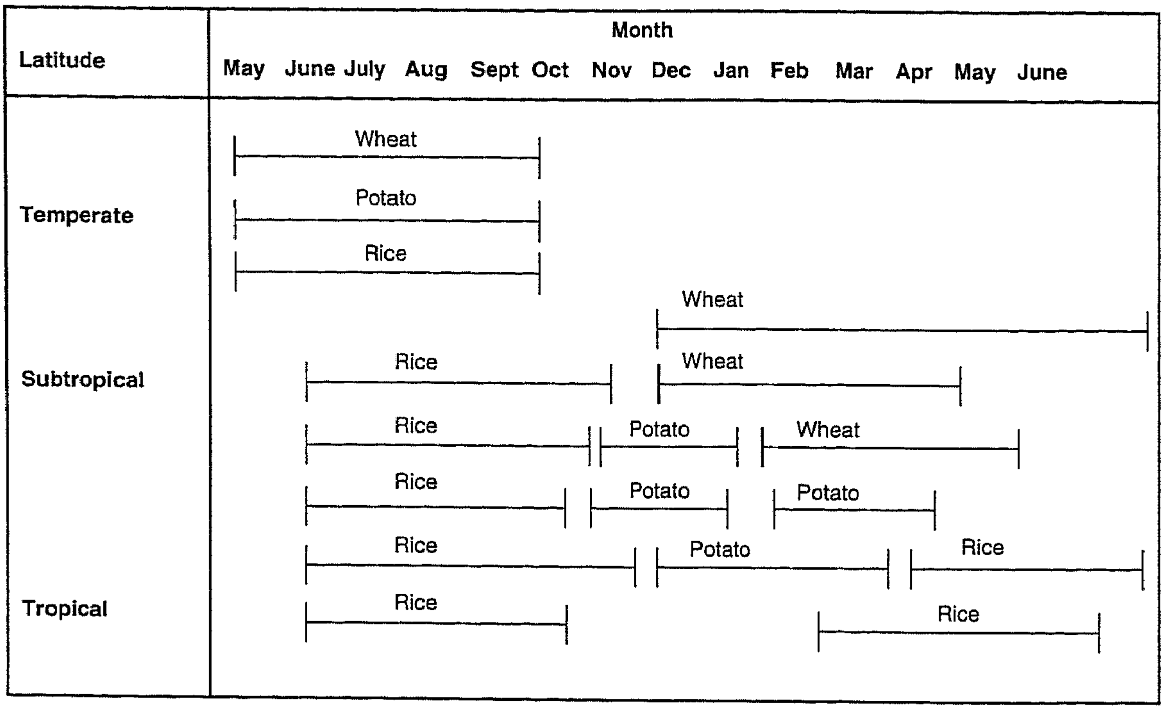

Figure 5 The roles of potato and wheat in rice-based cropping systems by latitude.

the temperate to subtropical zones in Asia can support all the cropping patterns of rice, wheat, and potato described in Fig. 5.

More than 80% of potato is cultivated after kharif (wet season) rice in the IGP. In selected agroecologies of North and Northwest India (Punjab, Haryana, and West Uttar Pradesh) and Punjab of Pakistan adjoining India, where the winter is prolonged, some farmers practice potato–wheat–rice. The early bulking potato varieties are planted in September/October and harvested in November/December. After potato harvest, the farmers sow wheat. The costs for land preparation and fertilizer requirements for wheat are reduced following potato. Where there is a longer winter, farmers can grow two crops of potato due to low aphid populations and economic bulking rate in both crops under the cooler temperatures. However, this pattern cannot be followed in the short, mild winters of Eastern and Central IGP. The cultivation of 80- to 90-day potato varieties does not allow sufficient time for wheat. Consequently, farmers plant either wheat or potato.

3. Crop Diversification

Fertile land and enhanced irrigation facilities provide farmers with opportunities for crop diversification and intensification. With the introduction of new, high-yielding cultivars and improved technologies, the cropping systems are changing rapidly. For example in the IGP of West Bengal, rice–potato–sesame, rice–potato–mustard, and rice–potato–jute cropping systems are being replaced by rice–potato–boro rice, rice–potato–groundnut, and rice–potato–vegetables (Bardhan Roy *et al.*, 1999). Diversification currently aims to increase productivity by the introduction into the rotations of alternate vegetables, field crops, fruit crops, flowers, and other options (Modgal, 1998), but ideally, diversification should also aim at improving diet diversity and nutritional balance for the farm families and the local population dependent on them. This will require further technology development and extension to accompany the new options at the farm level.

4. Limitations to Crop Diversification

Crop diversification depends on many factors such as physical, economic, marketing facilities, consumer demand, location specific technology, and suitable crop varieties. The IGP largely consist of hot subhumid and hot humid eco-regions with alluvium-derived soils (ICAR, 1990). The abiotic factors (rainfall, temperature, photoperiod, nutrients), availability of location-specific appropriate technologies, socioeconomic conditions of farmers, and marketing opportunities are factors that define the cropping pattern in a region. For example, the wide adoption of boro rice (summer rice) and groundnut due to increased productivity and enhanced income of farmers in some parts of West Bengal have changed the cropping pattern from rice–jute and rice–mustard to kharif rice (wet season)–potato–boro rice and kharif rice–potato–groundnut. The expansion of potato production has been impressive in the irrigated lowlands of South Asia. This growth in potato production can be attributed to the crop's ability to produce large amounts of food in short periods of time under conditions of land scarcity fuelled by population pressure. Illustrating the potato's contribution to satisfying food demand from population pressure, production in Bangladesh has tripled since the mid-1960s and about 40% of potatoes are now produced in Dhaka (Munshigoni), the most populous district of the country and an area where potato production share was slightly more than 10% prior to the Green Revolution.

5. Profitability and Sustainability of Potato–Rice System in the IGP

With the help of staff of the International Potato Center, activities in the IGP now take a commodity perspective and address the following issues: the potential for intensifying potato production, suitable varieties, displacement effects caused by introducing potato into various cropping systems, interactions between potatoes and other crops in the system, and the implications for natural resource management of intensifying potato production. For example, potato was introduced with maize as an intercrop with rice in North Bihar and between rice–wheat and rice–onion in South Bihar, based on the results of participatory trials that optimized varieties and management practices for specific locations, leading to greater productivity and enhanced profitability. In Bangladesh, potato was introduced into the wheat–rice cropping system in Dinajpur district, northern Bangladesh where the enhanced income from the rice–potato cropping pattern soon became apparent.

6. Intensification of Potato and Rice by Double Transplanting Technology

Rice is a staple food and potato an important cash crop for farmers in the subtropical Eastern IGP. The areas under rice and potato are 15 and 0.8 million ha, respectively. In the last 5 years, potato area has increased by about 10%, although the farmers face overproduction about every 3–4 years, and also potato is more vulnerable to abiotic and biotic stresses. The farmers continue with potato cultivation due to the net return from potato being, on average, significantly higher than for other crops. Kharif rice–potato–boro rice and kharif rice–boro rice are the cropping systems that dominate this region. Cultivation of potato and boro rice in sequence affects productivity of both crops due to an early harvest of potato or a delayed planting of boro rice. Researchers introduced double transplanting of boro rice in West Bengal with an objective to enhance the productivity by more efficient management of natural resources. Briefly the double transplanting system is as follows: rice nursery seedbeds are sown 8 days after potato planting, 40–45 days later the seedlings are sown into a larger plot, 10 seedlings per hill at 15 × 15 cm spacing, 40–45 days later the rice is transplanted for the second time, 5 tillers per hill at 20 × 15 cm spacing immediately after potato harvest at about 90 days after planting. All this allows summer rice to be established in main field after potato by the end of February to obtain maximum yields. The interpolation of user-friendly double transplanting technology in the kharif rice–potato–boro rice has provided better use of natural resources, leading to a potential per hectare benefit of US $143 compared to rice–potato–rice using traditional planting.

7. Nutritional Benefits of Potato

Potato provides carbohydrates, proteins, minerals, vitamin C, B group vitamins, carotenoids (in yellow types), and high-quality dietary fiber.

The net protein utilization or biological value of potato protein (about 71% that of whole egg) is higher than the other components of this food system, wheat (53%), maize (54%), peas (48%), and beans (46%), and is comparable to cows' milk (75%) (Gopalan *et al.*, 1972). The vitamin C of potato can enhance the bioavailability of nonheme dietary Fe such as phytate-bound Fe in co-ingested cereal or legume seeds, an important benefit for farmers growing potato who would otherwise use the potato as a cash crop rather than a beneficial component of the family diet. A detailed analysis of potato is presented in Section IV.E.

C. A Case Study: The Dysfunctional Rice–Pulse Food System of Southeast Bangladesh

The rice–pulse food system is a major subsistence farming system in eastern South Asia, including Bangladesh, Bihar, West Bengal, and Assam. While flooded rice dominates the fields of these areas, the secondary staple comes from one or more leguminous grain crops grown in the dry season, while in the same region an alternative secondary "staple" to rice comes from small dried fish caught in the rice paddies.

In the southeast panhandle of Bangladesh that has double monsoonal rainfall peaks each year and population density is high, this food system has changed in the last two or three decades. Under the pressure of high population, subsistence farmers have been forced to grow another rice crop in lieu of the pulse (in this case, cowpea) in order to produce enough calories for the growing numbers of mouths to feed (FAO, 1999). Whereas in their culture, these people describe themselves as "rice and pulse eaters," pulses have not kept up with the increasing population pressures, retaining the low productivity of decades ago (Fig. 8). While the near year-round rainfall can support up to three crops of rice per year; yields are low, yet the yield from the rice crop is generally higher and more environmentally stable than that from pulses. Modern rice generally has higher potential yield and less susceptibility to diseases. Under these circumstances, the change to less pulses and more rice is understandable but population growth and consequent changes in the food system have wrought a heavy cost in health and well-being, as the outside world discovered about 12 years ago (Cimma *et al.*, 1997).

About 10% of the children in the Chakaria district of the Bangladeshi Panhandle have rickets, weak and distorted bones, with potentially up to 50% of children with lesser symptoms. Rickets is a disease well known in northern European countries a century ago where it was shown to be due to deficiency of vitamin D, a cofactor in deposition of Ca in bones, the disease resulting from too little sunlight for sufficient biosynthesis of vitamin D in

Table II
Ca in Crops of Chakaria Village (Welsh, 2001b)

Crop	Ca concentration (mg kg^{-1})	References
Rice	89	Cimma *et al.* (1997)
Rice	107	Welch (2001b)
Chick pea	458	Welch (2001b)
Lentil	330	Welch (2001b)
Black gram	1808	Welch (2001b)

Cowpea also appears to be up to 15 times more concentrated in Ca than polished rice after cooking—from food composition tables in the United States (USDA-ARS, 2001).
The pulse samples were from the Chakaria market, imported from India.

exposed skin. However, the Bangladeshi children had high levels of vitamin D and it was eventually established that they and their diet were deficient in Ca itself (Cimma *et al.*, 1997; Fischer *et al.*, 1999). It is significant that no one over about 25 years of age in that area had symptoms of rickets, and as the abnormalities last for life except through orthopedic surgery, it appears that the diet began to change around 25 years ago, which was also when the cropping system began to change toward continuous rice culture. That this association in time is cause-and-effect is underpinned by the differences in Ca added to the diet by the pulses, vis-à-vis rice (Table II), and in a later supplementation trial in these children, their Ca status could be brought up to within the normal range by supplementation with as little as 50 mg Ca day^{-1} (Abed and Combs, 2001). As little as 25 g of cowpea could supply this daily amount of Ca, provided the forms in the seeds were bioavailable. More extensive surveys in Bangladesh now suggest that Ca deficiency rickets in the children of Chakaria is but the tip of the Ca-deficiency iceberg of eastern South Asia and also of parts of Africa (Meisner *et al.*, 2005; Thatcher *et al.*, 1999).

1. Analysis of the Food System

The soils of these high-rainfall tropical areas are acid-sulfate soils and generally low in nutrients owing to leaching by rain passing vertically through the soil profile into groundwater and eventually into the ocean. Deficiencies of N, P, and K are widespread (Table III), regardless of soil type, and soils are mostly very acidic. In addition, deficiencies of micronutrients are often limiting to crop production but may not be identified: deficient micronutrients include Zn (overall, 49% of all soils globally), B (31%), Cu (14%), and molybdenum (Mo) (15%). Therefore, for good productivity and nutrient

Table III
Percentage of Nutrient-Deficient Soils in Parts of Bangladesh (A) (Morris *et al.*, 1997) in Comparison with 190 Soils Worldwide (B) (Sillanpaa, 1990)

Nutrient	N	P	K	B	Cu	Fe	Mn	Mo	Zn
A. Bangladesh									
Extent of deficient soils (%)	100	22	2	69	3	1	24	15	85
B. The world									
Extent of deficient soils (%)	85	73	55	31	14	3	10	15	49

composition, crop production is likely to require N, P, K, lime or dolomite (to counter soil acidity and supply Ca and Mg), Zn, B, Mo, and, on highly organic soils, Cu. Productivity in the Chakaria area is low and rice, itself poor in nutrients especially after milling, dominates the food system.

2. Remedial Food System Strategies

Possible strategies to eliminate rickets in the Chakaria area are several. The first is the traditional nutritional intervention of supplying Ca pills; as demonstrated in the Ca supplementation trial (Abed and Combs, 2001), as little as 50 mg Ca day^{-1} may be sufficient, but while supplements are ideal for acute cases, they are generally not sustainable. Another approach (Meisner *et al.*, 2005) is the addition of a teaspoon of ground limestone to the rice during cooking, a strategy similar to that in Mexico in the making of tortillo.

Lime or dolomite could be added to the soil both to decrease soil acidity, a benefit to crop productivity in general, and especially to pulse production, and to increase the Ca and Mg levels in the crops. Even with a rice-dominated culture, this can be expected to increase the Ca concentration of rice itself, although the increase is insufficient of itself to supply the required additional 50 mg day^{-1} of Ca (Meisner *et al.*, 2005). However, if this is coupled with new, high-Ca rice varieties, it could well solve the Ca deficiency problem. In the International Rice Research Institute, rice varieties have been discovered with at least twice the Ca concentration as that of the widely distributed Green Revolution varieties. The rice analyzed from the Chakaria market averaged 89 mg kg^{-1}. A rice with 214 mg kg^{-1} Ca would supply an extra 30 mg Ca day^{-1} to children eating 150 g dry rice daily. This would seem to be a viable option, and would likely be sustainable if a Ca-enriched rice variety were introduced to the area with agronomic and organoleptic characteristics similar in most respects to the existing varieties. No change in behavior would be required at all, and so this strategy has the distinct advantage of sustainability. From our survey of Ca concentrations in the rice germplasm, this breeding program seems entirely feasible (Gregorio and Graham, unpublished). The bioavailability of Ca in the diet could be further increased by deploying rice varieties high in inulin (Welch, 2001b), inulin can promote absorption via the colon of Ca, Fe, Zn, and Mg (Van Loo, 2004; Yeung *et al.*, 2005). From the little evidence so far available, breeding a high-inulin rice variety would be feasible. It is noted here that resistant starch, which does not get digested in the small intestine is also a prebiotic like inulin and rice varieties with resistant starch are already known. A study of Ca bioavailability from such rice in the Chakaria context is warranted.

Human nutrition literature suggests that increasing Ca intake alone may not resolve the problem. Other nutrients if deficient may interact to affect the efficacy of supplied Ca: not only are Cu, Zn, and Mn required for deposition of Ca into bone (Saltman, 1996), but B may also be required (Nielsen, 1996). This is in addition to vitamin D that in this case study was not a limiting factor as it has been in cases of rickets elsewhere. Interestingly, B and Zn are highly likely to be deficient in this population that depends largely on the low-nutrient rice staple grown on nutrient-poor acidic soils. Notably, in this context, pulses are generally higher in B, Zn, Cu, and Mn than rice, as well as being much higher in Ca (Table II). Reintroducing pulses to the food system would seem to be an ideal solution as it is obviously part of the culture of the people, but how could this be achieved in the face of the opposite trend during the last 20 years or so?

3. Preferred Nutrient-Balanced Food System

A food systems strategy to change the diet in sustainable and acceptable ways could be developed along the following lines: We must first target rice production to make it more efficient and productive so that the needed rice could be produced on less area, leaving land available to the pulse crop, especially in the boro (dry) season. What is most needed are fertilizers to increase rice yield on these soils of poor fertility, and varieties adapted to the environment, and ideally higher in Ca and inulin. The fertilizers adopted must address all the deficiencies in the soil that limit crop productivity materially. Only with balanced plant nutrition will the economics become so favorable that the returns in yield are more profitable for the farmer than using no fertilizer. At the same time, balanced fertilizers are important for better nutrition of the subsistence farmers and their families. However, increased use of fertilizers will require credit facilities to allow the leap from a low-cost, low-yield system to a moderate-input, high-yield one. Increasing the existing pulse crop on the land no longer needed for rice will materially balance the diet, and balancing the nutritional requirements of the pulse crop as well will decrease the additional risk inherent in growing pulses as they will be better able to resist disease and abiotic stresses. Then, the supply of vitamins A and C must be addressed. It is likely that soup greens obtained locally from home or village gardens may be sufficient, but if not, yellow forms of cassava, sweetpotato, guc, or fruits may be needed. Some varieties of cowpea supply pro-vitamin A (B. Reddy, personal communication) so it is important that pro-vitamin A-containing varieties are available and mothers are made aware of their importance. Finally, the adequacy of I, Se, and Co (B12) in the diet or in blood/urine samples from the population should be checked. If any is inadequate, these three elements can be included in the pulse fertilizer mix to provide enough in the staples (Section III). While global evidence suggests that we have considered those nutrients most commonly deficient, others may be inadequate in a given food system, and the adequacy of other essential minerals and vitamins, particularly vitamins B1, B12, and E should be considered. Vitamins B1 and E are found already in this food system in the rice bran (aleurone layer and germ) and ways of adding a little bran to the diet in acceptable ways needs to be explored because the extent of beriberi (deficiency of B1) appears to be increasing (P. Newton, Laos, personal communication). Vitamin B12 as already discussed requires small amounts of (small) animal products. Taking care of this last group of vitamins is largely a matter of education of the value of small amounts of bran and animal products, rather than further changes to the underlying food system.

D. Bean Food Systems in Central America

Traditionally in Central America beans have formed part of a food system with maize as the principal cereal, or in dryer regions, with sorghum. Maize and beans have been traditional staples in Central America since precolonial times. In recent years and with increasing urbanization, the food system has become more diversified, although in rural areas and among urban poor, beans and maize remain the basis of the diet.

1. Nutritional Status Across Countries

Table IV presents data on several common nutritional and health parameters for all five Central American countries. Among these, Costa Rica is exceptional for its superior level of economic development and its public services, including its health system. At a glance the food system(s) in Central America would appear to be functioning reasonably well in terms of protein and caloric intakes. All countries report average intakes at acceptable levels (at or above the recommended minima of 55 g day^{-1} protein and 2200 kcal day^{-1} energy). However, in spite of an apparently positive overall

Table IV
Nutritional and Health Parameters in Central America

Country	Protein intake (g day^{-1})[a]	Caloric intake (kcal day^{-1})[a]	Stunting in children[a] (%)	Anemia in children under 5 years (%)	Infant mortality (per 1000 live births)[a]	Urban poverty[a] (%)	Rural poverty[a] (%)
Guatemala	55	2190	49	26[b]	35	27	74
El Salvador	65	2550	19	19[b]	32	43	55
Honduras	58	2350	29	34[c]	32	56	46
Nicaragua	60	2280	20	28[b]	30	30	68
Costa Rica	72	2860	6	26[d]	8	19	25

[a] http://www.fao.org/es/ess/faostat/foodsecurity/Countries
[b] http://www.fao.org/es/ESN/nutrition/profiles_by_country_en.stm
[c] http://www.jsi.com/intl/omni/up_3_98.htm
[d] Cunningham *et al.* (2001).

nutritional scenario for the whole region, Costa Rica reports levels of stunting and infant mortality far below the other four countries, suggesting serious problems still to be addressed by the other nations.

National data conceal internal variability among regions within countries that can present parameters of health differing widely from national averages. Indeed, Latin America is the region with the greatest inequities in income distribution in the developing world (Londoño and Székely, 1997), so national averages are bound to hide significant disparities. For example, in Nicaragua, which is one of the poorest countries in the hemisphere, the departments of Jinotega and Madriz present 39% and 49% stunting of children, respectively, compared to a national average of 28% (FAO, 2001), while in the northeast of Guatemala stunting can reach 70%, versus a national average of 49% (FAO, 2003). Almost all countries report higher levels of poverty in rural areas (Table IV), and this is often accompanied by more negative health parameters, as well as far poorer intakes of protein and calories. For example, in Nicaragua caloric intake among the poorest of the rural poor can fall below 1000 kcal day^{-1}, and protein intake can also be inadequate (FAO, 2001). Prevalence of stunting among children in Honduras increased in the decade of the 1990s when the economic state of the country was especially depressed (ACC/SCN, 2000). Poverty is an important determinant of nutritional status and of food consumption. Again in Nicaragua, bean consumption among rural dwellers varies from 17 to 36 kg per person per year, increasing with higher income level (FAO, 2001).

Furthermore, other social conditions have influenced nutritional parameters temporarily. During the civil war in El Salvador, food availability suffered and the nutritional state of many worsened (FAO, 2002).

However, it is noteworthy that Fe status, estimated by rates of anemia among preschool children, does not vary so widely across countries as other parameters (Table IV). While data from Honduras suggest the most critical situation, even in Costa Rica as many as 26% of preschoolers present anemia. Among public health problems for which data are readily available, it seems that anemia, and probably Fe-deficiency anemia, are among the most intractable, and a failing of the food system per se.

Vitamin A and I deficiencies have been addressed by food fortification but still occur at moderate levels, given imperfections in the fortification and delivery systems (see Sections D.3, D.4). Information on other deficiencies is sketchy but Zn deficiency often accompanies Fe deficiency. A recent report of the International Zinc Nutrition Consultative Group highlights Guatemala, El Salvador, Honduras, and Nicaragua as having high risk of Zn deficiency (Hotz and Brown, 2004). These countries present an estimated 41–49% of the population at risk of inadequate intake of Zn. As in the case of Fe, this is associated with the low consumption of animal products. Costa Rica, on the other hand, holds a medium level of risk with an estimated 29% of the population at risk. As more attention is directed to Zn and its levels of deficiency, it may well emerge as still another weak link in the present food system.

2. Bean Production

Beans are both a crop for home consumption and for market, and among traditional crops, are the most important income generator in Central America. Thus, market demands and commercial criteria for grain type and quality play an important part in farmer varietal preference. Although a wide array of colors is found in landraces, the small, light-red, shiny-seeded types are now the dominant class, followed by small opaque-seeded blacks. Two rainfed planting seasons, in May and September, account for more than 80% of production, while a third crop planted in December or January develops under residual moisture or requires irrigation. Drought, poor soil fertility (P and N) and diseases (fungal, viral, and bacterial) are important limitations. Although the yield potential of the crop is above 3000 kg ha^{-1}, regional yields average around 750 kg ha^{-1}, with El Salvador presenting the highest yields of about 950 kg ha^{-1}.

Depending on the region and season, beans may be interplanted with maize in May (one row of maize for every 3–5 rows of beans), or may be planted in relay as the maize crop is maturing in September. Fertilizer is widely available but its use depends largely on capital resources of the producers, and beans often receive no added fertility. In the case of relay planting with maize, farmers will often apply fertilizer to maize and the beans will be produced on residual fertility. Where beans are fertilized directly, rates of 65–130 kg ha^{-1} are typically used, most commonly with 18,200 (NP) although 121,012 (NPK) is also available in some areas. There is evidence that micronutrients (especially Zn) can be limiting in soils of Central America (ArrozGua, 2004; Bornemisza and Peralta, 1981). However, micronutrients are not applied to beans, and there is little awareness among producers of potential micronutrient deficiencies. It would probably be necessary to demonstrate a positive response to Zn fertilization across several crops to induce fertilizer producers to incorporate Zn into formula fertilizers, unless government policy demanded it.

3. The Role of Beans in the Diet

Work at the Institute of Nutrition of Central America and Panama (INCAP) in Guatemala established proportions of about 2.5:1 maize–bean for optimal amino acid balance (Navarrete and Bressani, 1981), although in fact beans are consumed in a lower proportion than this. Bean consumption levels vary widely between rural and urban areas. National statistics typically suggest per capita consumption of 15–20 kg $year^{-1}$, but both anecdotal accounts and reports of surveys testify to levels that can be twice as high in rural areas (FAO, 2001). It is not clear that all home consumption is calculated in production figures, and this is consumption that would escape official statistics.

Most protein in the Central American diet is of plant origin (FAO, 2001, 2002, 2003). This is particularly the case among the poor for whom animal protein represents less than 20% of protein intake, and as little as 10% among the poorest. Although maize is by far the most important source of energy (38–57% among countries), beans supply as much as 14% of calories, and are the third or fourth most important source.

Beans are also a source of dietary Fe, and are particularly important when consumption of animal products is low. If beans are consumed at a rate of 20 kg per person per year, this is the equivalent of 55 g day^{-1} of beans. At a concentration of 50 mg kg^{-1} Fe, this consumption level would provide 2.75 mg Fe day^{-1}. It has been observed that rural populations willingly consume double this quantity of beans if price and availability permit. Furthermore, the HarvestPlus Challenge Program has set itself the goal of doubling the concentration of Fe in bean cultivars through breeding. If both consumption and Fe concentration were doubled, this would result in 11 mg day^{-1} of Fe from beans, or an additional 8.25 mg day^{-1} of Fe in the diet. The nutritional benefits from this achievement will depend on bioavailability of the Fe, which is assumed to be low, but it is probable that bioavailability of the additional Fe will be equivalent to that in beans consumed at present, and that the total bioavailable Fe will, in any case, be proportional to the total Fe consumed.

It must be noted that to fulfill the HarvestPlus strategy and to maximize the benefits of biofortified beans, both Fe concentration and production must increase significantly. In the case of the poorest of the poor, whose yields are limited by a range of biotic and abiotic stresses, this implies a significant effort in crop improvement. In particular, abiotic stress (drought and poor soil fertility) must be overcome. Poor farmers often occupy the most difficult environments, and for them improving yield is more urgent than improving nutritional quality. Very promising results have been obtained at the International Center for Tropical Agriculture (CIAT) in Colombia in improving drought tolerance and combining this trait with disease resistance and commercial grain color. These traits must now be combined with improved Fe and Zn concentrations. Addressing low yields due to poor soil fertility requires a coordinated effort of agronomic management and improved genetic adaptation. The option of fortifying NP fertilizers with Zn to redress overt Zn deficiency, increase tolerance to drought and disease, increase the efficiency and adoption of carrier NP fertilizers, and increase Zn density may be widely successful in this food system where Zn deficiency in diets hovers around 50%, because it is likely that yield benefits will accrue that will cover the extra cost of Zn, and because both maize and bean are generally considered sensitive and responsive to fertilizer Zn.

In this maize-based food system, the greatest contributions from a HarvestPlus Challenge Program perspective must come from increasing Fe and Zn in beans and increasing pro-vitamin A in the maize crop. Beans should also be explored as a source of Se. Deficiency of I may be addressed by traditional fortification of salt but the agricultural strategy of deploying I-enriched NP fertilizers remains an option that may be more sustainable in the long run.

4. Other Components of the Food System

As is common, fruit and vegetable consumption is highly dependent on income, with very low levels among the poor in Nicaragua (FAO, 2001), but with much higher intakes across income levels in Guatemala (FAO, 2003). Horticultural crops have great potential to contribute vitamins to the diet. For example, chili peppers are an excellent source of vitamin C and are consumed in parts of Central America. Vitamin C can improve Fe absorption significantly and can play an important role in Fe nutrition. There is some evidence that pro-vitamin A (carotenoids) can have a similar positive effect on Fe absorption, especially when subjects are vitamin A deficient (Garcia-Casal *et al.*, 1998). If this is confirmed, the role of carotene-rich foods such as orange-fleshed sweetpotato, local varieties of squash, or fortified sugar could be important. However, at present consumption data usually are not discriminated by specific fruits and vegetables to estimate potential contributions. Furthermore, food preparation methods will greatly affect vitamin content and nutritional contribution. The role of complementary foods is a significant gap in our knowledge to analyze the food system realistically, and to plan effective interventions.

Food fortification has been employed for many years in Central America for vitamin A, using sugar as the vehicle. This has been successful, for example, in reducing vitamin A deficiency in Honduras from 40% to 14% since 1965 (OMNI, 1998). Sugar has the advantage of having few or no substitutes in the mass market (assuming that "light" products have little attraction among the malnourished), and therefore enjoys a "captive audience." On the other hand, Guatemala was the first country to implement sugar fortification in the region, and although 85% of sugar is fortified, fortification is not uniform (FAO, 2003). Rural populations benefit relatively less, and indigenous populations of the Guatemalan plateau continue to have serious problems. El Salvador reports 36% of the population as deficient in vitamin A across age groups, based on serum retinol (FAO, 2002). Iodized salt is widely used in the region, although in Guatemala quality of fortification is not optimal and intakes are moderately insufficient (FAO, 2003). Fortification of wheat flour with Fe has been contemplated, but rural populations that consume mostly maize tortillas would appear to benefit only marginally from this strategy.

5. Information Gaps

A more complete analysis of a bean–maize based food system in Central America requires specific data, including: better discrimination of consumption levels across rural versus urban areas, and across economic levels; more detailed data on consumption, preparation methods, and micronutrient bioavailability of specific complementary foods, especially chilies, vegetables, fruits, and animal products across age and gender groups; more localized data on nutritional status to target interventions; and broader data on micronutrient deficiencies in soil and potential response of crops to fertilization. This information and potential agricultural interventions in the food system must also be viewed in light of the potential of standard fortification strategies and their scope of adoption and impact.

E. Potato-Based Food Systems, Huancavelica Department, Peru

A multidisciplinary study at the International Potato Center (CIP) of high-altitude cropping and food systems in the Andes included base line studies, cropping systems analysis, poverty research, participatory GIS surveys, and nutrition studies in eight farmer communities of the Department of Huancavelica, Peru. Diversity across the department and the communities in which research was conducted makes this a relevant setting for exploring potato-based food systems more generally.

The department of Huancavelica covers over 2 million ha (6.1%) of the Peruvian Andes mostly at elevations between 3500 and 4500 m. The total population is just under 500,000 of whom three-quarters are rural and 97% are economically dependent on agriculture and livestock (INEI, 1994). Huancavelica is often considered the poorest of Peru's 24 departments; chronic malnutrition affects 52% of the children while average infant mortality reaches 112 per thousand in rural areas (MEF, 2001; Rubina and Barreda, 2000). Potato is the most important crop, covering more than a quarter of the total annual cropping area, followed by maize, barley, wheat, faba beans, and peas, which together account for another 27% (Rubina and Barreda, 2000). Agroecological classification of the study area was based on Pulgar Vidal's framework (1996) of natural zones. Although Huancavelica has five agroecological zones, Puna, Suni, Quechua, Yunga, and Selva Alta, only three of these contain potato production systems (Table V).

About 87% of the department's population lives in the Quechua and Suni zones where potato agriculture is concentrated (Rubina and Barreda, 2000). Farmers manage several production zones simultaneously, disbursing species, varieties, labor, and risk across environments. Sectoral fallowing systems, called *laymes*, are maintained in most high-altitude communities: all farmers plant the same crop in the same communally defined geographical sector. Rotation cycles begin with potatoes followed by barley and/or fallow (natural pasture). Fields at lower altitudes are managed by individual households.

Each production zone has a distinctive potato species and cultivar portfolio: bitter species and landraces at higher extremes (P2, P3, P4), diverse nonbitter landraces (four subspecies) at intermediate altitudes (P3, P4, S1, S2), improved varieties at lower levels (S1, S2, Q1), and commercial landraces in fields dedicated to a single variety (S1, S2). Farmers in all communities also maintain *chaqro* fields (production zones P3, P4, S1) in which mixtures of nonbitter/noncommercial landraces are managed together. These receive only locally available organic inputs as do bitter landraces, while commercial plantings (landrace and improved varieties) receive chemical fertilizers. Farmers generally use their own seed, but occasionally purchase additional seed after poor harvests. The informal potato seed systems cover most communities, maintain reasonable quality, are highly flexible, and can distribute seed widely; therefore, it is an important seed resource for farmers (Thiele, 1998).

Crop damage caused by abiotic factors such as frost, hail, and drought is more important than insect pest and disease damage at the upper altitudinal

Table V
Agroecological Zones, Potato Crop Production Systems, Biophysical Conditions, and Component Crops Within the Department of Huancavelica

Zone	Area (%)	Altitude range (m asl)	Production system	Biophysical conditions	Component crops
Puna	15	4200–4350	P2: Sectoral fallowing (communal land)	Rain dependent Very high incidence of frost/hail	Bitter potatoes followed by natural pastures
		4000–4200	P3: Sectoral fallowing (communal land)	Rain dependent High incidence of frost/hail	Mixed potato landraces, either bitter or nonbitter, followed by barley and natural pasture
		4000–4200	P4: Mixed cropping dominated by potato (private use)	Rain dependent High incidence of frost/hail	Mixed potato landraces, either bitter or nonbitter, commonly rotated with barley, wheat, oats, and/or minor tubers
Suni	35	3750–4000	S1: Mixed cropping dominated by potato (private use)	Rain dependent Moderate incidence of frost, hail, and late blight	Mixed or single nonbitter potato landraces and improved varieties commonly rotated with barley, wheat, oats, quinoa, tarwi, and/or minor tubers
		3500–3750	S2: Mixed cropping dominated by potato (private use)	Mostly rain dependent Intermediate incidence of late blight	Improved potato varieties and/or commercial nonbitter landraces, commonly rotated with barley, wheat, quinoa, faba beans, tarwi, and cultivated pastures
Quechua	32	2300–3500	Q1: Mixed cropping dominated by potato (private use)	Rain dependent or irrigated High incidence of late blight	Improved potato varieties rotated with diverse crops: wheat, faba beans, tarwi, maize, and cultivated pastures

limits of agriculture as practiced in the Huancavelica department. Farmers manage these factors through field-scattering practices (Goland, 1993), and consider that mixed landrace stands or *chaqro* fields reduce damage and loss; semi-traditional practices such as burning cow dung near fields to prevent frost damage and the use of fireworks for hail prevention are common.

Farmers harvest by hand; men usually dig up tubers and women start selection, separating out damaged and small tubers for processing into *chuño* by freeze-drying; large tubers for sale, and medium size tubers for seed. Seed and tubers for fresh consumption are taken to homesteads for storage while bitter potatoes are often left in the fields so that *chuño* processing can begin once nightly frosts become frequent.

Cultural dimensions and local knowledge systems of potatoes far exceed a simple catalogue of varieties and include terminology for the crop's agricultural and social ecology (Brush, 2004). Potato-related practices, knowledge, and culture including a characteristic Andean "cosmovision" are highly dynamic, continuously reinvented and frequently molded into new expressions at harmony with modernity. So it is not uncommon to find an improved variety with a local name being used for an indigenous process such as freeze-drying. This is typical of Andean agriculture, which purposefully absorbs new technologies and knowledge to reshape these for local utility.

1. Malnutrition in the Huancavelica Department

Data collected in six of the research communities showed that one in four children presented global malnutrition (weight for age). Only 7% of the children showed normal height for age ratios, while 20% were found to be severely malnourished, 43% moderately and 30% slightly so (chronic). The percentage of acute malnutrition (weight for height) was found to be minimal (INEI, 2000).

Farmers in all communities produce crops and animal products for home consumption. Potato in particular is often produced, yet rarely purchased. Strictly, subsistence farmers are virtually nonexistent in Huancavelica and although household consumption is largely determined by on-farm production, food systems are still dependent on purchase of some additional inputs. Andean peasants are highly articulated with the "outside world" (Mayer, 2002; Mayer *et al.*, 1992), and markets have played an important role in household economies for many centuries (Contreras and Glave, 2002). Farmers from all the study communities sell part of their produce, such as potatoes, tarwi (*Lupinus mutabilis*), maca (*Lepidium meyenii*), wool, and meat at regional markets. With the income, they buy certain foods, ingredients, and other necessities. Food expenditure varies within and between communities depending on resources. Nonmonetary exchange through reciprocal labor relations or barter of foods is still common. Off-farm employment has become much more common in recent decades for all of Huancavelica's rural communities and provides many households with complementary resources to enrich the food system. The dynamics of migration and off-farm employment have changed rural food systems, increasing possibilities to purchase new foods such as rice and pastas through monetary exchange. Families with access to off-farm employment were rarely ranked as being poor by local standards.

2. Access to and Availability of Food

There are three main pathways for rural households to obtain food: on-farm production, exchange or purchase, and food donation programs from the government or regional NGOs. Table VI provides an overview of foods commonly obtained through each pathway.

Access and availability of food is related to a household's relative wealth. Nonpoor households have more livestock while poor households are more crop dependent. The consumption of barley gruel, barley soup, and freeze-dried potatoes were mostly associated with being poor while consumption of

Table VI
Common Foods Obtained Through Three Basic Pathways by Families Surveyed in Huancavelica

On-farm produced foods	Purchased foods	Donated foods
Potato and *chuño*	Bread	Milk (powder/tins)
Barley	Rice	Oatmeal (cereal)
Wheat	Pastas	Fortified cookies
Oats	Salt	Rice
Oca	Sugar	Pastas
Mashua	Baking oil	
Olluco	Maize	
Faba beans	Faba beans	
Maize	Peas	
Peas	Fruits	
Sheep meat	Vegetables	
Alpaca or Llama meat	Tuna fish	
Guinea pig meat	Cheese	
Cow meat		
Milk		
Cheese		

Table VII
Foods Associated with Being Poor Versus not Poor Among Families Surveyed in Huancavelica

Community	Foods of those who are poor	Food of those who are not poor
Allato	Barley gruel, barley soup	Cheese, eggs, milk, meat
Pongos Grande	Barley soup, potato soup, *chuño*	Eggs, cheese, meat, legumes
Villa Hermosa	Barley soup, zanco (flour with pig fat)	Meat, eggs, vegetables
Pucara	Barley gruel, water from well	Rice, milk, meat, tap water
Dos de Mayo	Barley gruel, barley soup	Faba beans, meat
Libertadores	Barley soup, mashua, weedy vegetables (yuyos, berros)	Vegetables, zanco (flour with pig fat), potato, meat
Huayta Corral	Barley gruel, *chuño*	Meat, eggs, cheese, rice, pastas
Tupac Amaru	Barley gruel, *chuño*	Rice, pastas

Source: Participatory poverty analysis workshops (2005).

rice, pastas, eggs, meat, and vegetables were commonly associated with not being poor (Table VII).

Poor households on average spend S./157 (US$46) per month (52%) on food. Nonpoor household's total monthly spending is higher with S./262 (US$79) per month (44%) on food. Of the poor households, 68% consume only two meals a day, and consume more barley and less rice, pasta, milk, and fruit.

3. Diet and Nutrition

The nutritional contribution of potato in the diet of women with children from 6- to 36-month old was studied in six communities during the periods of abundance and scarcity (Burgos, 2006). Potato was dominant in the diets of both adult women and children, represented by a mean daily consumption of 839 and 645 g (women) and 202 and 165 g (children) during periods of abundance and relative scarcity, respectively.

During the period of abundance the total diversity of potato cultivars consumed was higher than during the period of relative scarcity, both for women and children: 90 versus 61 cultivars for women and 81 versus 41 cultivars for children. Within the group of "other roots and tubers," carrots and olluco (*Ullucus tuberosus*) were most frequently consumed during the period of abundance, while carrot intake alone was more frequent during the period of relative scarcity. Barley, rice, oats, and pastas were the most frequently consumed cereals by both women and children during both periods. For legumes, both women and children most frequently consumed faba beans and peas in both periods. Broadly, vegetable consumption was

Table VIII
Dietary Coverage from Potato and Total Diet in Huancavelica Compared to Recommended Intakes (FAO/WHO, 2001)

	Period of abundance				Period of relative scarcity			
	Coverage by total diet (%)		Coverage by potato (%)		Coverage by total diet (%)		Coverage by potato (%)	
	Women ($n = 76$)	Children ($n = 75$)	Women ($n = 76$)	Children ($n = 75$)	Women ($n = 77$)	Children ($n = 78$)	Women ($n = 77$)	Children ($n = 78$)
Energy	88.7	84.0	38.6	29.2	87.3	85.6	28.7	23.0
Protein	96.4	183.9	38.2	57.8	104.5	193.0	28.0	43.7
Fe (mb)	59.6	88.2	13.1	16.8	71.8	118.7	9.9	13.6
Fe (lb)	29.5	40.4	6.5	7.7	35.5	54.4	4.9	6.2
Zn (mb)	152.0	62.4	45.2	15.9	170.4	87.3	39.2	14.8
Zn (lb)	76.0	29.6	22.6	7.5	85.2	41.6	19.6	7.0
Ca	38.2	36.6	6.2	3.2	42.3	46.0	5.5	3.3

Source: Nutrition surveys 2004/2005; mb = medium bioavailability; lb = low bioavailability.

infrequent, mainly onions and garlic during both periods of inquiry, and sacha col or yuyo (*Brassica rapa*), a weedy vegetable, during the period of relative scarcity. Overall frequencies of fruit, meat, milk, and egg consumption were found to be extremely low for both groups and periods of inquiry.

The overall diet was found to be generally deficient in energy, Fe, Zn, and Ca. Potato provided over a quarter of the recommended total energy requirements for adult women and children, and contributed significant amounts of protein: 38% and 28% for women and 58% and 44% for children for the period of abundance and relative scarcity, respectively.

The contribution of potato to Fe intake was calculated at both low and medium bioavailability. At low Fe bioavailability, total mean potato Fe intake by women and children contributed 7% and 8%, respectively, of required intake during the period of abundance and 5% and 6% during the period of scarcity, whereas for the medium Fe bioavailability scenario, the corresponding figures are 12% and 15% (women, Table VIII) and 17% and 14% (children). The contribution of potato to Fe status may be more than these figures indicate if in fact potato is consumed together in the same meal with Fe from cereals, owing to potato's relatively high vitamin C content. The corresponding figures for low bioavailable Zn are higher (than for Fe) in women, about 23% and 20% but only 8% and 7% for children, for abundant and scarce conditions, respectively (Table VIII); for moderately bioavailable Zn, the corresponding figures are 45% and 34% of the required intakes (women) and 16% and 15% for children under abundant and scarce conditions, respectively. For both Fe and Zn, co-consumption with carrots that are high in β-carotene may enhance efficiency of absorption and utilization.

The data confirm that potato is a main staple that sustains food security for rural households and contributes significantly and positively to nutritional balance during periods of abundance and relative scarcity. Potato contributes more than 95% of the vitamin C requirements for both groups in the two periods, and contributes significantly to the recommended requirements for energy, protein, Ca, Fe, Zn, and vitamin C (Table VIII). Other food categories, especially cereals, also provide substantial contributions to the recommended requirements.

4. Potentially Beneficial Interventions

Malnutrition is a serious problem in Huancavelica. Food system interventions are needed to increase availability of energy, Fe, Zn, Ca, and pro-vitamin A to vulnerable groups including mothers and children. While overall protein intake is adequate, there is a need to enhance dietary diversity to satisfy the essential amino acids required.

Average potato yields of less than 8.6 tons a hectare are low. Increasing crop yields should increase food availability (potato, barley, and others cereals). This can be achieved through technological innovations such as fertilizer, soil management, integrated pest management, improved varieties, and water management. The challenge is to obtain significant yield increases on a sustainable basis and build on the rich ecological and agrobiodiversity that makes Andean cropping systems resilient.

A wide diversity of native Andean crops rich in protein, essential amino acids, and minerals are available to be incorporated into the cropping systems, including maca, quinoa (*Chenopodium quinoa*), and tarwi. Maca has a particularly high content of Ca (258 mg per 100 g) and Fe (15 mg per 100 g). It is also a good source of energy and protein (Hernándo Bermejo and León, 1994). Quinoa has high quality protein; it contains relatively more of the essential amino acids—lysine, arginine, histidine, and methionine. Tarwi is an exceptional source of protein (42% in dry grain, 20% in cooked grain, and 45% in flour) and fat (16% of dry grain).

Selection from existing varieties, or breeding, for nutritionally superior potato or barley varieties rich in Ca, Fe, Zn, and pro-vitamin A may have a positive impact if these varieties comply with other major preferences farmers look for, for example, taste, productivity, storability, and resistance to important biotic and abiotic stresses.

Enhanced processing of potatoes may potentially increase food security, especially for those months of the year that are critical in terms of availability of staples. This may be achieved by improving the sensitive steps and conditions in the process chain, for example, the kind of surface on which *chuño* is prepared.

The introduction of greenhouses and vegetable cropping has been promoted by several NGOs as a strategy to diversify diets and improve nutrition. Potential exists to expand and promote small livestock such as guinea pigs, rabbits, and chickens.

Food assistance programs can also make a positive contribution to improving the nutritional status of the population in Huancavelica if carefully managed, for there is a risk of a shift to foods that cannot be produced locally such as rice, promoting dependence and potentially undermining local food systems.

The farmers of Huancavelica are not passive recipients of knowledge and technology from outside, as has been described. "Interventions" by outsiders should build on this potential and involve farmers in reinventing their local food systems to make them more nutritious. Education about nutritional needs is one important component that can help farmers modify cropping systems and diets to include more nutritious foods, and could be included with farmer field schools and other participatory extension and training approaches that have typically focused on cropping systems rather than the food system as a whole. The challenge is to work with farmers on a diverse range of options and develop robust local food systems that not only provide more nutritious food but do so in a culturally appropriate way that strengthens the ecological and genetic diversity that characterizes the Andes.

F. Subsistence Food Systems of Eastern and Southern Africa

1. Potato and Sweetpotato/Bean Food Systems in the Great Lakes Region

The Great Lakes region of Central Africa, comprising Burundi, Rwanda, eastern parts of the Democratic Republic of the Congo (DRC), and southwest Uganda, covers approximately 65,000 km^2 lying between latitudes 2°N and 5°S. Altitudes range from 800 m on the shores of Lake Tanganyika in the south to over 3000 m along the high points of the mountainous Nile/Congo Divide. The predominantly rich volcanic soils of the Divide give way to acid lateritic soils to the east. The region has a bimodal rainfall pattern with the "short rains" occurring between mid-October and December and the "long rains" between March and June. Rainfall is concentrated along the Divide, with less and a marked June to September dry season on the eastern edge.

	Month											
Cropping season	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
Short rains	**<Beans, sweetpotato>** **maize/sorghum,** **potato,** coco yam											
Long rains						**<Potato, sweetpotato>** beans, peas, wheat						
Dry season										**<Beans, sweetpotato, potato, maize>** Rice, vegetables, coco yam		
Bananas and cassava are primarily planted at the beginning of the short rains, but grown and harvested throughout the year.												

Figure 6 Principal cropping seasons in the Great Lakes region of East Africa.

a. Cropping System. The region is densely populated with most of the approximately 20 million people living in the mountainous areas. Agriculture accounts for the livelihood of over 90% of the population. Farms are generally small, averaging 0.5 ha. Few animals are kept, except on the lower eastern plains. There are two main cropping seasons corresponding to the short and long rains with a third during the June to September dry season in the limited wet valley bottoms. Bananas (*Musa* spp.) are grown by over 70% of households and sweetpotato (*Ipomea batatas* L.) and cassava (*Manihot esculenta* L.) each grown by over 60%. Potato (*Solanum tuberosum* L.) is grown at elevations above 1600 m asl by approximately 40% of such households. *Phaseolus* beans are the main protein source, and also an important energy source, grown by over 80% of households. The cereals, sorghum (*Sorghum bicolor* L.) and maize (*Zea mays* L.), are grown on about 50% of farms. Coco yams (*Colocasia esculenta* L.), wheat (*Triticum aestivum* L.), and peas (*Pisum sativum* L.) are also grown seasonally.

The principal growing seasons are shown in Fig. 6. The three crops a year allow some continuity of food supply, but shortfalls occur at the end of the dry seasons, particularly where farmers have no access to the valley bottoms. The situation is aggravated by the perishable nature and poor storability of the root and tuber crops.

Crops are rarely grown as a sole crop, except for wheat, peas, recently introduced climbing beans, and recently some cash crops such as potato. More commonly, they are grown as complex poly-crops designed to reduce risk. Six or more crops are frequently grown on any small parcel of land and planted in a predetermined spatial and temporal arrangement to maximize the use of land, water, and light and ensure an extended harvest. Exact areas

Table IX
Area and Production of Selected Crops in Great Lakes Region, Central Africa

Country	Potato		Sweetpotato		Beans	
	Area planted (ha)	Production (t)	Area planted (ha)	Production (t)	Area planted (ha)	Production (t)
Burundi[a]	10,000	26,091	125,000	834,394	244,000	220,218
D. R. Congo[b]	20,000	92,300	44,000	224,450	200,000	109,340
Rwanda[c]	133,418	1,072,772	163,070	908,306	319,349	198,220
Uganda (southwest)[d]	32,034	315,084	64,167	276,265	108,767	76,088

[a] FAOSTAT Data (2004).
[b] Bouwe, personal communication.
[c] MINAGRI (2002).
[d] UBS (2003).

devoted to each crop are difficult to assess, but recent estimates are shown in Table IX.

The major constraints to production are the limited land holdings, leading to intensive cropping and land and soil degradation; low soil fertility away from the volcanic ridge and the almost complete lack of fertilizer use; lack of affordable inputs, particularly sufficient quantities of quality planting material; drought and unpredictable rains resulting in increasing cereal-crop failure; and disease, particularly the recent pandemics of cassava mosaic virus and banana bacterial wilt, which have reduced crop yields by as much as 100% over large areas, thus not only decreasing production but severely curtailing cropping options. Exacerbating these constraints has been the recent civil unrest that has not only reduced the labor force but resulted in a reduction in the animal population by over 60% with the concomitant loss of manure, the main source of soil fertility.

b. Cash Crops. Coffee, tea, and cotton are the major cash crops of the region. However, low prices and the domination of these crops by men means that little of the income derived from them enters the household budget, a possible exception being to pay school fees. General household income is derived from sales of excess bananas (usually for beer), potatoes, and beans. Such income is generally minimal from the small land-holdings per household.

c. Human Nutrition. Most areas in the Great Lakes region are considered capable of producing enough energy and protein for the population under peaceful conditions (United Nations World Food Program, WFP),

Table X
Range of Seasonal Energy and Protein Intakes Among Women Aged 21–48 Years in Six Provinces of Burundi (Nkunzimana *et al.*, 1995b)

Cropping season	Energy intake (kcal per person day^{-1})	Protein intake (g per person day^{-1})
Short rains	1287–1661	33–49
Long rains	1469–1833	50–67
Dry season	1688–1987	56–69

but FAO estimates that 50% of the population of Central Africa is undernourished (FAO, 2003). Approximately 3% of the region's food requirements are imported, mainly in the form of wheat for bread making. However, severe imbalances and deficiencies, often seasonal, in intake of both the major and minor nutrients among some sections of the population, critically women and young children, are common.

A survey by Nkunzimana *et al.* (1995b) in six provinces of Burundi indicated that roots and tubers (55%) and legumes (35%) provided approximately 90% of the daily energy intake: cereals (6%) and fish and meat, vegetables and fats (approximately 1% each) provided the balance. Also highlighted in this survey was the seasonal variation in dietary energy and protein intake (Table X). The low intake levels, 51–78% and 49–101%, of the energy and protein RDA during the short rains coincides with a period of food shortage after reserves have been depleted during the dry season.

In addition to the dietary intake of the major nutrients, numerous studies have shown that Fe and vitamin A intake in the most vulnerable groups (pregnant and lactating women and children from 6 to 59 months of age) are also suboptimal. While data on actual intake are very unreliable, Table XI shows recent estimates. In one recent study, Donnen *et al.* (1996) showed that vitamin A deficiency coexists in East Kivu with protein-energy malnutrition (PEM) and is characterized by a high prevalence of severe biochemical depletion and a low prevalence of clinical signs. It is interesting to note that despite the high proportion of children covered by vitamin A supplementation programs, over one-third of children still have a subclinical deficiency, even where post-conflict activities have been intense.

A survey in Burundi (Nkunzimana *et al.*, 1995a,b) found that 74% of nonpregnant women, 95% of pregnant women, and 51% of lactating women received less than the RDA of Fe suggesting that the figures in Table XI may be underestimates. Nkunzimana *et al.* (1995a,b, 1996) propose that Fe deficiency in these regions may be partly explained by a typical diet poor in highly bioavailable heme Fe and in promoters of nonheme Fe absorption

Table XI
Estimates of Vitamin A Deficiency and Fe Deficiency Anemia in the Great Lakes Region[a] (Anon, 2003, 2004)

	Vitamin A deficiency		Fe deficiency anemia	
Country	Children <6 years with VAD (%)	Children receiving at least one dose vitamin A per year (%)	Children <5 years with IDA (%)	Women 15–49 years with IDA (%)
Burundi	44	95	82	60
D. R. Congo	58	80	58	54
Rwanda	39	94	69	43
Uganda	66	37	64	30

[a] Due to difficulty in collecting data, all figures are estimates. VAD, vitamin A deficiency; IDA, Fe deficiency anemia.

and concluded that the lack of heme Fe and ascorbic acid in diets should be regarded as the main determinant of the low-potential Fe bioavailability in the Imbo region of Burundi. A major cause is the almost total lack of animal and fish products (approximately 4.5 kg per person year^{-1} or 3.5 g per person day^{-1}) in the diet, except for a narrow strip bordering Lake Tanganyika, and a low consumption of all groups of vegetables that provide minerals, ascorbic acid, and other vitamins. Such conditions apply to the whole region, with the exception of some parts of East Kivu, where leafy vegetables, including cassava and bean leaves, are eaten almost daily (Yazawa and Hirose, 1989). At higher elevations, Fe deficiency is often less and may be a result of the increased consumption of potato. The low levels of meat intake also affect adversely the ability of the body to absorb the fat-soluble β-carotene from the intestine since oils are rarely used for cooking.

While Fe and vitamin A are the most widely reported deficiencies in the region, there are often also deficiencies of I, Se, and Zn, commonly due to their low levels in soil. Systematic studies of the micronutrient status of Central African soils have not been completed; but there is evidence that all these elements are deficient to some degree and would be reflected in the human nutrition of these highly subsistence communities. All of these micronutrients interact in human metabolic processes and have important benefits to human vigor and immune competence. Thus ensuring adequate levels of any one may partially offset deficiencies in others.

Deficiency of I, endemic throughout the region, is now largely controlled by the use of iodized salt. However, the use of iodized salt does nothing for potential deficiencies of I for livestock production, the products of which would greatly improve the nutritional status of the population and increase farmers' income allowing for more diet diversification from purchased foods. About 42% of the population of Burundi continues to be affected by I deficiency but less than 15% in Rwanda and Uganda (Anonymous, 2003). Deficiencies of Se have been recorded in East Kivu (Fondu *et al.*, 1978) and are considered to play an important role in anemia.

Zn, found in red meat, legumes, and whole grain cereals, is not recognized as a major health problem, but adequate Zn is known to promote Fe and vitamin A utilization. Furthermore, soils in the region are deficient in Zn (Hotz and Brown, 2004), a situation exacerbated by the root crop-based diet low in Zn.

d. Nutrition and Disease. The population in the Great Lakes region has a high incidence of HIV/AIDS, malaria, acute respiratory infections, tuberculosis, and diarrhea resulting in very high levels of morbidity and mortality in children and women of childbearing age. Deficiencies in macro- and micronutrients affect the body's ability to resist disease. Conversely, malaria, parasites and infectious diseases affect the absorption of micronutrients. The increased incidence of these ailments severely impinges on the individual's and household well-being, reducing the ability to work the land, impairing child development, and cognitive ability with an increase in the number of days lost at school, thus reducing the individual and country's potential.

e. Implications of the Cropping/Nutrition Balance. War, civil unrest, and HIV/AIDS have resulted in many woman-headed households throughout the region. In Burundi, for example, it is estimated that households headed by women are now 18%. Field labor for food crop production is supplied mostly by women. Much of the land preparation is carried out at the end of the dry season, when many marginal families are restricted to only one meal a day. Thus women, at a time when maximum energy reserves are required, are weakened and liable to illness. This situation is severely aggravated, when the rains begin and the mosquito population increases, by a seasonal outbreak of malaria. Scarce financial resources are often used to employ outside labor. Micronutrient deficiencies, particularly vitamin A deficiency, which lowers immunity to disease, exacerbate the situation. Timely planting and weeding are often missed and yields reduced. It is estimated that the economic impact of vitamin and mineral deficiencies alone amounts to 2.5% and 1.1% of GDP in Burundi and Rwanda, respectively (Anonymous, 2004). Children, especially young girls, are pressured to fulfill their mother's role resulting in lost educational opportunities.

A high rate of population increase, currently over 2.5% throughout the region, returning refugees, pressure for land and movement to marginal areas, failure of traditional staple crops due to disease, drought, and unpredictable rains are all likely to place pressure on traditional short-duration, energy and protein crops, potato, sweetpotato, and bean. The question arises as to how these cropping systems can supply a sufficient and balanced diet.

f. ***Breeding for Nutrition.*** Sweetpotato is potentially a major source of β-carotene. Cultivars of sweetpotato have been identified that are capable of providing the RDA of β-carotene from only 100 g day^{-1} of fresh root and breeding is under way to incorporate this character into locally adapted cultivars. Already, locally selected cultivars with increased β-carotene contents are being grown in neighboring areas of Kenya, Uganda, and Tanzania.

Bean cultivars with high Fe and Zn contents have also been identified (Welch *et al.*, 2000) and similar intensive breeding programs should make available locally adapted, high Fe and/or Zn cultivars. However, the proportion of Fe and Zn that can be absorbed from beans is low due to their antinutrient content, especially certain polyphenols. Bollini *et al.* (1999) have shown the possibility of breeding for a reduction in antinutrients. Wild potato species with high carotenoids, vitamin C, or Fe contents have also been identified and are currently being assessed for the possibility of incorporating these traits into improved genetic material. If consumed with beans, high levels of these constituents may enhance the absorption of bean Fe.

g. ***Future Scenarios.*** Immediate improvement in the PEM and the incorporation of a better nutrient balance is most likely to arise from intensification of current cropping systems and will rely heavily on the currently grown crops, particularly potato, sweetpotato, and beans. Traditional polyculture techniques are likely to be preferred as they reduce risk and the time taken for cultural practices such as weeding and pest control. New cultivars combined with optimal use of animal manures and compost will form the basis of intensification. Dietary mineral and vitamin deficiencies could be addressed through the incorporation of vegetables, including leaves of sweetpotato and bean, fruits rich in minerals, vitamins, and essential oils, and small livestock or fish that promote the bioavailability of plant sources of Fe, Zn, and pro-vitamin A.

The longer term trend within the region is market orientated and the need for a consistent, quality product. Monocropping and the intensive use of inputs, such as new cultivars, improved seed, pesticides, poles for climbing beans, is becoming more common; as is the use of low levels of fertilizer through which soil micronutrient deficiencies may eventually be corrected. However, many inputs remain beyond the financial resources of farmers, making them liable to failure. The changing practices have significant environmental and human health implications. The success of a future market- and nutrient-orientated farming system will depend heavily on the development of integrated methods for the control of the major pests and diseases, while at the same time safeguarding the environment and developing sustainable market linkages. Ultimately, however, the marketing of crops with better nutritional qualities will benefit the region at large as the fast-increasing urban population, particularly the poor, has access to them.

The change to a market orientation may have serious social consequences if the income is confined to the male head of household and the women have even fewer resources with which to maintain the household, a situation exacerbated by ever smaller land holdings. Fortunately, in Rwanda at least, where due to the civil conflict, women outnumber men by 60% to 40% in many areas, recovery has resulted in a more equitable sharing of both workload and income.

h. Conclusions. A review of 30 agricultural projects by Berti *et al.* (2004) showed that most agricultural interventions increased production, but not necessarily nutrition or health within the participating households. Of the interventions that did have some positive effect, most invested in four or five types of "capital": physical, natural, financial, human, and social. Those interventions that invested in nutrition education and considered gender issues were particularly successful. Also, interventions involving "home gardens" and vegetable production were more likely to be successful.

Traditional agricultural and health projects have not fully benefited the peoples of the Great Lakes region. The traditional root and legume crops are the most suited to the difficult environmental conditions and have the potential to address both PEM and micronutrient deficiencies. To maximize the value of these crops a holistic intervention is needed that not only introduces nutrient-rich cultivars, but improves understanding of the interactions of micronutrients on nutrition and health, increases total production, and addresses the important social issues of gender, nutrition education, including food preparation and the use of green leafy vegetables, and the partitioning of household income.

2. A Case Study: Maize–Cowpea Intercrop System, Zimbabwe

During the period 1996–2002, a development project was implemented in communal areas in low rainfall (300–500 mm) parts of southern Zimbabwe. In the communal areas, farmers are allocated small parcels of land, 1–3 ha, by the traditional chiefs, but have no title deed to that land and consequently have no collateral through which loans for production development might be accessed. Grazing areas are communally held. Only 15% of farmers are food self-sufficient in most years, 25% in some years, while 60% are never self-sufficient.

During an extensive series of participatory rural appraisals focused on community resource management, agricultural development problems and possible solutions, low or declining productivity of the maize crop was signaled as the most universal cropping problem. Mostly the soils are coarse granitic sands having poor moisture-holding capacities, with a hard pan formed at about 12-cm depth due to many years of superficial moldboard tillage with cattle. Deep tillage to allow roots to explore more soil volume for moisture and nutrients was not a practical option.

Low soil fertility was implicated—the few available soil analyses indicated most elements were low, but fertilizer application studies utilizing compound fertilizers had rarely resulted in economically viable responses. Further, due to their financial circumstances and a poorly developed distribution system, very few farmers (7–12% depending on district/rainfall) either used inorganic fertilizers or had tried and rejected them. Although some farmers (who had cattle) had attempted fertilizing with farmyard manure, the majority had rejected its use due to crop burning, particularly under the erratic rainfall conditions; it was found that they were applying manure at rates recommended for higher rainfall conditions.

Studies of N use, either mineral or organic (farmyard manure) at low rates, were shown to give yield increases of 30–100% but cost and availability meant that these were options for only the best resourced farmers (10–20%). Other options were needed for the poorer farmers.

In the past, cowpeas were a regular component of the cropping system in the low rainfall, communal areas of Zimbabwe. Severe droughts in the 1980s and early 1990s caused the loss of cowpea seed either directly from crop failure or consumption of seed cowpeas. Lack of a seed distribution network in the dry areas resulted in the almost complete disappearance of cowpeas. Cowpea was reintroduced to the cropping system in an experimental way with farmers each conducting an experiment on their own plot to compare cowpea intercropped with maize to maize monoculture. Nearly 700 farmers participated in this study.

Cowpeas were available from a seed company in Harare and the study team provided an initial distribution network and later established local seed multiplication initiatives utilizing innovative farmers. The question became, how to plant the cowpeas—as a sole crop or as an intercrop in maize? Older farmers spoke of maize–cowpea intercropping in earlier years but more recently extension messages had discouraged the practice. Further, the few experiments which had been carried out on a dryland research station near the study areas suggested very large maize yield losses due to intercropping, depending on seasonal conditions (Shumba *et al.*, 1990), although the sole maize yields were very much greater than expected by farmers. On the other hand, most farmers were constrained by the lack of draft animal power such that no more land could be cultivated for cropping. This latter factor and

Table XII
Yield Results (t/ha) from 685 Farmer-Managed Maize–Cowpea Intercropping Trials in Three Districts, Zimbabwe, 1998–2001 (Lough *et al.*, 2002)

	Shurugwi district	Zvishavane district	Mberengwa district
Maize without cowpea	1.10	0.75	0.50
Maize with cowpea	1.75	1.24	0.80
Increase with cowpea	0.65	0.49	0.30
Cowpea yield	0.14	0.22	0.08

shortages of labor for weeding an additional crop convinced the team to cautiously opt for intercropping.

Collaborating farmers were given small packs of various varieties, both long and short season and determinate and indeterminate types. These they planted in participatory adaptive trials—completely farmer managed, the innovation (cowpea) management dictated by the farmer's management techniques. This allowed a range of outcomes to be observed and analyzed.

Generally, maize was planted in 90- to 100-cm-wide rows with 30 cm between plants. Depending on the type, cowpeas were planted in one (indeterminate) or two (determinate) rows between the maize rows, normally at first weeding (about 4–5 weeks after maize planting). No fertilizer application to either crop was the norm.

Surprisingly, there were substantial yield increases obtained by the farmers (Table XII), admittedly from a low base. Furthermore, they indicated almost no runoff after rainfall, with accompanying elimination of erosive action, and a reduction in weeding required, particularly with indeterminate types.

In one administrative area (Ward 5) in Shurugwi district, there was nearly 100% adoption of this technology by the year 2000, the highest of all wards in the district. After harvest in that year, the headmaster of the Ward 5 Primary School remarked that since the children had been bringing lunches comprising cowpeas and maize rather than maize alone, the children had developed noticeably longer attention spans that he attributed to the cowpeas. The following year, this previously unexceptional school was the highest achiever in terms of academic results in the whole district! The local extension worker, Mrs. Dominica Shumba, working with more than 1000 farmers in 350- to 500-mm rainfall country won the National Extension Worker of the Year Award.

It is worth considering what improvements to the food system could possibly underpin the putative causal link between cowpea in the diet and improved scholastic performance identified by the headmaster. For a start, it is clear that the system is deficient in N that the cowpea can contribute through N fixing nodules on its roots and its consequently higher protein level in the grain. While legume protein is commonly deficient in sulfur amino acids, it can complement maize protein with more lysine. More importantly for scholastic performance, cowpeas are not only higher in Fe and Zn than maize, but they contribute promoters of absorption and utilization of both these two elements that have been widely linked to cognitive ability in children but which are widely deficient in resource-poor populations. The leaves of cowpea if consumed fresh in soup with Fe from either maize or cowpea itself, as is common practice, contain vitamin C that strongly promotes Fe absorption; moreover, selected varieties contain significant pro-vitamin A (also in yellow, orange, and red varieties of maize but not in white types common in Zimbabwe) that promotes absorption and/or utilization of Zn as well as Fe. In addition, addressing likely deficiencies of vitamin A, Fe, and Zn will greatly improve immune competence that should result in less absenteeism through childhood diseases like diarrhea and colds and flu.

Cowpea thus makes a major contribution to the quality of the food system as well as to the agronomy of the cropping system in terms of food productivity. It is important to consider how this food system could be further improved with respect to the health of the population, especially children. On a global scale, after Fe, Zn, and vitamin A, the most common deficiencies in subsistence diets are of I and Se, both deficiencies are widespread in East Africa generally. Deficiency of I is endemic in Zimbabwe, being most severe in the north and northeast of the country. These two deficiencies can be corrected through the food system by use of I- and Se-fortified fertilizers that have been successful in other countries, but this strategy depends on widespread and extensive use of base fertilizers that is not the case in this target area. As only minute amounts of these two nutrients are required, it may be practical to spread them by air over large areas in a matter of hours, an initiative that would need to be undertaken by the government after consultation with FAO, WHO, and the communities. The advantage of this method is that no change in behavior would be needed from the farming community. The benefits in vigor, immune competence, and resistance to the spread of HIV are discussed in earlier sections. Finally, encouraging the use of small amounts of fresh, homegrown vegetables, herbs, and spices and small livestock can contribute functional components to the diet both known (especially vitamin B12) and not yet known to science.

G. The Rice–Fish System: The Value of Rice–Fish Farming Systems as a Nutrient Delivery System for Households and Communities

Rice–fish farming systems have been in practice for over two centuries by Asian communities where monsoon rains ensure the reliability of rain-fed rice–fish systems. However, with the expansion of aquaculture and further rice–fish system research, these systems have expanded into other areas throughout the world, particularly those areas having high human population densities or where native fish naturally found in ponds and rivers have been heavily fished. This section will summarize some of the potential productivity levels that have been reached successfully, the agronomic/aquaculture practices necessary for sustainable productivity while emphasizing the potential for these rice–fish systems to deliver important nutrients and diet diversity to communities where malnutrition still exists. Constraints to the systems' expansion will also be discussed and possible improvements suggested as to its sustainability and dietary, agronomic, and societal acceptability.

1. Productivity Levels

Rice–fish systems can be either "capture" or "cultivated" depending on whether fish are allowed to enter from a surrounding pond or fields to reproduce within the rice field or are stocked from fingerlings released to the rice field. Mixing fish culture with rice cultivation often provides an increase in rice productivity and profits due to fewer pesticides required, and the contribution of fish to rice soil fertility. Some have reported fewer weeds in shallow rice–fish cultivation, adding to productivity and profit of the system.

China, where rice–fish systems developed centuries ago, had over 138,000 ha area in 1986. This represented only 1.5% of all rice lands of which 50% are claimed to be suitable for rice–fish. The productivity of the fish then was 183 kg ha^{-1} (Defu and Maoxing, 1995; Renkui *et al.*, 1995). This increased dramatically during the next decade to 1.2 million ha with an average productivity of over 310 kg ha^{-1} fish and generally 10–20% increases in rice yields in most locations (Table XIII).

There are many countries that record rice–fish production, some having expansion rates up to 34% , for example in Egypt (Fig. 7). Productivity levels vary widely among the countries, depending on the intensity of cultivation and length of maturity of the rice varieties. In China, yields of fish above 3 t ha^{-1} have been recorded for a range of conditions (MacKay, 1995). However, even with the averages recorded in Table XIII, there is substantial benefit from fish cultivation concurrent with rice. One study recorded fish yields ranging between 62 and 81 kg ha^{-1} were sufficient to "break-even" with the additional resource investment (Gupta *et al.*, 1998).

2. Agronomic Management Practices

There have been many papers describing the various technical details of the physical modifications required to create an environment suitable for rice–fish cultivation [Gregory, 1997; Halwart, 1998 (lists many of those

Table XIII
Countries Having Rice–Fish Systems Listed, Although not All Countries Record Data

Country	Area (ha) in rice–fish cultivation	Rice–fish productivity (kg ha^{-1})	References
China	1.2 million	310 (average) 150–450	FAO, 1997 Renkui *et al.*, 1995
Egypt	173,000		Halwart, 1998
Indonesia	138,000		Siregar *et al.*, 1998
Thailand	25,500	25	FAO, 1997
India	Not determined but practiced		Halwart, 1998
Sri Lanka	Not determined but practiced		Halwart, 1998
Philippines	Not determined but practiced		Halwart, 1998
Madagascar	13,400	100	Randrianiarana *et al.*, 1995; WARDA, 2003
Malawi	Not determined but practiced		WARDA, 2003
Vietnam	40,000	90–155	Lazard and Cacot, 1997
Bangladesh	Not determined but practiced	212–233	Gupta *et al.*, 1998

review papers); Halwart and Gupta, 2004]. However, the practices common to most systems are listed here. For rice varieties, the choice of modern varieties or landraces does not offer any constraints to the system—both work equally well as long as they are locally adapted and suitable (Halwart, 1998). Many species of fish can be used with varying commercial and nutritional values. Obviously the grass carp and other fish that consume plants are not encouraged. Also, carnivorous fish need to be cultivated singly or not at all for obvious reasons. Integrated pest management (IPM) is practiced by most rice–fish cultivators owing to concern about the use of pesticides on fish cultivation. Fish themselves can further reduce pest populations by their pest consumption, offering further savings of pesticides. Fish feeding activities has been shown to reduce weed growth in shallow rice–fish systems (Piepho, 1993). Increased supplemental fertilization in this system over rice monoculture is usually practiced. Fish have been shown to increase the soil fertility, thus increasing rice yields in many locations (Gupta *et al.*, 1998). Additional irrigation is required for areas where rainfall is unreliable. In Bangladesh, the average additional water requirement for fish was

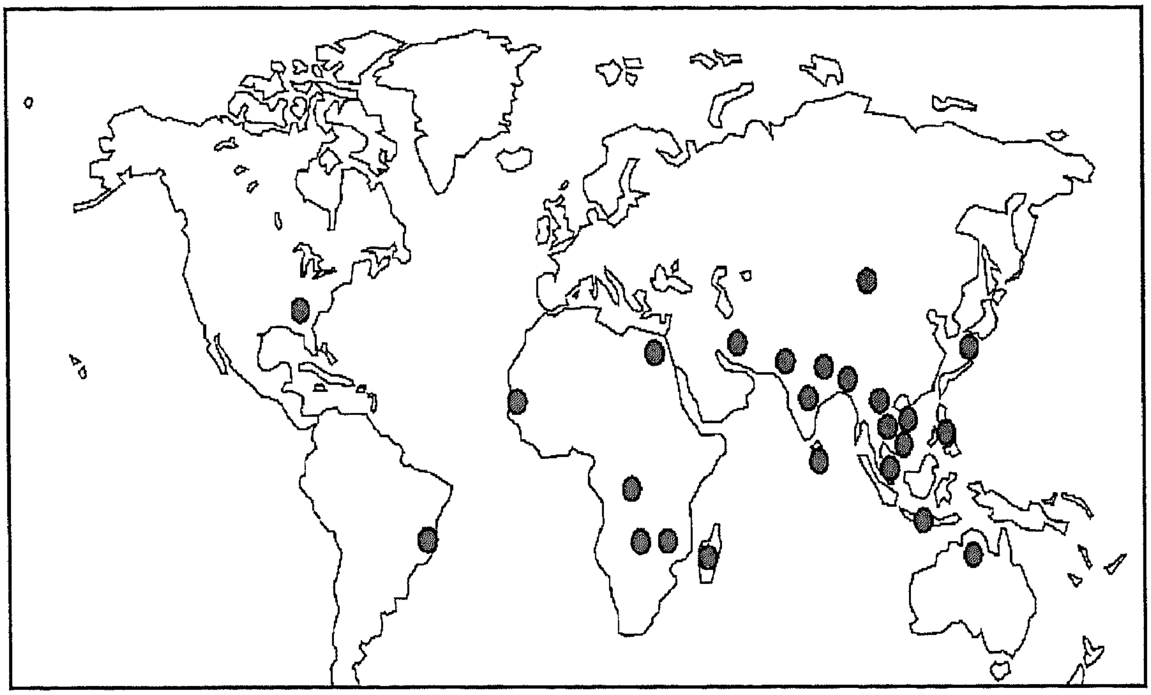

Figure 7 Map of the world showing areas where rice–fish and/or rice–crustacean farming is practiced (Halwart and Gupta, 2004).

estimated at 26% more than for rice alone (Gupta *et al.*, 1998). Aquaculture alone now accounts for 31% of fish consumed but will expand further as captured fish from ponds and rivers is becoming depleted.

3. Sustainability Issues

Reliable rainfall is necessary for cultured fish in the rice fields. Sometimes fields can have depressions where fish can "escape" when rainfall level drops or supplemental irrigation is unavailable. Growers with larger land properties can have the rice fields open up into a pond to avoid any temporary drought so the fish can escape to the pond and be self-released when the rice paddy is again flooded. Thus, marginal farmers with less land become less involved in rice–fish due to the risks, labor time, inability to obtain credit, and less land available for rice–fish to allow for "escapes" in times of drought (Gupta *et al.*, 1999). Theft of fish in the rice fields is a concern where there are too few growers practicing aquaculture or the rice–fish system. Table XIII indicates those countries having or trying rice–fish cultivation, but whose area is so low that it is not officially recorded. Literature indicates potential for expansion in all these countries in the future. The case study of rice–fish expansion in Madagascar may be studied as "lessons learned" since external assistance had ended (Halwart, 1998).

4. Food Composition Values Emphasizing Genetic Variability in and Reliability of Food Composition Data

Much of the data concerning food composition will concentrate on Bangladesh, where much nutritional literature and valid data can be found (Table XIV). In Bangladesh, only 6% of the daily protein intake of 48 g per capita came from fish in 1983 (Ahmad and Hassan, 1983). However, of the protein derived from animals, 59% is from fish. Thus, the potential remains for rice–fish to address malnutrition. The addition of fish to a rice-based diet has potentially huge benefits nutritionally. Rice, especially milled, white rice, is relatively low in protein, very low in Fe, low in Zn, low in Ca, supplies no vitamins A and C, and is further deficient in fat, B vitamins, including B12, folate, I, and Se. Fish, especially small fish such as mola that are eaten whole, can complement rice in covering practically all of its nutritional limitations with the possible exceptions of the last two in the case of freshwater fish (sea fish are valuable sources of I and Se). It is important that such subsistence farmers realize the great nutritional advantage in consuming these small fish rather than using them only as a cash crop. In an I-deficient area, freshwater fish are likely to be as deficient as the people so other sources of I must be

Table XIV
Nutrient Intake (per capita day^{-1}) in Bangladesh During 1962–2001

Nutrient	1962–1964[a]	1975–1976[b]	1981–1982[c]	1995–1996[d]	2000–2001[e]
Energy (kcal)	2118.0	2094.0	1943.0	1868.0	2080.0
Protein (g)	55.3	58.5	48.4	46.9	64.5
Fat (g)	20.1	12.2	9.8	15.9	19.6
Carbohydrate (g)	Not reported	439	412.0	384.0	421.2
Ca (mg)	286.7	305.0	260.0	335.3	379.6
Fe (mg)	9.4	22.2	23.4	11.4	17.6
Vitamin A (I. U.)	1670	730	763.0	1668.0	1892.0
Thiamin (mg)	1.35	1.65	1.38	1.17	2.68
Riboflavin (mg)	0.54	0.87	0.68	0.48	0.87
Niacin (mg)	20.5	22.21	13.15	18.34	–
Vitamin C (mg)	39.9	9.51	13.00	32.8	71.1

[a] Nutrition Survey of East Pakistan (1962–1964), Ministry of Health, Government of Pakistan in collaboration with the University of Dhaka, Dhaka, 1966.

[b] Nutrition Survey of Rural Bangladesh (1975–1976), Institute of Nutrition and Food Science, Dhaka University, 1977.

[c] Nutrition Survey of Rural Bangladesh (1981–1982), Institute of Nutrition and Food Science, Dhaka University, 1983.

[d] Jahan and Hossain (1998).

[e] Computed from the reported food intake in "Household Income and Expenditure Survey (2000), Bangladesh Bureau of Statistics, Dhaka (2003)."

found. Iodized salt is the most likely but seaweed from the ocean can suffice if available and part of the culture. If the area is Se deficient, a solution from outside is necessary although garlic has the capacity to concentrate Se and much of its odor can be due to Se compounds. External sources are obviously foods from Se-adequate or Se-rich areas, such as wheat from North Dakota where soils are unusually high in Se and wheat Se is an unusually bioavailable source of this essential mineral. Fertilization with Se as sodium selenate is very effective but it is not widely used as no yield advantage can be expected.

Among fish, small indigenous fish are usually consumed whole and thereby provide a substantial source of Ca from their bones. Vitamin A content varies widely among fish species: from more than 15,000 RE kg^{-1} raw edible part for mola, a small indigenous species *Amblypharyngodon mola*, to less than 1000 RE kg^{-1} for most of the cultivated carp fish species (Roos *et al.*, 2002, 2003). Most of the vitamin A comes from the retinol in the fish eyes and viscera. In their study, fish consumption was unaffected by the domestic aquaculture production indicating that fish cultivation did not change household fish consumption. However, 84% of the total fish consumed was from the small indigenous species, contributing 40% of the recommended vitamin A intake at the household level. Thus, while fish consumption may be unaffected by rice–fish or aquaculture, the species of fish such as mola can be integrated in existing carp culture without negative effects and can contribute to increased household vitamin A intake. It is noteworthy here that in high arsenic (As) areas, mola also contain high concentrations of As but being entirely in the organic form, it is nontoxic to humans.

Halwart and Gupta (2004) reviewed papers relating to nutritional advantages to rice–fish cultivation and concluded that improvements of a farming household's nutrition as a result of culturing fish in the rice fields may just be an incidental and perhaps even indirect effect such as being able to buy meat or chicken as a result of the extra cash earned from fish. The main benefit of rice–fish farming is often seen as providing an opportunity to earn cash, so an education program of the nutritional advantages of household consumption of some of the fish harvested is required.

5. Socioeconomic and Policy Environments and Constraints

Because of the increased system benefits of rice–fish to both enterprises, most studies reviewed have shown very favorable increases to profitability with rice–fish cultivation with few of the net benefits from rice–fish culture being lower than that of rice monoculture alone (Gupta, 1998; Halwart and Gupta, 2004; MacKay, 1995).

Reliable rainfall or external water sources must be maintained for rice–fish culture to continue to expand. When water becomes limiting, many studies show that rice–fish cultivation loses its appeal due to the risks. Additionally, most literature reviewed indicates the major constraint to the systems' expansion is the lack of fingerlings at the time of rice–fish cultivation (Halwart, 1988; Little *et al.*, 1996). Where this system is well established, fingerlings are available and rice–fish cultivation is more widespread, such as in China.

6. Conclusions (Improvements to the System)

The main beneficial effects of rice–fish systems are related to environmental sustainability, system biodiversity, farm diversification, and household nutrition (Rothuis *et al.*, 1998). Research results on rice–fish systems indicate that with proper classification of rice-producing areas for their suitability for rice–fish farming, and consideration of the capacity of the irrigation infrastructure, general soil characteristics, physical requirements as well as the socioeconomic situation, its area can expand. This expansion can make impacts in maintaining marketable fish within the communities but when these same communities are empowered with knowledge of nutrients found in the varying fish species, their choice of species can affect their household and community nutritional status. Hidden benefits of rice–fish farming such as risk reduction through diversification of the farming system may have a strong attraction to many farmers and their families (Halwart and Gupta, 2004).

V. THE SOCIOECONOMIC AND POLICY ENVIRONMENTS

A. Household Incomes, Food Prices, and Agricultural Development

Interventions to improve the minerals and vitamins supplied by the cropping system at any given time should be understood in the context of agricultural and economic development over time. In this context, per capita intakes at the household level are generally a function of that household's income and food prices. We first examine income.

Table XV shows per capita energy intake and share of food expenditures by broad food groups by income group for three countries. At low incomes the poor give priority to purchasing food staples, the most inexpensive source of energy, to keep from going hungry. Then at the margin as income increases, they buy non-staple plant foods (e.g., lentils, fruits, vegetables) and animal products (including fish) because of a strong underlying preference for the tastes of these foods.

Table XV

Per Capita Energy Intakes (kcal day^{-1}) and Food Budget Shares by Broad Food Group by Income Group for Three Countries

	Bangladesh				Kenya					Philippines				
	Income tercile				Income quartile					Income quartile				
Per capita energy intake	1	2	3	All households	1	2	3	4	All households	1	2	3	4	All households
Staples	1805	1903	1924	1879	1283	1371	1388	1394	1360	1361	1431	1454	1381	1406
Non-staple plant	281	347	394	340	256	348	363	464	357	197	229	304	395	281
All animal	44	61	89	64	112	120	161	187	145	67	102	118	207	124
Total	2130	2311	2407	2283	1651	1839	1912	2045	1862	1625	1762	1876	1983	1811
Food budget share (%)														
Staples	46	41	36	40	Data not available					43	36	28	24	33
Non-staple plant	32	35	36	34						30	36	39	37	35
All animal	22	24	28	26						27	28	33	39	32
Total	100	100	100	100						100	100	100	100	100

Derived from data of Bouis (1996) and Bouis *et al.* (1992, 1998).

Although diets are expressed in Table XV only in terms of energy (and not minerals and vitamins), because non-staple plant foods and animal products are denser than food staples in bioavailable minerals and vitamins, percentage increases in mineral and vitamin intakes rise much more sharply with income than do energy intakes. Animal products are the most expensive source of energy, but the richest sources of bioavailable minerals and vitamins.

There is a natural underlying tendency, then, for dietary quality to improve as economic development proceeds. As household income rises and demand for non-staple plant foods and animal products rises, prices for these better quality foods will tend to rise, all things being equal. These price signals, in turn, will give rise to supply responses from agricultural producers. The essence of economic (in this case agricultural) development is that technological improvements will be stimulated (e.g., development of higher yielding varieties either through public or private investments in agricultural research) which in turn will lead to more efficient production, faster supply growth rates, and eventually lower non-staple food prices.

It is the role of public food policies to influence this long-run process so that aggregate growth is rapid and so that all socioeconomic groups (importantly the malnourished poor) share in the benefits of this growth. With this as background, we now briefly examine food prices and the role of the Green Revolution in influencing food prices.

Figure 8 shows the percentage increases in developing country population, in cereal production, and in pulse production between 1965 and 1999. Developing country population doubled during this period. It is the great achievement of the Green Revolution that cereal production more than doubled due to rapid technological change. After adjusting for inflation, real cereal prices have fallen over time despite the doubling of developing country population. As suggested in Table XV, the poor spend a high percentage of their income on food staples, and lower cereal prices frees up income that eases their burden and can be spent on a range of necessities, including better quality food.

Pulse production in Fig. 8 is representative of increases in production for any number of non-staple plant foods. Production increased significantly, but did not keep pace with growth in demand—due both to population growth and income increases as developing country economies have grown. There was no commensurate technological change in the non-staple food sector. Consequently, inflation-adjusted prices of many non-staple foods have increased over time.

This change in relative prices—lower food staple prices and higher non-staple food prices—has made it even more difficult for the poor to achieve mineral and vitamin adequacy in their diets. Certainly, in the absence of knowledge among the poor about the importance for health of a nutritious diet and what relatively inexpensive non-staple foods can provide in terms of

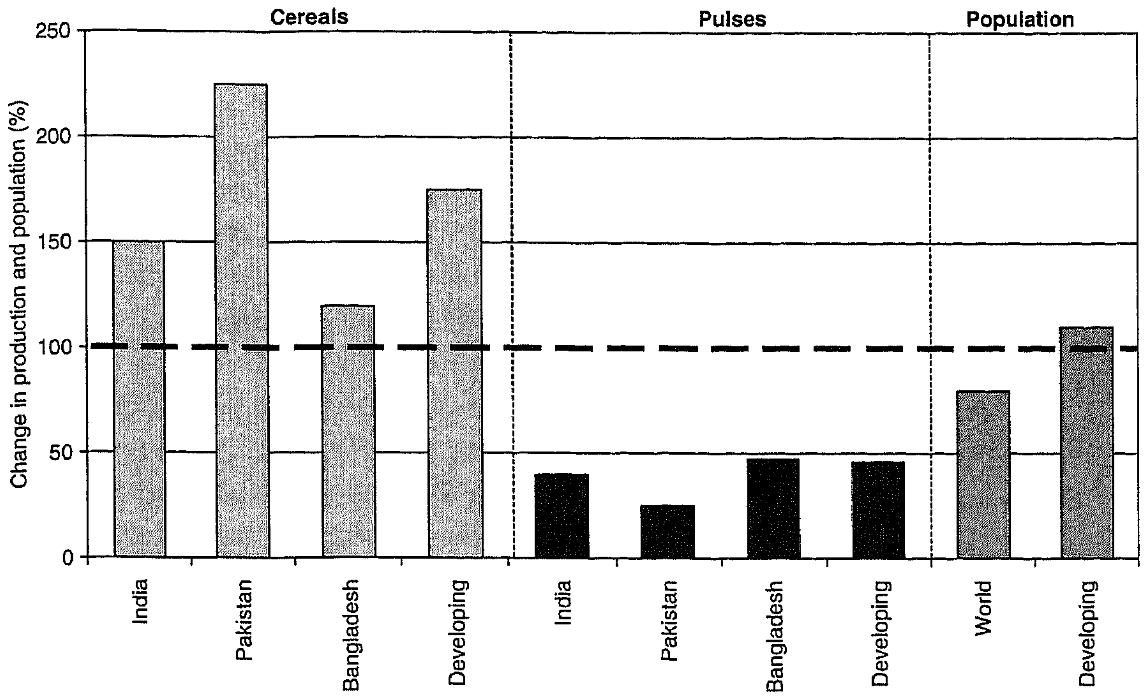

Figure 8 Percentage changes in cereal and pulse production and in population, 1965–1999.

minerals and vitamins, for those poor whose incomes have remained constant, price incentives have shifted the diet more and more toward reliance on food staples. As described in previous sections, this has led to a worsening of mineral and vitamin intakes for many segments of developing country populations, micronutrient malnutrition, poor health, and much misery.

To reiterate, the long-run task of public food policy is to stimulate growth in the non-staple food sector (sometimes referred to as "high-value" agriculture) through any number of instruments-agricultural research, education, building infrastructure, improving markets for agricultural inputs and outputs to name a few. However, this is a several-decades-long process. In the meantime, again as described in previous sections, there are specific, cost-effective steps that can be taken to utilize agriculture to improve mineral and vitamin intakes. Policy aspects are discussed below for three interventions already discussed in agronomic terms in earlier sections: (1) additions of essential trace elements to soils, (2) biofortification, and (3) introduction of novel, nutrient-dense crops into the food system.

B. Additions of Essential Trace Elements to Soils

As documented in previous sections, minerals severely lacking in human diets can be added to food systems by additions to the soil—using commercially produced fertilizers applied on the ground, by air and through irrigation systems. To justify implementation of any variants of this strategy, the basic economic principles are (1) that the benefits to human health and greater agricultural production are greater than costs of implementation and (2) that where the private sector is involved there are proper incentives for participation and equal treatment of companies.

1. Direct Additions Through Public Action

The DeLong study in western China (Cao *et al.*, 1994) already discussed provides evidence that a strategy of adding I to an irrigation system provides a simple, low-cost method for getting I into the food system and into the diets of people who are I deficient. In this well-documented case, the benefits to public health are substantially higher than costs. Moreover, there are benefits to livestock production as well.

While this one case demonstrates a principle, much of agriculture, however, is rainfed and often it will not be possible to use an irrigation system as a delivery mechanism. Other means of delivery such as through spraying by air and adding the nutrient to other fertilizers already in use are practicable and may be cost-effective in given situations. To the extent that both human and plant health are limited by the availability of the trace mineral being applied, Zn for example, benefits will be high. To the extent that a single application may be sufficient to generate benefits over several years, costs will be low (unlike N that needs repeated applications). Economies of scale in delivery and lack of alternative means of delivery (e.g., in areas of Africa where fertilizer markets are poorly developed or nonexistent) may provide the rationale for public intervention as compared with relying on private incentives to improve soil fertility. Carefully researched pilot activities which successfully document high benefits and low costs will be required to convince policymakers that innovative solutions to supplying trace minerals to soils should be implemented.

2. Fortification of Fertilizers

In areas where fertilizer use by farmers is already widespread, it is technically feasible to "fortify" fertilizers with specific trace minerals—as a vehicle for getting limiting trace minerals into soils, then into plants, and the overall food system. In the case of Zn where the profits from increased yields can far exceed the extra cost of Zn-enriched fertilizers, it may be enough through public research simply to document the benefits of Zn for yields to jump-start private sector efforts to develop supplies and a market for fertilizers with Zn—as happened in Turkey (Cakmak, 2002).

Where an increased supply of trace minerals could contribute to public health, but not to agricultural productivity, two related strategies are possible. The government could require (pass laws) that all fertilizers be fortified with particular trace minerals to certain minimum standards. This will increase fertilizer costs to farmers (fertilizer producers will pass the increased production costs on to their customers) and necessitate establishing institutions so that the law will be enforced. If fertilizer prices were significantly affected, the government could choose alternatively to subsidize these additional production costs so that fertilizer prices would remain unchanged; laws mandating fertilizer fortification would still require enforcement and subsidy payments would require oversight.

Again, carefully researched pilot activities which successfully documented high benefits and low costs would be required to convince policymakers to implement such laws and to incur the cost of such subsidies.

C. BIOFORTIFICATION

Technical issues associated with biofortification and the potential economic benefits of biofortification have been discussed in previous sections and elsewhere (Graham *et al.*, 2001). With this as background, there are two primary policy issues: (1) should the government require that all new releases (public and private) for given crops contain minimum levels of specific minerals and vitamins and, related to this, (2) what level of public resources should be invested in biofortification as part of its investment in agricultural research?

As more scientific knowledge and experience is gained with biofortification, as more efficient methodologies are developed, the costs of including mineral and vitamin density as part of "standard practice" in breeding may become quite manageable. If so, then there will be strong incentives in terms of improved public nutrition and health to require minimum levels of minerals and vitamins in the edible portions of new releases.

What levels to investments in biofortification are appropriate will depend in part on the costs of alternative instruments which are available for providing nutrients in the food system—for example, supplementation, fortification, fertilizer strategies discussed above, and introduction of new crops in cropping systems which is discussed below. Biofortification may be conceptualized as a subset of this last activity—introducing a new crop line into the food system if not a completely novel crop. It has the advantage over the supplementation, fortification, and fertilizer strategies that most costs are incurred up front. That is, they do not involve the same recurrent costs year after year.

D. INTRODUCING NEW NUTRIENT-DENSE CROPS INTO CROPPING SYSTEMS

To illustrate this strategy, consider the case of the introduction of orange-flesh sweetpotato (for which there are specific lines very dense in β-carotene) into a food system that is severely deficient in vitamin A. In some cases, it may be that white sweetpotato varieties are already being consumed. In other areas, sweetpotato may be a completely novel crop. In either case, a communication strategy would need to be developed, directed not only at users but at policymakers and diffusers of this technology (diffusers ultimately report to policymakers who provide, or do not provide, an enabling environment to implement the dissemination strategy). Effective communication creates demand for vines, ensures suppliers, and markets to link supply. Demand would need to be motivated by a message of improved nutrition. Finally, after the initial public investment introducing the new crop into the food system, at some point public activities would need to be withdrawn, leaving in place a supply–demand marketing chain operating within the market economy.

VI. CONCLUSIONS

Many national food systems have become dysfunctional, failing to supply all the nutrients required for healthy crops and for healthy people dependent on those crops for nutriture. This is a global problem affecting most people, rich and poor. However, agricultural strategies and tools are available to redress these problems that appear to date back to the loss of diet diversity induced by changes in agricultural systems during the Green Revolution. Agronomists, and indeed the whole agricultural sector, need to understand the implications their activities have on the nutrient delivery of the food systems they work with, and to consider their role as developing, in partnership with nutritionists and primary healthcare officials, sustainable cropping systems that can deliver nutrients in balance to whole populations. Much of this new agenda will need to focus on micronutrient inputs and outputs of farming systems, and will require access to analytical laboratories and careful attention to nutrient interactions in soils, crops, animals, and humans. The complexities of food systems, of micronutrient chemistry and biology, as well as the opportunities available in molecular and digital technologies offer exciting challenges to agronomists willing to tackle, collaboratively, one of the world's most pressing issues—malnutrition and the devastating effects it has on human health and well-being and on societies as a whole.

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