The Fight Against Hunger and Malnutrition

The Role of Food, Agriculture, and Targeted Policies

Edited by
David E. Sahn

OXFORD
UNIVERSITY PRESS

2015

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The Micronutrient Deficiencies Challenge in African Food Systems

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Introduction

Per Pinstrup-Andersen was among the first to call attention to the "triple burden" of malnutrition that transcends insufficient dietary energy supply to encompass problems of overweight/obesity and micronutrient deficiencies as well (Pinstrup-Andersen 2005, 2007). He has also been among the most articulate analysts of the complex linkages between producers, consumers, and marketing intermediaries in food systems in developing countries (Pinstrup-Andersen 2007, 2010; Pinstrup-Andersen and Watson 2011; Gómez et al. 2013). In this chapter, we celebrate Per's insights in both of these dimensions with a review of the oft-overlooked role of micronutrient deficiencies and their relation to nutrition-related poverty traps, with an emphasis on the many entry points within food systems where micronutrients deficiencies might originate and be remedied.

"Hidden hunger" due to micronutrient (mineral and vitamin) deficiencies is widespread. Iron deficiency is one of the most common nutritional disorders worldwide (McDowell 2003). About 1.6 billion people (25 percent of the global population and almost 50 percent of children worldwide) suffer from anemia, of which half is iron-deficiency anemia, while iron deficiency without anemia is equally common (Horton and Ross 2003; WHO 2008). One-third of school age children and a similar share of the global population suffer from insufficient iodine intake and are, therefore, at risk of iodine deficiency disorder (IDD), even though over half of the world's population has access to iodized salt (WHO 2004). Vitamin A deficiency affects up to 21 percent of children under 5 (WHO 2009). Food availability data suggest that at least one-third of the global population suffers from zinc deficiency (Hotz and Brown 2004).

Widespread micronutrient malnutrition is particularly problematic, given the potential irreversibility of its effects. Even short periods of severe micronutrient malnutrition in utero or during early childhood can permanently damage a child's future physical ability, cognitive capacity, and civic and economic productivity. For example, severe iodine deficiency is the most common cause of preventable mental defects worldwide, and even mild iodine deficiency, which also falls under the broad category of IDD, reduces cognitive abilities (Hetzel 1990; Hetzel and Wellby 1997). Severe selenium deficiency in utero is associated with cretinism, and even mild selenium deficiency in pregnant women can have lifelong health impacts for their unborn children through miscarriage, preeclampsia, and pre-term labor (Mistry et al. 2012). Vitamin A deficiency is a leading cause of acquired blindness in children (WHO 2009). Zinc deficiency causes abnormal labor and fetal abnormalities in pregnant women, retards physical growth and cognitive capacity in children, and delays sexual maturity in adolescents (Prasad 2003; Hotz and Brown 2004). Micronutrient deficiencies can thereby lead to permanent impairment, especially among young children who neither understand the consequences of insufficient intake nor have much agency over their diets. And by degrading human capital, such irreversible cognitive and physical impairment may readily lead to poverty traps (Barrett 2010; Barrett and Carter 2013).

The widespread prevalence and stubborn persistence of micronutrient deficiencies is illustrated in Figure 3.1, which depicts the association between global national income (GNI) per capita and the national-scale prevalence of wasting (weight-for-height Z-score < –2), several micronutrient deficiency indicators, and stunting (height-for-age Z-score < –2). This relationship depicted reflects a simple univariate logarithmic regression, using the most current indicators available in reasonably consistent form.[1] Note that the prevalence of wasting, characterized by extremely low weight-for-height and caused primarily by insufficient macronutrient (mainly calorie and protein) consumption, poor sanitation, and early childhood infections, starts relatively low and falls rapidly with growth in a country's GNI. This suggests that people increase macronutrient intake fairly immediately with a rise in income.

By contrast, stunting (characterized by extremely low height-for-age) and indicators of micronutrient deficiency appear much less responsive to growth in GNI. Stunting reflects the cumulative impact of all insults to health, including macro- and micronutrient deprivation, and particularly in early childhood (Thomas et al. 1991; Fogel 2004). The primary clinical indicator for zinc deficiency, for example, is stunting (Hotz and Brown 2004), and iron deficiency is also associated with stunting (Yip 2001).

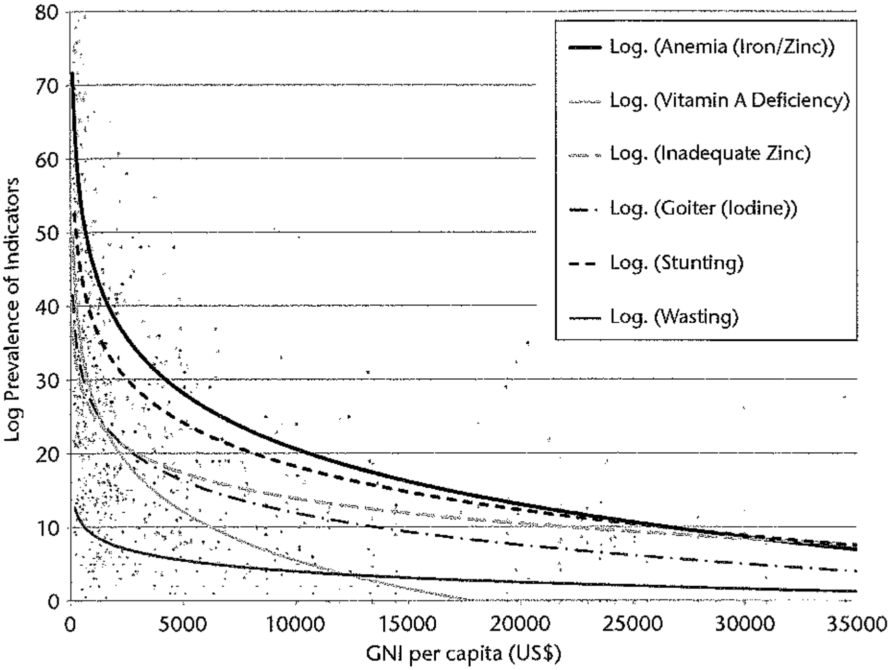

Figure 3.1 Associations among income and malnutrition indicators

Data sources:

GNI data from World Bank (2014).

Anemia, vitamin A, and zinc indicators from United Call to Action (2009).

Goiter data from World Health Organization's *Iodine Status Worldwide 2004* (WHO 2004).

Stunting and wasting data from UNICEF (2013).

With the exception of vitamin A deficiency, which declines at a faster rate than wasting, micronutrient deficiencies and stunting appear much less responsive to growth in GNI per capita than does wasting. The average prevalence of each micronutrient indicator is higher than the average prevalence of wasting at all levels of GNI and remains at unacceptably high levels of 30 percent or more throughout the low-income range and above 10 percent throughout the middle-income range.[2]

Figure 3.1 strongly suggests that while dietary energy intake increases as income rises, leading to reasonably rapid improvements in the undernourishment measure that serves as the United Nations' Food and Agricultural Organization's (FAO's) central indicator of hunger and food insecurity, micronutrient intake does not always increase at the same rate.

This pattern is somewhat counterintuitive, as economists commonly believe that the income elasticity of dietary diversity, the main source of dietary minerals and vitamins, is greater than one, meaning dietary diversity increases faster than income. So why are micronutrient deficiencies so much less responsive to income growth than are the wasting or undernourishment indicators that guide most popular and high-level policy and popular discussions of hunger and food insecurity? There are multiple prospective reasons for the apparent slow response of micronutrient deficiencies to income growth, each related to different, important features of food systems. Knowing where within the food system these problems originate, and why, is essential to targeting and prioritizing among candidate policy and technology interventions. It is therefore important to begin integrating the disparate research findings that exist on the etiology and effective treatment of micronutrient deficiencies into a more holistic food systems perspective. That is the central aim of this chapter.

Is this primarily a downstream problem due to inadequate consumer understanding of micronutrient deficiencies, and dietary transitions associated with income growth and urbanization, as well as consumer response to changing relative prices among food groups? In such circumstances, consumer education and outreach, and perhaps subsidies for micronutrient-rich foods and/or "sin taxes" on unhealthy foods that too often substitute for mineral- or vitamin-dense ones, may be policy instruments of choice.

Or maybe the problem originates mainly—or is most cost-effectively addressed—within the marketing channel that delivers food from farmers to consumers. This would be especially true if supply chain intermediaries fail to preserve micronutrients in perishable or processed products or to fortify foods with minerals and vitamins where feasible and affordable. Addressing micronutrient deficiencies along the value chain may require improved fortification, processing, and storage technologies, along with, potentially, food quality certification.

Alternatively, the problem might originate primarily at the upstream end, either in cropping patterns and practices that limit the mineral and vitamin content of harvested foods, or in micronutrient deficiencies in the soils and water from which edible plants extract essential minerals. In the former case, research and extension, improved marketing arrangements, or other interventions to induce greater production of micronutrient-rich foods may be a policy priority. If the problem is micronutrient deficiencies in the natural resources used to produce food, however, then minerals must be added, either as nutrient amendments in fertilizers or irrigation water, or by advancing new, micronutrient-dense cultivars (biofortified crops) that can be grown in the appropriate setting, or through post-harvest fortification.

Where should policymakers invest in order to accelerate the reduction of micronutrient deficiencies during the process of economic development and income growth? Unfortunately, the scientific community presently lacks compelling, integrated evidence to inform clear prioritization of the limited resources that governments, non-profits, and agri-food firms have to address the widespread micronutrient deficiencies that plague the low- and middle-income world. While we know something about where in the food system micronutrient deficiencies originate, this knowledge is not being integrated, in the sense of being able to assess comparatively sources of micronutrient deficiencies. Nor do we know much about the relative effectiveness of alternative policies or technologies to remedy these problems. Moreover, it seems highly likely that problems exist at multiple points along the food value chain, that the relative balance among them varies sharply among distinct sub-populations, and that policymakers lack guidelines to steer communities through this intrinsic heterogeneity.

In this chapter we examine a few specific reasons why micronutrient deficiencies might not decline quickly with rising GNI per capita. We nest this within a food systems perspective, in an effort to make a small step towards a more holistic approach to diagnosing and treating the serious challenge of micronutrient deficiencies. We focus primarily on African food systems, as this is the world region in which micronutrient deficiencies are most severe.

Consumer Demand Patterns

As incomes grow from a very low level, the elasticity of macronutrient (calorie and protein) intake with respect to income growth appears to decrease rapidly (Deaton 1997). Beyond some rather low level of food expenditure at which energy and protein intake becomes sufficient to transcend the physical discomfort of hunger, consumers' non-nutritional preference for variety, taste, appearance, convenience, and social status of foods—and demand for non-food goods and services—seems to predominate (Strauss and Thomas 1998; Barrett 2002). By contrast, micronutrient malnutrition is often called "hidden hunger" because, unlike the physical sensations of stomach pain or fatigue that commonly signal energy or protein deficiency and trigger food consumption to take in macronutrients, mineral and vitamin deficiencies rarely manifest themselves in obvious sensory ways until the condition becomes severe. Thus, individuals are often unaware that they lack essential minerals and vitamins.

The difference in the sensory feedback loop between macro- and micronutrients could help explain the apparent income elasticity differential between micronutrient deficiencies and more palpable forms of protein-energy malnutrition as an information problem. If true, then educating consumers and cooks, especially mothers who commonly make food choices on behalf of their children, about micronutrients would seem a logical strategy. Indeed, efforts to promote breastfeeding and appropriate complementary feeding practices for young children aim in part to reduce child micronutrient malnutrition (Isabelle and Chan 2011). However, little empirical evidence exists on the linkage between information/education and micronutrient deficiency. Existing studies that do evaluate nutrition education interventions tend to focus on macronutrient rather than micronutrient intake, to be located within the developed rather than developing world, and to evaluate interventions using potentially biased, self-reported outcomes rather than objective, measured outcomes such as biomarkers (Abood et al. 2004; Kroeze et al. 2011; Poelman et al. 2013). Until more research is done, the linkage between nutrition knowledge and micronutrient deficiency will remain a largely untested hypothesis.

Information gaps are just one of the candidate explanations at the downstream, consumer end of the food system. Across the developing world, rising GNI is associated with a "nutritional transition" as consumer diets naturally evolve with increasing disposable income. This transition differs across regions, but is generally characterized by a diversification away from traditional staples of coarse grains, legumes, and roots and tubers, and accompanied by increasing consumption of finer grains like rice and wheat, of animal-source foods, of temperate fruit and vegetables, and of "Western" processed foods high in sugars and fats (Regmi 2001; Pingali 2006).[3] This dietary transition can either accelerate or decelerate micronutrient intake. We review a few potential impacts next.

Rising income is almost always accompanied by greater consumption of animal-source foods (Regmi and Dyck 2001). Not only does this decrease wasting in places where children suffer from hunger and protein deficiency, it should also increase intake of iron, zinc, selenium, vitamin B12, and other micronutrients commonly found in animal-source foods. Zinc, for instance, is primarily found in animal-source foods, particularly in meat and shellfish but to a lesser extent in eggs and dairy products (Dibley 2001; Hotz and Brown 2004).[4] While the majority of iron intake comes in the form of plants and dairy products, the bioavailability of iron found in animal flesh is much higher. Additionally, consuming even small amounts of meat along with other foods increases the iron absorption from the non-meat foods by a factor of around four (Yip 2001). Selenium is most bioavailable in cereals, but is also found in high—though slightly less bioavailable—levels in meat, poultry, and milk (Mistry 2012). Animal organs, such as kidney or liver, hold particularly high levels of selenium. Vitamin B12 is found almost solely in animal-source foods, including milk, honey, and eggs, though an animal's ability to synthesize B12 is dependent on sufficient cobalt in their feed, and thus in soils (Graham et al. 2007).

The nutritional transition is also characterized by a shift in staple foods. Often this includes reduced consumption of coarse grains, such as millet and sorghum, and of roots and tubers, and increased consumption of wheat flour, particularly in the form of breads, and polished rice (Regmi 2001; Pingali 2006; Dapi et al. 2007). There is, of course, considerable variation in such patterns. For example, estimates of the income elasticity of demand for cassava are routinely very low, sometimes negative, in contrast to relatively robust income elasticity of demand for potato in most developing countries and to highly variable elasticity estimates for sweet potatoes and yams (Scott et al. 2000).

One reason the shift in staple foods matters is that the mineral and vitamin content differs considerably among staple foods. Table 3.1 compares selected micronutrient and vitamin levels in a number of unprocessed grains and roots and tubers commonly eaten in Africa. The common roots and tubers typically contain less minerals, but considerably more of certain essential vitamins, than do grains. And among the cereals there are important differences in, for example, iron, zinc, or beta-carotene content. The nutritional transition, therefore, often implies some reduction in micronutrient density of staple foods, which may or may not be compensated for by an increase in the volume of staples consumed or increased consumption of non-staple foods as dietary diversity increases.

Like the rest of the developing world, Africa is urbanizing rapidly. Urban residents typically face especially high opportunity costs to their time, as they increasingly work away from home and spend extended periods commuting to and from jobs. Multiple studies show that increased opportunity cost of women's time, specifically, increases demand for convenient "food away from home," often from street vendors, and for foods that are faster to prepare (Regmi 2001; Regmi and Dyck 2001; Pingali 2006). For example, Dapi et al. (2007) note that urban youth in Cameroon, and particularly those from poorer families, consume high quantities of fried dough because "it is always around."

Without context-specific information, the relationship between increased reliance on fast food/street food and micronutrient consumption is ambiguous. It seems, however, that a high proportion of street food relies on wheat flour and/or rice, as well as fats, oils, salts, and sugars (Regmi and Dyck 2001; Pingali 2006; Dapi et al. 2007). Thus, if income and urbanization are associated with increased consumption of time-saving street food, this may exacerbate a more general shift towards processed wheat and rice consumption and anti-nutrients, i.e., to foods offering "empty calories" rather than essential minerals and vitamins.

Consumer choice among foods responds to relative prices. Food supply growth has been concentrated disproportionately in cereals for the past half century, resulting in falling relative prices for grains and products made from processed cereals—flours, corn syrup, etc. Ironically, then, crop productivity growth, a primary mechanism for achieving success in reducing

Table 3.1. Vitamin and mineral quantities found in 100 g of West African raw food items

Foods (all raw)	Iron (mg)	Zinc (mg)	Vit C (mg)	RAE*/ Vit A (mcg)	B-carotene equiv/Vit A (mcg)	Thiamin/Vit B1 (mg)	Riboflavin/Vit B2 (mg)	Niacin/Vit B3 (mg)	Vit B6 (mg)
Daily EAR for adult males	6	8.5–9.4	75	625	NA	1	1.1	12	1.1
Daily EAR for adults females	8.1	7.3–6.8	60	500	NA	0.9	0.9	11	1.1
Maize flour: whole-grain, yellow	3	1.73	0	28	366	0.44	0.13	1.9	0.3
Maize flour: whole-grain, white	3.8	1.73	0	0	1	0.5	0.12	1.4	0.37
Maize flour: degermed, white	1	0.51	0	0	0	0.13	0.04	0.8	0.08
Wheat grains: whole-grain	4.7	1.7	0	0	3	0.47	0.1	5.6	0.29
Wheat flour: white	2	1.8	0	0	1	0.28	0.1	1.2	0.2
Pearl millet: whole-grain	[7.6]	2.83	0	0	[3]	0.32	0.27	2.4	0.74
Pearl millet: flour without bran	[5.8]	2.91	0	0	[3]	0.18	0.14	1.3	NA
Rice: whole-grain	1.9	2.02	0	0	0	0.38	0.07	5	0.51
Rice: white, polished	0.7	1.1	0	0	0	0.07	0.03	0.4	0.13
Sorghum: whole-grain	3.7	1.79	0	1	[17]	0.36	0.16	3.3	0.25
Sorghum: degermed flour	3.8	2.14	0	0	1	0.18	0.12	1.4	0.25
Cassava tuber	0.7	0.34	30	1	15	0.04	0.05	0.7	0.09
Cocoyam tuber	0.6	0.38	8	NA	NA	0.1	0.03	0.8	0.24
Sweet potato (pale yellow)	1.1	0.39	22.3	3	39	0.09	0.04	0.6	0.27
Irish potato	0.9	0.35	17.3	1	14	0.08	0.12	1.2	0.27

Notes:

Table 3.1, Rows 3–17

Data from the *West Africa Food Composition Table* (FAO 2012).

[] indicates an alternative analytical method or expression, or low-quality data.

NA indicates that no data was available.

* RAE—Retinol activity equivalent, a measure of vitamin A activity based on the capacity of the body to convert provitamin carotenoids into retinol.

The foods in Table 3.1 represent average values of the collected compositional data from nine countries (Benin, Burkina Faso, Gambia, Ghana, Guinea, Mali, Niger, Nigeria, and Senegal). Data sources for rows 3–17 included scientific papers, theses, university reports, as well as food composition databases. These data were supplemented by other sources of food composition data (mostly from outside Africa) to complete the missing values, especially minerals and vitamins. For some vitamins, especially vitamins A and E, data were not available and no sources were found from which to derive reliable data.

Table 3.1 Rows 1–2

Estimated Average Requirement (EAR) is the nutrient intake value that is estimated to meet the requirement defined by a specified indicator of adequacy in 50 percent of a population defined by gender and age. The exact age of reference in the EARs listed above changes according to micronutrient: 19–50 years for iron and zinc, 19–70 years for vitamin C, >18 years for vitamin A, and 18–30 years for all B vitamins.

All EAR data are taken from the latest USDA Dietary Reference Intake reports, which can be found at USDA (2014).

Recommended Daily Allowance (RDA) is often used alongside EAR when discussing adequate levels of micronutrient intake. RDA is defined as the nutrient intake value that will meet the requirement of most (97–98 percent) individuals in a given population. When the standard deviation of EAR (SD) is known, RDA is calculated by allowing RDA = 2*SD + EAR. When the distribution of EAR is unknown, RDA is calculated using RDA = 1.2*EAR.

macronutrient deficiencies manifest in hunger and undernourishment estimates, may have inadvertently attenuated advances against micronutrient deficiencies, by increasing the relative prices of more micronutrient-dense foods and thereby discouraging price-sensitive poor consumers from buying such foods (Pinstrup-Andersen 2005; Gómez et al. 2013).

All of the consumer patterns associated with income growth and urbanization in Africa (and elsewhere in the developing world) point to the prospective role of information and education in efforts to decrease micronutrient deficiency rates. Policy instruments such as commodity-specific subsidies (for micronutrient-dense foods) or taxes (on foods offering few micronutrients) could accelerate micronutrient intake within income growth, relative to what might occur in the absence of policy interventions.

Micronutrients along the Food Value Chain

Another central feature of income growth and the structural transformation of economies is the rise of commercial food market intermediation, as people exit farming for the non-farm economy and migrate from rural areas to cities and towns. In the food market chains (FMCs) in traditional agrarian societies, traders buy primarily from smallholder farmers and sell fresh, recently harvested food in primarily local markets (Gómez and Ricketts 2013). As households decrease autoconsumption of foods produced at home and rely increasingly on store and market purchases, the nature of FMCs changes considerably. "Modern" FMCs rely more heavily on domestic and multinational food manufactures and commercial farmers, and more often sell food through supermarket outlets (Gómez and Ricketts 2013). As a transition from traditional FMCs to modern FMCs occurs, the post-harvest functions of preservation, processing, storage, and transport clearly grow in importance. This makes food market intermediaries a natural focus of attention for understanding the slow response of micronutrient deficiencies to income growth.

There are at least three different ways in which the food value chain affects micronutrient intake. First, perishable foods naturally lose vitamins over time, so the speed with which fresh foods are delivered and the means by which foods are preserved matters fundamentally to their micronutrient content. Second, the technology of processing of grains, tubers, and so on, often shifts with a transition from household-scale to bulk milling, and that change often carries implications for the minerals and vitamins retained in staple foods. Third, unlike individual households, food manufacturers and processors can often cost-effectively add micronutrients through fortification in processing.

Urban residents often enjoy higher availability of many processed food items, while suffering lower availability of fresh food items (Regmi 2001; Pingali 2006; Gómez and Ricketts 2013). In many low- and middle-income countries, fruits and vegetables, especially, are either less available to poor urban residents or at least less fresh. This has clear implications for micronutrient intake, as it is well known that the vitamin content of fruit and vegetables declines over time after harvest. For example, the content of vitamin C, one of the most unstable vitamins within food, declines by 20–60 percent in broccoli, carrots, green beans, and peas within one week of storage at an ambient temperature, and by even more in spinach (Favell 1998; Hunter and Fletcher 2002; Rickman et al. 2007). B vitamins, especially thiamin (vitamin B1) and riboflavin (vitamin B2), degrade similarly over time after harvest. Losses are reduced significantly when vegetables are stored at colder temperatures, but cold chains are not readily available in most of Africa.

So the micronutrient content of vegetables and fruits is likely compromised by longer-distance FMCs, with exceptions perhaps for the highest-end supermarket chains that charge better-off consumers higher prices to cover the costs of refrigeration along the supply chain. In Africa, the "garden fresh" vegetables consumed in rural areas are almost certainly optimal when it comes to micronutrient intake, with frozen or refrigerated vegetables the best alternative. On the other hand, "garden fresh" is often only seasonally available in rural areas, as micronutrient-rich foods typically become scarce in lean seasons. Thus, modern FMCs could actually boost micronutrient intake for some urban consumers, if the compromised levels of micronutrients in their food is offset by their year-long food availability thanks to imports (Gómez and Ricketts 2013). The real losers are likely to be the urban poor and working class, who have neither access to seasonally available "garden fresh" food nor constantly available, higher-end food available in supermarkets or particularly efficient markets.

A different form of micronutrient loss occurs due to changes in post-harvest processing technologies as grains, legumes, and tubers shift from home-based artisanal processing to industrial milling (Welch 2001). For example, before the advent of large-scale mechanical milling machines in villages, rice was processed for cooking mainly by pounding or parboiling. Now, rice is most commonly eaten after "polishing," a process which removes the bran, or outer layers, of the rice grain. This bran includes the pericarp, seed coat, testa, and the nutrient-rich aleurone layer; the germ of the grain is often removed along with the bran. Thus, much of the iron, zinc, calcium, vitamins, and some of the protein are lost to polishing (Lauren et al. 2001). Similarly, wheat is usually milled before use. In semi-subsistence rural settings, this is typically done by stone grinding, which retains all components of the wheat, including the aleurone layer and the germ, in the final product (Welch 2001). As with rice, however, modern milling removes both the bran and the germ of the wheat grain, shearing away the vitamins, most of the minerals, and most of the healthy oils carried in wheat grain (Pollan 2013).

Welch and Graham (1999) show that rice and wheat lose 69 and 67 percent of their iron contents to milling, respectively, as well as 39 and 73 percent of their respective zinc contents. Even more dramatic effects were found on the iron and zinc reductions in sorghum and maize due to milling. Table 3.1 similarly compares micronutrient levels of both processed and unprocessed wheat, rice, maize, sorghum, and pearl millet from West Africa. Processed cereals of all types have lower levels of both minerals and vitamins.[5] Insofar as larger-scale, longer-distance market intermediation induces a switch in processing technologies that strips the bran and germ from the milled grain, the mineral content of the food degrades.

Food fortification aimed at increasing micronutrient intake has been widely implemented in the developed world. Oils, sugar, and cereal flours are commonly fortified with vitamin A; iodized salt is now consumed across much of the globe; milk is often fortified with vitamin D; and polished rice, white bread, and other processed staples and cereals are commonly fortified with iron and even zinc. Food fortification is most feasible where there exist large, centralized food processors capable of fortifying, packaging, and labeling the relevant food items. Food fortification is most likely to be effective if implemented among a population of well-educated consumers who are (1) aware of the value of added micronutrients in their food and (2) willing to pay for that value addition (Dary and Mora 2002). Both of these conditions slow the development of commercially viable post-harvest fortification of foods by processors in Africa, although there has been some progress over the past decade or so.

It is also necessary, in any given setting, to consider which food(s), once fortified, will be the most effective vehicle(s) for any given micronutrient with respect to a particular target population (Mora et al. 2000). Utilizing nationwide consumption data for Uganda, for example, Fiedler and Afidra (2010) found that vitamin A fortification of vegetable oil is 4.6 times more cost effective than vitamin A fortification of sugar, but that the Ugandans most at risk of vitamin A deficiency would benefit disproportionately from the introduction of sugar rather than oil fortification.

The effectiveness of food fortification preparation relies on a few issues. To begin with, fortification methods must be appropriate to local food preparation practices. Rice "dusting" for instance, which entails dusting polished rice grains with a powdered form of micronutrient premix, is not appropriate in countries where rice is washed and rinsed before cooking (Alavi et al. 2008). Quality control is also key and requires government monitoring. Such monitoring may be difficult for cash-strapped countries, or for countries where processing occurs at many small facilities rather than a few larger facilities (Alavi et al. 2008).

The Production End of the Food System

The central role of food production to address nutrient deficiencies is well known. The Green Revolution of the 1960s–1980s aimed to reduce malnutrition, understood then as protein and energy deficiencies. It largely succeeded in that task, significantly expanding the per capita supply of both calories and protein (Evenson and Gollin 2003). It failed, however, to similarly expand the per capita supply of minerals and vitamins. Thus, the agricultural technological change associated with the Green Revolution may have inadvertently shifted relative profitability and prices, by decreasing per capita micronutrient supplies and driving up the relative prices of micronutrient-rich foods, thereby discouraging price-sensitive poor consumers from buying such foods (Gómez et al. 2013). Today, as the world has come to appreciate that improving nutrition requires more than just rapidly increasing the global production of calories and protein, attention is slowly shifting away from calorie-dense staple grains toward micronutrient-rich fruits, legumes, vegetables, and animal-source foods.

The upstream, production end of the food system impacts micronutrient intake through at least four distinct pathways. First, the soils and water that farmers use are the primary source of minerals in the plants that humans eat or feed to livestock (Allaway 1986). Thus, if the soil of a region is low in particular minerals, families who rely only on locally produced foods will typically suffer from a deficiency of the locally scarce nutrient.

Iodine exemplifies this rule. It is rare in the earth's crust and found primarily in seawater. Thus, mountainous areas or inland areas, where wind and rain are unable to carry iodine in trace amounts from the sea, are most likely to have iodine-deficient soils (McDowell 2003). These are precisely the areas where iodine deficiency and goiter—the most prevalent clinical manifestation of iodine deficiency—are most widespread. For example, in the High Atlas Mountains of Morocco, far from the ocean with soils severely lacking in iodine, a large majority of households suffer iodine deficiency. The likelihood of such deficiency was explained largely by how much purchased fish a family consumed, since ocean fish imported from the coast was the only source of dietary iodine available in the valley, which did not have iodized salt available (Oldham et al. 1998).

The linkage between soils and plants is particularly strong for certain micronutrients. Zinc, nickel, iodine, and selenium are all nutrients that are clearly transmitted from soils to crops to humans; iron levels in soils, however, do not correlate well with iron levels in plants or humans (Bouis and Welch 2010; Graham et al. 2012). Scientists first realized the importance of soil micronutrients to animal and human health when they noticed that certain animal "diseases" (those associated with micronutrient deficiencies) occurred consistently in particular grazing areas, but disappeared once animals were relocated to a different grazing ground (Allaway 1986). Not all soils that are productive in terms of crop yields (product weight per unit area) produce micronutrient-rich food for man and animals.

Farmers can supplement the natural availability of micronutrients with fertilizers, but there has thus far been relatively little attention paid to micronutrients amid the burgeoning interest in fertilizers in African food systems. This is a pity, as soil has been shown to be a highly effective entry point for reducing micronutrient malnutrition in various areas of the world. For example, iodine deficiency was widespread in Xinjiang, the westernmost province of China, until policymakers decided to try increasing soil iodine levels via irrigation water (Cao et al. 1994). Subsequent results were startling: measurements of soil, crops, livestock, and human urine indicated that added iodine persisted in the soil for more than four years, continuing to elevate levels of iodine in plants, animals, and humans (Ren et al. 2008). What is more, infant mortality declined by 50 percent, with similar rates of decline for neonatal mortality, and children born after treatment had larger heads and taller statures (Delong et al. 1997; Ren et al. 2008). Ren et al. (2008) wrote that soil proved an efficient entry point for iodine into the food system, since this intervention did not require any medical expertise or knowledge on the part of local families, and it improved livestock production as well as human health.

Similarly, certain regions have soils low in selenium, and thus produce both crops and humans with low selenium status. In Finland, for example, selenium added to fertilizers and applied to soils increased the selenium status of the entire Finnish population from below WHO deficiency levels to above them (Mäkelä et al. 1993). In Malawi, Chilimba et al. (2011) measured widespread deficiencies in soil levels of selenium across the country, and calculated that mean dietary intake of selenium was at 40 and 60 percent of recommended values in two particular districts, respectively. Because maize is so heavily consumed in Malawi, it contributed the bulk of all selenium intake for most families. Later field trials showed that applying selenium-enriched fertilizers to maize fields could likely raise the selenium intake of households into the recommended intake levels (Chilimba et al. 2012).

Similar examples can be found for soil-to-human zinc transmission. In rural Bangladesh, Mayer et al. (2007) showed that soil pH, rice variety, and soil zinc status affect the zinc content of rice, and that the zinc content of rice is strongly and statistically significantly associated with zinc levels in human hair. They concluded that zinc-enriched fertilizers, as well as a few other soil management techniques, may significantly improve human zinc status in rural Bangladesh. Similarly, Tidemann-Andersen et al. (2011) found that zinc intake was low in Ugandan populations, primarily due to staples being low in zinc. They suggested that the low zinc content of Ugandan staples, as compared to Kenyan and Malian staples, stems from differences in soil zinc content or soil zinc availability.

The most serious micronutrient deficiencies commonly arise in rural areas of developing countries where families depend heavily on locally grown food crops and have little access to processed foods that are subject to post-harvest mineral or vitamin fortification. In such situations, income growth that leads to increased food consumption might lessen hunger or wasting rates, yet does little to decrease the prevalence of micronutrient deficiencies that stem from the soils. Farmers, and even agriculture ministries and local researchers, rarely know the micronutrient status of soils in rural Africa, however, because soil testing is expensive, and macronutrient analysis to increase crop yields, and thereby farm incomes, typically takes priority. While micronutrient-enriched fertilizers may increase crop yield in highly deficient soils, this is not always the case. For instance, Cakmak (2002) explained that while foliar application of zinc and application of zinc-enriched fertilizer often increased zinc content in grain, there was no direct economic motivation for such application, since grain yield does not increase along with zinc density. Thus, appropriately targeted micronutrient fertilizer regimes, such as those implemented in some high-income countries that have focused specifically on health benefits rather than yield increase, remain largely unknown in Africa.

The second pathway through which production practices affect micronutrient availability and intake arises through crop choice patterns. The Green Revolution prioritized high-yielding cereal varieties—especially, rice and wheat—and encouraged widespread use of fertilizer, irrigation, and other yield-increasing technologies, substantially expanding dietary energy supply. In doing so, however, it also inadvertently decreased the production—and thereby, increased prices and decreased consumption—of micronutrients across much of the developing, resource-poor world (Tontisirin et al. 2002; Graham et al. 2012).

One major trend, the induced shift toward cereal monocropping and away from varied, intercropping or rotation agricultural systems, meant that lower micronutrient crops became more prominent in diets (Welch 2001). In South Asia, the introduction of "modern" rice and wheat production practices resulted in a 200 percent increase in rice production and a 400 percent increase in wheat production over 30 years. Over the same period, however, production of iron-rich legumes decreased; iron density in South Asian diets (mg iron per kcal) declined dramatically; and the percentage of anemic women increased (ACC/SCN 1992; Welch 2001). Similarly, in West Africa, high rates of micronutrient malnutrition are believed to occur in large part because cereals are becoming increasingly important sources of dietary protein, while production of legumes and animal products has been declining, resulting in reduced iron and zinc in the diet (Lopriore and Muehlhoff 2003). Legumes, including beans and pulses, are a richer source of micronutrients than grains, both because most legumes are simply higher in micronutrients than are cereals and because legumes are generally consumed whole, while many cereals are processed in such a way that their micronutrient-rich husks are removed.

The third pathway concerns the use of new and "improved" agronomic practices, which—irrespective of crop choice—may have inadvertently reduced micronutrient availability in harvested crops. Of particular concern, given the current high-level emphasis on promoting inorganic fertilizer use in African agriculture, fertilizer use can increase, decrease, or leave unchanged the micronutrient content of crops (Welch 2001). For example, excessive nitrogen fertilization can adversely affect the accumulation of vitamin C in various horticulture crops such as lettuce, beets, kale, endive, or Brussels sprouts, and also in fruit crops such as oranges, lemons, mandarins, cantaloupes, and apples (Nagy and Wardowski 1988; Salunkhe and Desai 1988; Welch 2001). Harris (1975) wrote that the negative effect of nitrogen on vitamin C accumulation, in fruits at least, could be due to increased acid metabolism.

Similarly, nitrogen fertilization often causes a marked decrease in grain iron content or grain iron uptake (Speirs et al. 1944; Solimon et al. 1992). Panda et al. (2012) found that excessive application of NPK (nitrogen-phosphorus-potassium) fertilizer decreases the iron content of high-yielding tropical rice. Solimon et al. (1992) found that at high levels of sulfur application, application of nitrogen is positively related to corn uptake of manganese, but negatively related to corn uptake of iron and zinc. They discuss a number of other studies that find similar effects with rice, oats, barley, and soybeans. The inverse relationship between manganese and iron/zinc reflects their competition for uptake by plant roots.

Many commercial fertilizers mix phosphorus and/or potassium with nitrogen, and the effect of these additional macronutrients on crop vitamin content appears mixed. Potassium fertilizer usually increases the accumulation of vitamin C in horticulture and fruit (Ijdo 1936; Welch 2001), although phosphorus application to citrus fruits can either increase or decrease vitamin C content (Salunkhe and Deshpande 1988). Application of potassium has sometimes been found to increase beta-carotene content in sweet potatoes (George et al. 2002; Abd El-Baky et al. 2010; Laurie et al. 2012), though not always

(Swanson et al. 1933; Samuels and Landrau 1952), while the effect on horticulture is varied (Fellers et al. 1934; Whittemore 1934; Ijdo 1936). Maynard and Beeson (1943) reviewed a number of studies on the effect of phosphorus application to horticulture and concluded that very little effect could be found of phosphorus fertilizers on crop beta-carotene content. Gao et al. (2011) wrote that potassium chloride fertilization generally decreased zinc in 15 different types of wheat, across a variety of environments. Both grain zinc and grain cadmium were inversely related to grain yield—more grain usually meant less zinc and cadmium per volume. This is not surprising, given that an increase in grain yield is often driven by larger grain size, which comes with a smaller bran to grain interior ratio (R. M. Welch, personal communication[6]). Application of phosphorus fertilizer seems to lower zinc uptake in certain cereals and results in phytate-to-zinc ratios that are less favorable for the bioavailability of zinc to humans (Robson and Pitman 1983; Cakmak 2002). For example, Moraghan (1994) found that applied phosphorus acts as an antagonist to zinc in navy beans, lowering both zinc content and zinc concentration in all areas of the plant.

A longstanding body of agronomic evidence thus suggests that NPK fertilizers are likely to negatively affect the iron, zinc, and vitamin C content of various crops, at least if used in excess. Most interactions between fertilizer application and crop micronutrient levels, however, are context specific. Thus, fertilization has the power to greatly increase micronutrient production if utilized carefully, but also to negatively impact micronutrient production if used without care or without knowledge of these potential interactions.

Fourth, the rise of new crop varieties bred specifically to increase the plant's production of bioavailable micronutrients—a process known as "biofortification"—offers a new mechanism for expanding micronutrient supplies from specific farming systems. Biofortification is designed to target resource-poor, rural, usually agrarian populations in the developing world, who would be unlikely to purchase most fortified foods, even if fortification was feasible in their country (Miller and Welch 2013). So far, biofortified foods have targeted vitamin A, iron, and zinc; and crops developed or under development include sweet potato, maize, cassava, rice, wheat, pearl millet, beans, cowpeas, lentils, sorghum, pumpkin, Irish potato, and banana (Saltzman et al. 2013).

Biofortified foods are primarily meant to be produced and consumed at the household level, rather than purchased (Miller and Welch 2013). In Uganda, for example, HarvestPlus introduced beta-carotene rich Orange-Fleshed Sweet Potatoes (OSP) by distributing 20 kg of free OSP vines to all target households as planting materials, and providing training to farmers' groups on planting techniques (Hotz et al. 2012). As OSP intake increased, the prevalence of inadequate beta-carotene intake fell, and the vitamin A status of children seemed to improve. It is possible, however, that some of the increase in OSP intake was due to families purchasing OSP locally from their neighbors, rather than producing it themselves.

This question of marketability will always be important in gauging the potential impact of biofortified foods. Rates of adoption and disadoption are also clearly important, as is the rate of product failure, or the "breeding out" of increased micronutrient content.[7] Visibly identifiable characteristics of biofortified foods may be useful in differentiating them from similar, non-biofortified foods, though characteristics viewed as undesirable might reduce marketability. Introducing iron-rich beans to Uganda may prove more challenging than introducing OSP, given that no visible marker differentiates their seeds for planting or their pods for sale (Anna-Marie Ball, personal communication[8]). Crop yields are also clearly important; farmers are unlikely to adopt a biofortified cultivar if its yields are lower than those more typically found at market (Saltzman et al. 2013).

Some of these production-level concerns regard variation in micronutrient levels across crops, such as the iron density of grains as compared to legumes. Others regard variation in micronutrient levels within a particular crop but across different settings (high nutrient soil vs. low nutrient soil), or across various cultivars (traditional crops vs. biofortified crops). It may be hard to know a priori which type of variation is most important in any given setting. For some communities food diversification, or the introduction of new foods, may be the only way to significantly increase micronutrient intake. For others, increasing the micronutrient density of one particular food through biofortification, or a particular set of foods via nutrient-enriched fertilizers, may be equally effective and more feasible.

Added Complexity due to Cross-Complementarities

Micronutrient status suffers (or benefits) from cross-complementarities between nutrients; deficiency in one micronutrient may inhibit absorption of another nutrient or worsen the effects of another deficiency. Selenium deficiency, for example, exacerbates the harmful effects of iodine deficiency on the thyroid (Arthur et al. 1999). In a longitudinal study carried out by Zimmermann et al. (2000) in Côte d'Ivoire, selenium deficiency decreased the thyroid response to iodine supplementation in goitrous patients. In the Democratic Republic of the Congo (DRC) where both iodine and selenium deficiencies are common, a combination of these deficiencies exacerbates hypothyroidism and may manifest itself as myxoedematous cretinism (Vanderpas et al. 1990). Myxoedematous cretinism is one of three forms of cretinism—the other two are called neurological cretinism and Keshan's disease. Foster (1995) wrote that although neurological cretinism is clearly associated with iodine deficiency, and Keshan's disease is clearly caused by selenium deficiency, it seems likely that myxoedematous cretinism stems from a deficiency in both micronutrients.

Similarly, Graham et al. (2012) argued that much of the current iron deficiency in the world may be due to underlying zinc deficiency. Iron status depends both on iron consumption and on iron uptake—how much iron a human body absorbs from consumed foods that contain iron. Graham et al. (2012) explained that iron absorption is partially regulated by a molecule called hepcidin. For example, injections of hepcidin decreased iron absorption both in iron-deficient and iron-adequate mice populations (Laftah et al. 2004). Hepcidin synthesis is induced by infection and inflammation, and zinc deficiency aggregates oxidative stress in cells, causing systematic intestinal inflammation. Thus, it is possible that zinc deficiency contributes to reduced iron absorption by inducing hepcidin synthesis.

Graham et al. (2012) also supported their argument geographically. Much of the world's iron-deficient populations live on the acidic soils of the wet Asian and African tropics, where iron deficiency in crops is rare but soils are often zinc deficient. Should this connection between iron deficiency and zinc deficiency prove true, zinc deficiency would be all the more crucial a public health issue, given that 1.6 billion people are anemic across the globe (WHO 2008). The hypothesis is still new, however, and more research is necessary to uncover whether zinc deficiency truly plays a role in driving iron deficiency.

Zinc deficiency has potential implications not only for iron status, but for vitamin A status also. The metabolism of vitamin A depends on zinc-containing enzymes (Welch 1997). Zinc-deficient populations cannot utilize vitamin A efficiently, and may therefore become vitamin A deficient. Giving such populations vitamin A supplements, however, without first treating the underlying zinc deficiency, will have little effect (Shrimpton 1993). Similar interrelationships have been shown for iron, because the metabolic activation of provitamin A carotinoids depends on an iron-containing enzyme (National Research Council 1989).

Micronutrient malnutrition that stems from multiple, interacting mineral and/or vitamin deficiencies will clearly be harder to treat than forms of malnutrition that merely require more food, more protein, or more of one particular micronutrient. Such complementarities in micronutrients lead to diseases like myxoedematous cretinism, which stems from both iodine and selenium deficiency. In areas where this disease is prevalent, iodine prophylaxis alone will not prevent widespread depression of IQ (Foster 1995), nor will selenium supplementation alone. Rather, both underlying deficiencies must be addressed to reduce these severe manifestations of micronutrient malnutrition. Recent research supports the hypothesis that many micronutrient deficiencies are at least nominally impacted by the status of multiple micronutrients. If true, micronutrient malnutrition is inherently more difficult to treat than more classic forms of protein-energy malnutrition that result in wasting or stunting. Not only are more inputs required in order to reduce deficiency levels, but more "expert" knowledge is necessary in order to choose the appropriate inputs.

Conclusions

Can we begin to draw any conclusions as to why micronutrient deficiencies stubbornly persist in the face of income growth? By analyzing the challenge throughout the food system, it quickly becomes apparent that at each level—the upstream producer end, the downstream consumer end, and the market intermediation in the middle—there exist factors that both ameliorate and aggravate micronutrient deficiencies in diets. Because severe micronutrient deficiencies are associated with a range of irreversible cognitive and physical effects that can cause chronic conditions of ill health and poverty, the returns are high to improving our understanding of how and where to intervene in food systems in order to address persistent micronutrient deficiencies.

At the upstream end of the food system, soil deficiencies seem a very real problem, which points both to the prospect of fertilizers (and irrigation) and post-harvest fortification as paths to augment supply, as at least 90 percent of the food consumed in Africa is grown on the continent. Current debates about fertilizer policy are strikingly silent on the topic of fertilizers' micronutrient content, however. Biofortified foods hold promise for increasing certain micronutrient levels, but it remains to be seen how rates of adoption and disadoption, as well as marketability of adopted foods, shape their impact on human health. Increased attention to these micronutrient issues in agricultural technology development is, however, a promising improvement on the Green Revolution era.

Farm-level solutions, however, may be less cost-effective for an increasingly urban population. Improvements in market intermediation hold considerable promise, especially refrigeration and improved storage to preserve perishable foods' mineral and vitamin content, as well cost-effective fortification of nutrients that are difficult to get into foods through fertilizers or biofortified crop varieties. The tremendous success of salt iodization in sharply reducing cretinism, as well as milder forms of IDD, offers encouragement that low-cost interventions can remedy dietary nutrient shortfalls that stem fundamentally from minerals lacking in native soils.

But with the continent urbanizing rapidly and enjoying much faster economic growth than before, managing consumers' nutritional transition is equally important. Consumer education and simple policy instruments for nudging consumers toward healthy food choices (e.g., using subsidies or taxes to change relative prices, school meal menus) offer possible solutions, albeit inconclusively tested in Africa.

The lack of any integrated assessment of alternative intervention options to combat mineral and vitamin deficiencies is one of the main stumbling blocks to mounting a serious effort to accelerate the reduction of micronutrient deficiencies as incomes grow in Africa and other low-income regions. The research and donor communities must come together to begin a more systematic assessment of (1) where micronutrient deficiencies are severe and widespread; (2) the root sources of those deficiencies for distinct subpopulations—especially those most vulnerable to falling into nutritional poverty traps: pregnant and lactating women, infants, and young children; (3) the comparative cost-effectiveness of alternative approaches to remedy those deficiencies; and (4) appropriate targeting rules for interventions to assist priority subpopulations. This sort of systematic, integrative, cost-effective solutions-oriented approach to addressing the micronutrient deficiency challenges of African food systems would fit with and honor the laudable policy-oriented research tradition of Per Pinstrup-Andersen.

Acknowledgments

The authors thank Joanna Barrett for excellent research assistance and Anne-Marie Ball, Miguel Gómez, Dennis Miller, Per Pinstrup-Andersen, and Ross Welch for helpful conversations that have helped shape this chapter, as well as David Sahn and two anonymous reviewers for helpful comments on an earlier draft. All remaining errors are solely our responsibility.

Notes

1. For each indicator, log prevalence is regressed on log GNI via ordinary least squares, and then predicted log prevalence is graphed over GNI. GNI data are either for 2000 or 2009, as appropriate to the time period of the indicator.
2. The World Bank currently classifies countries as low income if annual GNI per capita is $1,035 or less, and middle income if annual GNI per capita is $1,036–$12,615.
3. Relatedly, the nutrition transition is also associated with an epidemiological transition characterized by decreasing levels of infectious diseases and a rise in chronic (non-communicable) diseases (Delisle et al. 2011). The four primary types of non-communicable diseases are cardiovascular diseases (like heart attacks and stroke), cancers, chronic respiratory diseases (such as chronic obstructive pulmonary disease and asthma), and diabetes.

4. Zinc content is also fairly high in nuts, seeds, legumes, and whole-grain cereals.
5. While Table 3.1 displays only the minerals iron and zinc, the FAO food composition table from which these data are drawn contains many other minerals: copper, manganese, calcium, etc. Processing reduces levels of the other minerals, just as it reduces iron and zinc content.
6. Until his retirement, Ross Welch worked as a plant pathologist and the Lead Scientist at the US Department of Agriculture's Agriculture Research Service (USDA-ARS), the Robert W. Holley Research Center for Agriculture and Health, located on the Cornell University campus. He was also a Professor of Plant Nutrition within the Department of Crop and Soil Sciences at Cornell University. Dr. Welch was one of the first scientists in the United States to study human-to-soil micronutrient transmission, beginning work on the topic in the 1960s. He is still one of the leading experts on the phenomenon today.
7. Biofortified foods are theoretically designed to be stable across many generations, unlike hybrid seeds that must be purchased afresh each season in order to maintain desired qualities.
8. Anne-Marie Ball is the country manager for HarvestPlus in Uganda. She joined HarvestPlus in 2006 to lead the Reaching End Users Orange Sweet Potato Project, which introduced biofortified sweet potatoes to farmers across Uganda between 2006 and 2009.

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