AGRICULTURAL AND MOLECULAR GENETIC APPROACHES TO IMPROVING NUTRITION AND PREVENTING MICRONUTRIENT MALNUTRITION GLOBALLY

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Keywords: Agricultural systems, food crops, food systems, bioavailability, essential trace elements, genetic modification, human nutrition, human health, intervention strategies, iodine, iron, iron deficiency anemia, nutrient output, nutritional quality, nutritional traits, plant breeding, vitamin A, zinc.

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The world population is expanding very rapidly, and expected to grow from 6 billion in 2002 to around 8 billion in 2020, with very high numbers of undernourished people. About 50 percent of the world population suffers from micronutrient deficiencies (micronutrient malnutrition), particularly in the developing world. Micronutrient deficiencies, such as iron (Fe), zinc (Zn), and vitamin A deficiencies, are critical nutritional issues and result in severe impairments of human health and development, such as impaired physical growth, immune system function, mental and cognitive development, and increases in anemia, maternal mortality, and infections. A large number of the world’s peoples rely on a few staple cereals (e.g. wheat, rice, and maize) as a major source of dietary energy and protein, which, as commonly eaten, are extremely poor in certain micronutrients such as Fe, Zn, and vitamin A. Currently, food systems cannot provide enough balanced micronutrients to meet the daily requirements and sustain the well-being of people in the developing world. Heavy and monotonous consumption of cereal-based foods with low concentrations and limited bioavailability of micronutrients has been considered a major reason for the high prevalence of micronutrient deficiencies in many developing countries. Traditional plant breeding approaches hold great promise and provides more cost-effective and sustainable solutions when compared to other approaches, such as supplementation and food fortification programs, in reducing the extent of micronutrient deficiencies globally. In recent years, international agricultural research institutes, especially the Consultative Group on International Agricultural Research (CGIAR) centers, have made impressive progress in screening and developing plant genotypes with enhanced amounts and utilization (biological availability) of micronutrients in edible parts of staple food crops, such as cereal grains. Substantial genetic variations have been found in different food crops for higher levels of Fe, Zn and vitamin A and also for lower levels of antinutrients (i.e. phytic acid and tannins). These variations are currently being exploited to increase levels of micronutrients and eliminate antinutritional substances by using traditional and marker-assisted breeding approaches as well as genetic engineering techniques. The efforts to manipulate the genes affecting nutritional quality traits of food crops have already yielded significant progress. Presently, several transgenic plants are available containing enhanced concentration of Fe, vitamin A, and S-containing amino acids and lower levels of antinutrients such as phytate. In the future, top priority should be given to development of plant genotypes with enhanced levels of more than one micronutrient. To speed progress and maximize international awareness, agriculture, health, and nutrition sectors, at both national and international level, should stress social, economic, and health consequences of micronutrient deficiencies, and provide significant funding opportunities for the development of sustainable, agriculture-based approaches to preventing micronutrient deficiencies.

1. Introduction
Micronutrients are the essential mineral elements and vitamins that are required by humans in tiny amounts. Their low, required intake notwithstanding, they are absolutely essential for human life and just as important as all other nutrients (e.g. essential amino acids, fatty acids, and water) for good health and well-being. Remove any one of them from people’s diets and those individuals will develop deficiency disorders that dramatically diminish health, vitality, cognitive abilities, work efficiency, longevity, and quality of life.

Disturbingly, deficiencies of micronutrients (i.e. micronutrient malnutrition or “hidden hunger”) currently afflict more than 2 billion people or about half of the world’s population. The consequences of micronutrient deficiencies to human health and well-being are insidious and devastating to those people and societies most affected. Micronutrient malnutrition mostly occurs in women, infants, and children of resource-poor families in the developing world. These deficiencies lead to increased national mortality and morbidity rates, substandard health, lost worker productivity (impairing social and national development efforts), impaired cognitive function, and reduced educational attainment, depressed family livelihoods, and a poor quality of life.

1.1. Agriculture, the Availability of Micronutrients, and Health

People’s health depends on their consuming enough nutrients in proper proportions to meet their daily requirements. Importantly, nearly all the nutrients consumed by humans are derived either directly from agricultural products (i.e. food crops and animal products) or via processed foods prepared from such products. Therefore, the agricultural sector plays a paramount role in providing nutrients to satisfy human needs. If agricultural systems do not provide enough nutrients in proper balance to meet these needs then some people in certain sectors of society will develop nutrient deficiencies that adversely affect their lives and society suffers.

Unfortunately, providing adequate nutrient output to meet human needs has never been an accepted or explicit goal of agriculture. Generally, crop productivity and profit motives drive agricultural enterprises in free market economies. These driving forces behind agricultural production can result in over production of some nutrients while the needed levels of some nutrients are not met. This is especially true for the micronutrients. It is essential that governments support agricultural policies that will encourage adequate levels of all nutrients for their citizenry. If not, widespread nutritional diseases will develop, the underprivileged will suffer, economies will decline, national development may stagnate, society will regress, civil unrest may ensue, and political systems may falter. Examples of imbalances in nutrient output of agricultural systems and the effects on human health are discussed below as they pertain to certain global regions.

1.1.1. Micronutrient Requirements

The known micronutrients include fifteen trace elements and thirteen vitamins. Table 1 lists these nutrients, their required dietary levels for adult males and examples of food sources rich in these nutrients. Other micronutrients may be added to this list in the...
future. For example, cadmium (Cd), aluminum (Al), lithium (Li), and lead (Pb) have been considered for inclusion on the list of essential micronutrients, although available scientific evidence does not warrant their inclusion to date.

<table>
<thead>
<tr>
<th>Micronutrient</th>
<th>RDA\textsuperscript{a} (mg day\textsuperscript{-1})</th>
<th>Examples of foods that are rich sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>10</td>
<td>meats, poultry, fish, eggs, liver, peas, nuts, dried fruits</td>
</tr>
<tr>
<td>Iodine (I)</td>
<td>150</td>
<td>iodized salt, seafood, seaweed, dairy products</td>
</tr>
<tr>
<td>Zinc (Zn)</td>
<td>15</td>
<td>meat, poultry, fish, dairy products</td>
</tr>
<tr>
<td>Selenium (Se)</td>
<td>0.07</td>
<td>shellfish, kidney, liver, meats, poultry, garlic, Brazil nuts</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>1.5–3.0\textsuperscript{b}</td>
<td>liver, shellfish, nuts, seeds, whole grains, potatoes</td>
</tr>
<tr>
<td>Molybdenum (Mo)</td>
<td>0.075–0.25\textsuperscript{b}</td>
<td>milk, beans, whole grains, leafy vegetables, liver</td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>0.05–0.2\textsuperscript{b}</td>
<td>meats, whole grains, broccoli, brewer’s yeast</td>
</tr>
<tr>
<td>Manganese (Mn)</td>
<td>2.0–5.0\textsuperscript{b}</td>
<td>whole grains, nuts, vegetables, fruits, beans</td>
</tr>
<tr>
<td>Silicon (Si)</td>
<td>—\textsuperscript{c}</td>
<td>whole grains, pectin from citrus fruits, high fiber vegetables</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>—\textsuperscript{c}</td>
<td>buckwheat, rye, barley, peas, beans</td>
</tr>
<tr>
<td>Boron (B)</td>
<td>—\textsuperscript{c}</td>
<td>fruits, leafy vegetables, nuts, legume seeds, wine, beer</td>
</tr>
<tr>
<td>Vanadium (V)</td>
<td>—\textsuperscript{c}</td>
<td>whole grains, shellfish, spinach, parsley, mushrooms</td>
</tr>
<tr>
<td>Arsenic (As)</td>
<td>—\textsuperscript{c}</td>
<td>seafood</td>
</tr>
<tr>
<td>Tin (Sn)</td>
<td>—\textsuperscript{c}</td>
<td>canned foods, nuts</td>
</tr>
<tr>
<td>Fluoride (F)</td>
<td>1.5–4.0\textsuperscript{b}</td>
<td>seafood with bones, tea</td>
</tr>
<tr>
<td>Vitamins</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vitamin A</td>
<td>1.0</td>
<td>liver, eggs, cheese, butter, red peppers, carrots, pumpkin</td>
</tr>
<tr>
<td>Vitamin C</td>
<td>60</td>
<td>fruits, vegetables, organ meats</td>
</tr>
<tr>
<td>Vitamin D</td>
<td>0.005</td>
<td>fish liver oil, salmon, sardines, corn oil, poultry skin</td>
</tr>
<tr>
<td>Vitamin E</td>
<td>10</td>
<td>wheat germ, sunflower and safflower oils, whole grains</td>
</tr>
<tr>
<td>Vitamin K</td>
<td>0.08</td>
<td>green leafy vegetables</td>
</tr>
<tr>
<td>Thiamin</td>
<td>1.5</td>
<td>brewer’s and baker’s yeast, liver, cereal grains</td>
</tr>
<tr>
<td>Riboflavin</td>
<td>1.7</td>
<td>green leafy vegetables, meats, dairy products, broccoli</td>
</tr>
</tbody>
</table>
Table 1. Micronutrient requirements of adult men and examples of rich food sources

1.1.2. Changing Cropping Systems: Unforeseen Consequences of the “Green Revolution”

During the middle of the twentieth century the agricultural community was faced with an enormous challenge: how to provide enough food to feed a global population that would more than double during the subsequent fifty years. Not having done so would have resulted in widespread famines and extensive human misery in many developing countries. The success of this massive agricultural undertaking (now referred to as the “Green Revolution”) is one of the most impressive accomplishments of the millennium. Its success was almost entirely the result of dramatic increases in the yields of the cereal crops—rice, wheat, and maize—in the developing world. Unfortunately, there were some unforeseen consequences of the cereal cropping systems used to create the “Green Revolution.”

Providing enough “food” does not necessarily mean that the food produced will supply enough of all the nutrients needed to support good health. This appears to be the case for the agricultural systems fostered during the “Green Revolution.” While whole cereal grains provide enough carbohydrates (calories) and protein to stave off famine, they do not provide enough of all the utilizable micronutrients needed to sustain life, being very low in bioavailable amounts of many micronutrients compared to other staple food crops, such as pulse seeds (see Table 2). For example, they fail to provide enough iron and zinc as well as several vitamins (e.g. vitamin A and vitamin C).
Additionally, modern refining operations further degrade the nutritional value of cereal grain (see Table 3) by removing the micronutrient-rich germ and aleurone layers of the grains. Thus, other foods besides cereals must be eaten with processed cereals to maintain the micronutrient balance needed for good health.

### Table 2. Comparisons between the micronutrient element concentrations in whole cereal grains and pulse seeds

<table>
<thead>
<tr>
<th>Micronutrient</th>
<th>Brown rice</th>
<th>Polished rice</th>
<th>% removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron (mg kg$^{-1}$)</td>
<td>30</td>
<td>10</td>
<td>67</td>
</tr>
<tr>
<td>Copper (mg kg$^{-1}$)</td>
<td>3.3</td>
<td>2.9</td>
<td>12</td>
</tr>
<tr>
<td>Manganese (mg kg$^{-1}$)</td>
<td>17.6</td>
<td>10.9</td>
<td>62</td>
</tr>
<tr>
<td>Zinc (mg kg$^{-1}$)</td>
<td>18</td>
<td>13</td>
<td>30</td>
</tr>
<tr>
<td>Biotin (µg kg$^{-1}$)</td>
<td>120</td>
<td>50</td>
<td>58</td>
</tr>
<tr>
<td>Folic acid (µg kg$^{-1}$)</td>
<td>200</td>
<td>160</td>
<td>20</td>
</tr>
<tr>
<td>Niacin (mg kg$^{-1}$)</td>
<td>47</td>
<td>16</td>
<td>66</td>
</tr>
<tr>
<td>Pantothenic acid (mg kg$^{-1}$)</td>
<td>20</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>Riboflavin (mg kg$^{-1}$)</td>
<td>0.5</td>
<td>0.3</td>
<td>40</td>
</tr>
<tr>
<td>Thiamin (mg kg$^{-1}$)</td>
<td>3.4</td>
<td>0.7</td>
<td>80</td>
</tr>
<tr>
<td>Vitamin B$_6$ (mg kg$^{-1}$)</td>
<td>6.2</td>
<td>0.4</td>
<td>94</td>
</tr>
<tr>
<td>Vitamin E (IU kg$^{-1}$)</td>
<td>20</td>
<td>10</td>
<td>50</td>
</tr>
</tbody>
</table>

Notes: aDry weight basis.
Modern cereal cropping systems have resulted in dramatic reductions in food diversity for all nations. Today, twenty-two crop species (see Figure 1) account for most of the food crops produced on earth. Not only have the types of food crop species declined, but the genetic diversity in each food crop has also dramatically decreased since the turn of the century (see, for example, the data for the United States in Figure 2). Indeed, the spread of modern cereal cropping systems has been paralleled by a decline in production of many traditional staple foods that are much richer in micronutrients compared to processed cereal crops, as shown for pulses in Figure 3. Clearly, increases in cereal production more than kept pace with population growth during the twentieth century, but pulse production lagged far behind cereal production not even keeping up with population increases. This shrinking diversity in the world’s food basket has lowered the availability of foods rich in many micronutrients. Obviously, those agricultural changes that occurred during this period have resulted in greatly increased cereal production, but at the expense of food crop diversity, resulting in lower balanced micronutrient output of these modern agricultural systems.

Table 3. Polishing and milling operations dramatically reduce many micronutrients in whole brown rice grain

Figure 1. Globally, twenty-two major food crops dominated available food supplies in 1996

Source: Mann (1997).
What effects have modern cereal cropping systems had on the nutritional health of people in the developing world? As a result of reductions in food diversity resulting from the introduction of these systems, the availability of certain micronutrients has
declined and micronutrient deficiencies have increased in certain population groups within developing countries.

Figure 4. Trends in South Asian dietary Fe density and in Fe deficiency anemia in women 1970–88

Source: redrawn from Welch and Graham (1999).

This is especially true for iron deficiency anemia among women of childbearing age in South Asia (see Figure 4). Globally, iron deficiency has grown from about 30 percent in the 1960s to over 40 percent in the mid-1990s. These trends are expected to continue unless ways are found to increase the availability of iron and other micronutrients in food systems of developing nations.

Bibliography


Biographical Sketches

Ismail Cakmak received both his B.S. (1980) and M.S. (1981) degrees in Soil Science and Plant Nutrition from the University of Cukurova in Adana, Turkey, and his Ph.D. (1988) in Plant Nutritional Physiology from the Hohenheim University in Stuttgart, Germany. After postdoctoral studies in Germany during 1989 to 1992, he worked at the Cukurova University, Department of Soil Science and Plant Nutrition, where he became a full professor (1994) in Plant Nutrition. In 2000, he moved to Sabanci University, Department of Biological Sciences, in Istanbul. His research focuses on physiological aspects of plant adaptation to adverse soil conditions, particularly micronutrient-deficient and heavy metal-toxic...
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Robin D. Graham received his B.Sc. and D.Agr.Sc. degrees from the University of Queensland (1962,1993) and his M.S. and Ph.D. degrees from the University of California (1968,1970) in chemistry, soil science and plant nutrition. He has worked in the Queensland Department of Primary Industries and, since 1970, at the Waite Agricultural Research Institute of the University of Adelaide where he is Professor of Plant Science. He is also Adjunct Professor of Soil and Crop Sciences at Cornell University. He is the Scientific Co-ordinator of the CGIAR Micronutrients Project (since 1994) and a Research Associate of the International Food Policy Research Institute. He has studied in the UK and the USA. He is a Fellow of the Australian Institute of Agricultural Science and Technology. His research interests include the interactions of plant genetics and plant pathogens with plant nutrition, and the role of all these factors in the nutritional quality of plants for human consumption.

Dr R. M. Welch is a Plant Physiologist and Lead Scientist employed by the USDA-ARS at the US Plant, Soil, and Nutrition Laboratory on the Cornell University campus in Ithaca, N.Y. He is Courtesy Professor of Plant Nutrition within the Department of Crop and Soil Sciences. He received his B.Sc. (1967) in soil science from the California State Polytechnic University, and his M.Sc. (1969) and Ph.D. (1971) in soil science/plant nutrition from the University of California. He has carried out research at Murdoch University and at the University of Adelaide, Australia. He is a Fellow of the American Society of Agronomy and Soil Science Society of America. His research is directed to improving the nutritional quality of food crops for humans and finding sustainable ways to increase the bioavailable levels of micronutrients in staple foods. He co-organizes the Food Systems for Improved Health program at Cornell University. He co-operates with various international institutions on projects directed at increasing the micronutrient density and nutritional quality of food crops through plant breeding, molecular biology and improved agronomic practices to enhance human health globally.