Still No Free Lunch:
Nutrient levels in U.S. food supply eroded by pursuit of high yields

by Brian Halweil

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“A knowledge of the chemical composition of foods is the first essential in dietary treatment of disease or in any quantitative study of human nutrition.”

R.A. McCance and E.M. Widdowson,

The Composition of Foods, 1940

Dr. Alan Greene is the Founder of www.DrGreene.com and the Chief Medical Officer of A.D.A.M., a leading publisher of interactive health information. He teaches medical students and pediatric residents at the Stanford University School of Medicine, and is an Attending Physician at Stanford University's Lucile Packard Children's Hospital.

Foreword

The Organic Center's second "State of Science Review" came out in early 2005 and focused on antioxidant levels in organic and conventional foods. We found that, on average, organic food contained 30 percent higher levels of antioxidants based on then-published studies.

This surprising finding triggered new research by the Center into the roots of food quality. We sponsored a symposium on the topic at the 2006 meeting of the American Association for the Advancement of Science, and asked Brian Halweil of the Worldwatch Institute to write a report on the impact of rising crop yields on food nutrient density. We are pleased to release Brian's report and are confident it will help focus the attention of agricultural scientists, farmers, private industry and government on the importance of reversing the slow, incremental erosion in the nutrient density of many staple crops.

Why is this report so important and timely? Many of our most common and costly health problems are diet related. America's public health is suffering because of the way we grow food, the chemicals we apply to crops, the drugs we administer to farm animals, our excessive reliance on processing, and too much added fat and sugar in way too many foods. In the years ahead, progress in reducing the frequency and severity of many diseases will depend increasingly on improving food nutritional quality and patterns of dietary choice, rather than simply an ever-widening dependence on drug-based therapies and surgery. A renewed focus on increasing nutrient density in step with crop yields is long overdue and a step in the right direction.

Dr. Alan Greene
Vice-Chair of the Board
The Organic Center

The Organic Center

Executive Summary

Farmers have doubled or tripled the yield of most major grains, fruits and vegetables over the last half-century. They have done so by capitalizing on the work of plant scientists, crop breeders and companies manufacturing a wide range of inputs—from fertilizer to water, pesticides, sophisticated machinery and diesel fuel.

Yield increases per acre have come predominantly from two sources—growing more plants on a given acre, and harvesting more food or animal feed per plant in a given field. In some crops like corn, most of the yield increase has come from denser plantings, while in other crops, the dominant route to higher yields has been harvesting more food per plant, tree, or vine.

But American agriculture's single-minded focus on increasing yields over the last half-century created a blind spot where incremental erosion in the nutritional quality of our food has occurred. This erosion, modest in some crops but significant in others for some nutrients, has gone largely unnoticed by scientists, farmers, government and consumers.

The Evidence

Government data from both America and the United Kingdom have shown that the concentration of a range of essential nutrients in the food supply has declined in the last few decades, with double-digit percentage declines of iron, zinc, calcium, selenium and other essential nutrients across a wide range of common foods. As a consequence, the same-size serving of sweet corn or potatoes, or a slice of whole wheat bread, delivers less iron, zinc and calcium.

Fewer nutrients per serving translate into less nutrition per calorie consumed. This erosion in the biological value of food impacts consumers in much the same way as monetary inflation; that is, we have more food, but it's worth less in terms of nutritional value.

The accuracy and reliability of historical data-sets on food nutrient composition have been questioned, since testing methods have changed so much over the years. Contemporary experiments, though, have confirmed that the nutrient decline observed in historical data-sets is real.

These experiments entail planting modern and historical crop varieties—or high- and low-yield varieties of assorted crops—side-by-side, using comparable agronomic practices (e.g., tillage, planting method, sources and levels of nutrients, harvest method and timing). Studies with wheat, corn and broccoli have found that modern, high-yielding varieties generally have lower concentrations of nutrients than older, typically lower-yielding varieties.

The tradeoff between yield and nutrient level seems to be widespread across crops and regions, as plants partition their limited energy between different goals. Substantial data show that in corn, wheat and soybeans, the higher the yield, the lower the protein and oil content. The higher tomato yields (in terms of harvest weight), the lower the concentration of vitamin C, levels of lycopene (the key antioxidant that makes tomatoes red), and beta-carotene (a vitamin A precursor). High-production dairy cows produce milk that is less concentrated with fat, protein and other nutrition-enhancing components, and are also more vulnerable to a range of metabolic diseases, infections and reproductive problems.

Given these negative consequences linked to increasing yields and production levels, why the continuing, nearly universal focus on increasing yields and production, regardless of the associated costs?

Crop breeders have focused predominantly on developing varieties that produce higher yields because that is what farmers have asked for, and what farm commodity markets, federal farm policy, and those funding agricultural research and extension programs have rewarded. In fact, according to several scientists, there are few systematic breeding efforts currently underway in the United States with the goal of raising the nutrient content of major foods. Breeders are unlikely to change without incentives. The same is true among animal breeders, scientists and livestock farmers.

Agronomic practices have worked hand-in-hand with plant breeding in setting the stage for this nutrient decline. Together, the tactics farmers use to increase yields—including close plant spacing and the widespread use of chemical fertilizers, irrigation and pesticides—tend to create big plants that grow fast, but do not absorb a comparable quantity of many soil nutrients. The plants are dependent on highly soluble, readily available sources of nutrients applied by the farmers, as opposed to those distributed through each acre's layer of topsoil. In fact, recent studies have shown that crops grown in poor quality, low organic matter soil sometimes have higher rates of root disease, and can struggle to absorb nutrients even when the nutrients are present at high levels in the soil profile.

No Free Lunch

Think of this relationship between yield and nutritional quality as farming's equivalent of "no free lunch." That is, higher yields, while desirable, may come with the hidden cost of lower nutritional quality, and in some cases, heightened risk of food safety and animal health problems.

As breeders have programmed plants to produce larger tomatoes, shorter-statured wheat with bigger grain heads, and corn that can tolerate closer spacing in the field, these plants have devoted less energy to other factors, like sinking deep roots and generating health-promoting compounds known as phytochemicals, many of which are antioxidants and vitamins.

The unintentional and largely unnoticed slippage in nutrient density has been accepted as a price of progress in boosting yields. After all, more total nutrients are harvested from a field of corn producing twice the yield, even if it means 20 percent less protein or iron per bushel. In addition, fortification of food with vitamins and minerals has been available, and used, to address blatant deficiencies in nutrient intake.

Many farmers now plant 30,000 or more corn seeds per acre, about three times the planting density common in the 1940's. The volume of corn grain harvested per corn plant has changed little in the last half-century.

Further erosion in nutrient density should be avoided for several reasons. Americans need to consume foods that deliver more nutrients per calorie consumed. Science has yet to identify, much less understand, the nutritional benefits linked to thousands of phytochemicals produced by plants. Many epidemiological studies have concluded that there are likely many beneficial nutrients in fruits and vegetables that we do not know about.

Plus, the relative levels, or ratios of nutrients in food, may also play important roles in human nutrition and health promotion. And what we surely do not need are staple crops delivering more sugar and starch per serving, and lower levels of vitamins, minerals and antioxidants.

Turning the Corner

Recent research shows that existing varieties of a given crop, whether pumpkins or peas or plums, vary widely in terms of their vitamin and mineral content. And this variability is inheritable, and it doesn't necessarily interfere with crop yields. So it should be possible for crop breeders to favor these varieties or use them in breeding efforts to make our food more nutritious, with only modest impact on average yields.

Moreover, given that part of nutrient decline has resulted from farmers pushing crops towards maximum yields, changing certain farming strategies should help reverse the decline. For instance, although organic farming results in lower yields in many cases, studies show that it also tends to produce crops with higher concentrations of micronutrients, phytochemicals and other health-promoting compounds. The increases range from a few percent to sometimes 20 percent or more for certain minerals, and on average, about 30 percent in the case of antioxidants.

A recent study documented a near-doubling in the levels of two antioxidants in organic tomatoes.

Some studies have reported even more dramatic differences in concentrations of specific phytochemicals—for example, nearly twice as much of two common antioxidants in organic tomatoes compared to conventional tomatoes. Organic forms of fertilizer, like manure or cover crops that offer more balanced mixes of nutrients and release the nutrients more gradually, encourage plants to develop more robust root systems that more aggressively absorb nutrients. At the same time, for a wide range of fruits, vegetables and grains, reducing pesticide use has been shown to boost phytochemical content, sometimes dramatically.

Might this general nutritional superiority of organic produce help justify the premium that consumers typically pay for organic food, or government policies to encourage a shift towards organic practices? Clearly, advantages linked to organic management will vary depending on the crop, soil quality and growing conditions, as well as on the technologies, inputs and systems in use on nearby conventional farms growing the same crop.

There will be some cases, usually linked to weather conditions, and pest levels and management, where conventional crops have higher nutritional quality than nearby organic crops. And, as organic farmers find ways to push yields close to the levels on conventional farms, the nutritional advantage of organic systems may narrow, and even disappear in some cases. Research is needed to identify farming systems and plant genetic innovations capable of increasing the nutrient content of foods without significant impacts on yields.

Significant erosion in the nutritional quality of the American diet rests on declining nutrient density in staple crops, coupled with increasing consumption of largely "empty" calories ("empty" in the sense that some foods contain high levels of added sugar and fat, and deliver very few nutrients per calorie consumed). Compared to half a century ago—when crop yields first began to climb dramatically—we are eating fewer nutrient-rich foods like fresh fruits and vegetables, and whole grains, and more highly processed foods. Contemporary epidemics of obesity and diabetes are among the direct consequences. This is why the U.S. government has placed so much emphasis on doubling average per capita consumption of fresh fruits and vegetables.

Improving the nutritional quality of these foods, and indeed all crops, will be an important part of addressing larger nutritional and health problems, particularly as the baby-boom generation ages. Cost-effective health promotion and disease prevention will likely depend more and more on improving dietary choices, and the nutritional quality of the foods we choose to eat, rather than on ever-greater dependence on drug-based therapies and invasive surgical procedures.

The good news is that farmers, crop breeders and agricultural scientists will almost certainly be as successful in increasing nutrient density, as they have been in raising yields, once they shift their priorities. But for this to happen, our clear-cut need for food that delivers more nutrition per calorie consumed must drive the system on equal footing with the pursuit of ever-higher yields. It's that simple, yet also exceedingly complex.

Lessons Learned

Despite impressive increases in crop yields around the world, much of humanity remains malnourished, including the 3 billion people in poorer nations who suffer from caloric and micronutrient deficiencies, and those in wealthy nations who consume too many calories on a daily basis, yet inadequate levels of several essential nutrients.

The single-minded focus by agricultural scientists and farmers on pushing plants and animals towards higher yields and levels of production has produced food with lower nutrient concentrations. In some cases, it has also created new food safety challenges, and made plants and animals more vulnerable to pests, diseases and reproductive problems.

Nutrient decline stems, in part, from the fact that high-yield crops devote energy to producing large fruit, grains or seeds, and put less emphasis on absorbing micronutrients. Faster growing plants that produce larger fruits and vegetables tend to dilute nutrient concentrations, a phenomenon labeled the "dilution effect" by scientists in the early 1980s.

High levels of readily available nitrogen tend to reduce nutrient density and the intensity of flavors, and sometimes make crops more vulnerable to pests. Nutrients in compost, manure, cover crops and other soil amendments tend to be released more slowly in step with crop needs, and often help to boost crop nutrient levels, the efficiency of nutrient uptake, and flavor profiles.

The large amounts of organic matter returned to the soil in organic farming systems encourage healthier, more robust roots, higher levels of available micronutrients, water infiltration and retention, and below-ground microbial activity that can help increase crop nutrient density.

A comprehensive strategy to improve public health by increasing nutrient levels in the food supply should include R+D investments and economic incentives focused on raising crops with greater nutrient density. Fortunately, farmers and scientists will likely excel in pursuit of this goal, as their focus shifts from maximizing yields at any cost, to maximizing yields and nutrient density.

Hunger still impacts about three billion people around the world, like this mother in the Kalahari desert. For the chronically malnourished, an increase in caloric consumption is essential to improve well-being. As people reach sufficient caloric intakes to maintain health, assuring proper balance across nutrients in the diet becomes the next hurdle that must be crossed for sustained progress toward food security and improved human health.

1. Meeting Human Needs?

The quest for calories

At its least romantic level, agriculture is a struggle to keep up with human demand for food calories. Getting enough vitamins, minerals, and other essential nutrients is a lesser concern, ideally one that we address by eating a diet that is diverse—legumes to complement grains, leafy greens to complement starch, meat and seafood to complement vegetables.

Although agriculture has dramatically expanded both the human food supply, and in turn helped increase population, diseases and disorders rooted in nutritional imbalances and deficiencies have lingered. Archeological evidence of those human societies that made the shift from hunter-gatherers to agriculturalists found that diets tied to cultivation of a few major crops lacked the diversity, and therefore the full range of vitamins and minerals, that hunter-gatherers had enjoyed. Episodes of hunger were less frequent, but health suffered nonetheless. There was a decrease in body size, bone length, and physical strength. The lower dietary quality, in association with the move towards denser settlements, meant the rise of infectious illness that had been much less common among hunter-gatherers. [1]

This decline in the nutritional quality of our diets has continued, and indeed in some ways has accelerated. Crop breeding, food processing,

and lifestyle changes have also helped to transform our diets. The Green Revolution, the shift to higher-yielding grain varieties adapted to high-input farming systems in poorer nations that is often credited for averting mass hunger in the 1960s and 1970s, led to a large increase in caloric availability. But increased grain production often came at the expense of more nutritious legumes, root crops, other minor grains, and vegetables, reducing dietary diversity and contributing to widespread micronutrient deficiencies.[2] In South Asia, for instance, per capita grain consumption increased about 15 percent in the last 40 years, but per capita consumption of legumes has dropped more than 50 percent.[3]

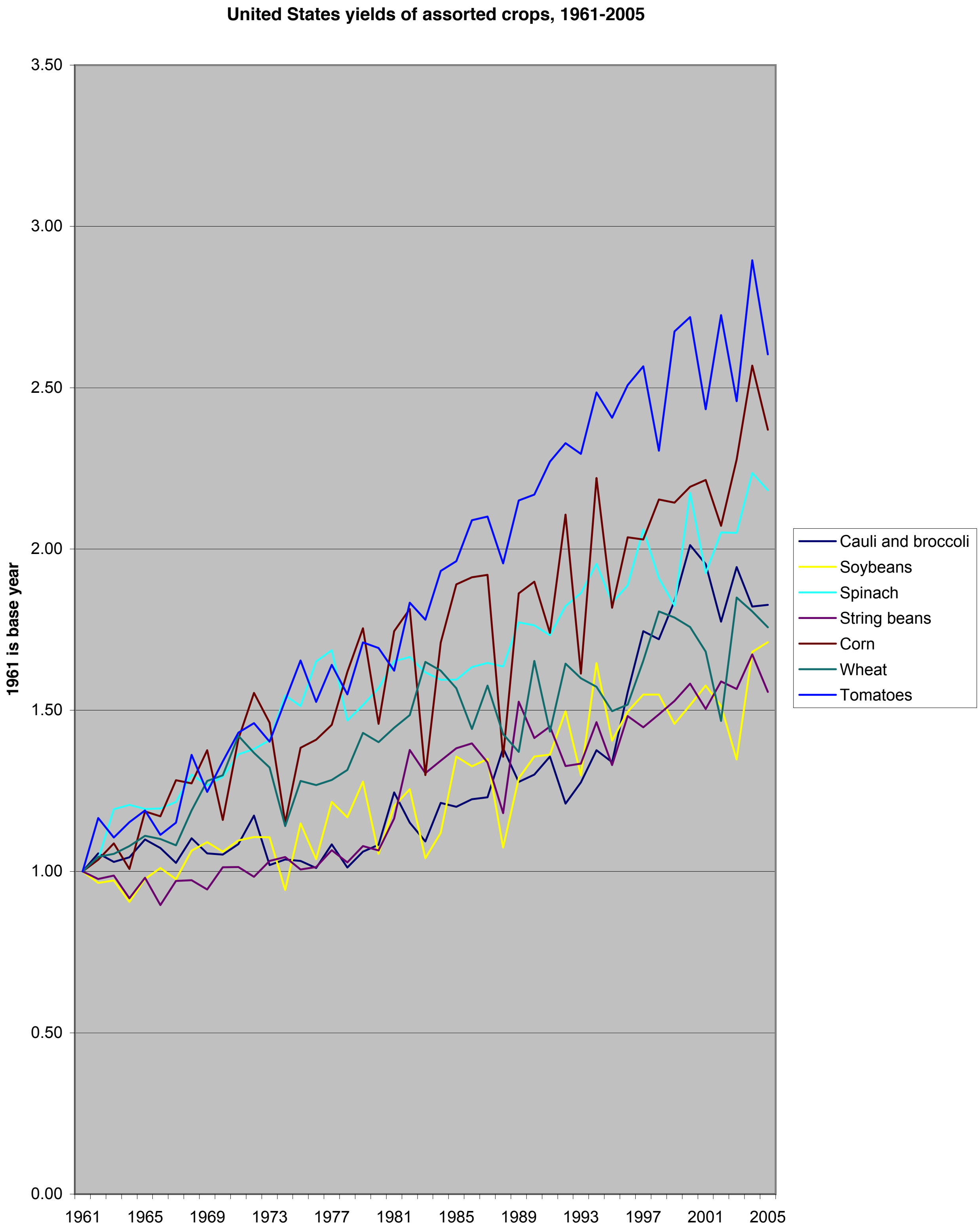
Remarkable increases in milk production per cow in the last century have come at a cost to consumers and cows. Modern milk contains reduced nutrient levels and more water per serving or ounce.

The Green Revolution isn't the only case of increasing yields. Over the past 50 years, using agricultural chemicals and mechanization, farmers around the world have been able to dramatically increase the yields of most crops. (See Figure 1.) In the United States since 1960, corn yields have more than doubled, wheat and soybean yield nearly doubled, and tomato yield nearly tripled.[4] In the Yuma Valley of Arizona, yields of broccoli doubled in just the last two decades, while cauliflower yields tripled over the same period.[5] Strawberry yields in the United States have jumped eightfold.[6] Pushing yields ever higher became part of the culture of farming: for decades, Pioneer Hi-Bred International, one of the world's leading seed companies, used the slogan, "technology that yields."

While the Green Revolution increased the yields and per capita caloric intakes from staple grains like rice, it also led to a narrowing of the human diet, greater dependence on chemicals and costly farm inputs, and degradation of soils.

The average amount of milk produced by a dairy cow has quadrupled in the last century from about 5,000 pounds per cow in 1900 to roughly 22,000 today.[7] In 1928, before modern breeding began for chickens, the average broiler required 112 days and 49 pounds of feed to reach a 3.5-pound market weight.[8] Today, broilers eat less than one-fifth the feed and reach slaughter weight in about one-third the time.[9] Laying hens produced an average of 93 eggs per year in 1930, 174 eggs per year in 1950, and 252 eggs per year in 1993.[10] These increases have ensured that more food is available for both domestic consumption and exports. But as yields increased, something else happened.

Figure 1, Yields of Assorted Crops Grown in the United States, 1961-2005. [11]



Overfed and undernourished

Despite all of this extra food, roughly 840 million people worldwide suffer from chronic hunger. A considerably larger population—more than 3 billion, or about half the world's people—suffer from a less lethal, more insidious deficiency of particular nutrients. It is estimated that four billion people are iron deficient, with hundreds of millions also suffering from health-impairing deficiencies of iodine, zinc, copper, selenium and vitamin A.[12] The consequences range from anemia in the case of iron deficiency to blindness for those not getting enough vitamin A, and higher rates of mental retardation for those deficient in iodine. (See "Symptoms of Common Mineral Deficiencies.")

Even in wealthier nations, deficiencies of assorted nutrients are widespread, and have been implicated in a range of conditions, including alcoholism, cancer, rheumatoid arthritis and diabetes.[13] The fact that Americans are overfed but still undernourished is a uniquely modern paradox. An estimated 66 percent of the adult population is overweight or obese, compared with 47 percent in 1980.[14] Americans consume several hundred more calories each day than they did 30 years ago: men consumed 2,450 calories in 1971 and 2,618 calories in 2000; and women jumped from 1,542 calories to 1,877 calories.[15]

Despite this increase, Americans still consume too few servings of fruits, vegetables, and other nutrient-dense foods for optimal health. Thirty percent or more of the U.S. population ingests inadequate levels of magnesium, vitamin C, vitamin E, and vitamin A, all nutrients we get from plants.[16] (See Figure 2.[17]) Put another way, the average American consumes inadequate levels of 2.9 essential nutrients each day (See Table 1, and see Appendix 1 for a similar table covering additional nutrients). The number and degree of such deficiencies increases with age and are more severe in women compared to men of the same age. Over 97 percent of American women 19 years of age or older consume inadequate daily intakes of vitamin E; the average woman in this category gets just over one-half daily needs.[18] Even if most healthy Americans do not show signs of nutrient deficiencies, clinical or otherwise, there's little doubt that consuming more nutrient-dense foods would yield health benefits. A 2002 review of the scientific literature by the Produce for Better Health Foundation found numerous studies showing reduced risk for cancers, cardiovascular disease, stroke, diabetes, bone disease, birth defects, and a range of severe and less severe conditions when people consumed higher amounts of fruits and vegetables.[19] The greatest benefits were often for individuals who consumed more than the recommended daily servings of these foods.[20]

Symptoms of Common Mineral Deficiencies

Calcium
Muscle cramps or tremors, joint pains, insomnia, brittle nails, eczema, nervousness.

Magnesium
Muscle twitch, tremors, personality changes, depression, anxiety, irritability, PMS, gastro-intestinal disorders.

Iron
Anemia, constipation, brittle or spoon-shaped nails, tiredness, apathy, reduced brain function, headache.

Chromium
Poor glucose tolerance leading to sugar and stimulant cravings, irritability, drowsiness, need for frequent meals, poor weight control.

Manganese
Poor glucose tolerance, poor muscle co-ordination, dizziness or poor sense of balance.

Selenium
Premature aging, growth retardation, higher risk of cancer and heart disease, poor fertility.

Zinc
Retarded growth, poor wound healing, poor sense of taste or smell, frequent infections, stretch marks, poor fertility.

Vitamin C
Susceptibility to infections, easy bruising, bleeding or tender gums, difficulty shifting infections, lack of energy.

Source: Adapted from Shane Heaton, Organic farming,food quality, and human health: a review of the evidence, (Bristol:Soil Association, 2001), and G.J. Kirschmann and J.D. Kirschmann, Nutrition Almanac, 4th edition, (McGraw-Hill Press, 1996).

Figure 2. Percentage of Americans Whose Intake of Essential Nutrients Falls Below the Estimated Average Requirement.

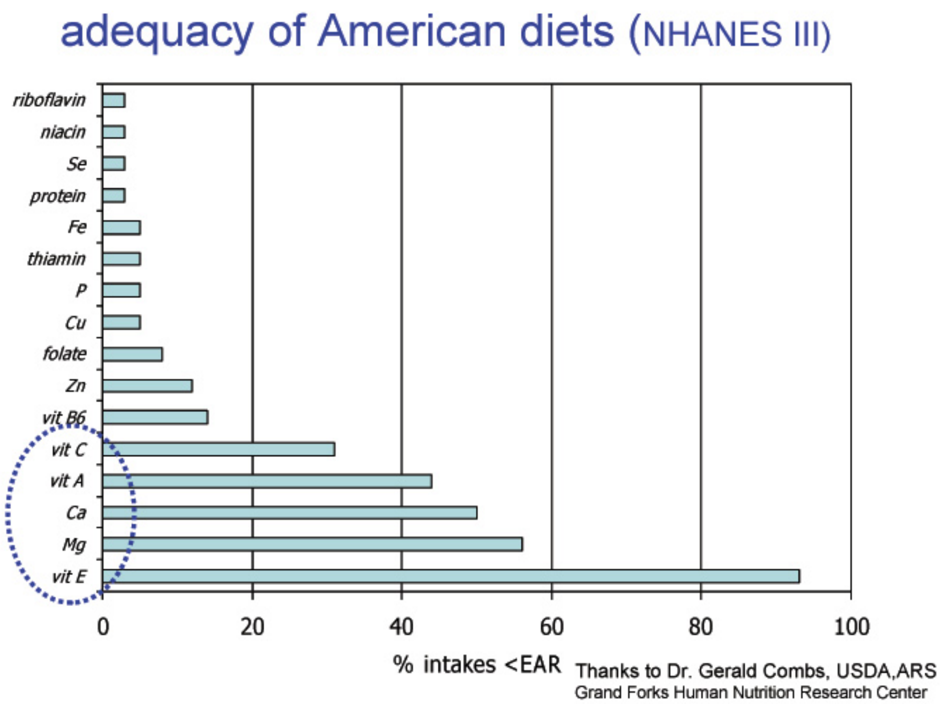


Table 1. Selected Deficiencies in Nutrient Intakes in the U.S. Population

Average Number of Nutrient Deficiencies by Population Segment

Population Segment	Average Number of Nutrient Deficiencies
Children 1-3	1.2
Males 9-13	1.77
Females 19-30	3.78
All Persons 1+	2.9

Source: Analysis by Chuck Benbrook, Organic Center, based on data from What We Eat in America, NHANES 2001-2002, USDA Agricultural Research Service, Washington, DC, September 2005.

Moreover, such deficiencies in daily intakes have spread over time: 15 percent of adults are vitamin C deficient today compared with 3-5 percent 25 years ago.[21] The minimum nutrient requirements set by the government do not consider the larger amounts of nutrients needed by individuals fighting off illness or disease, as well as the millions of individuals who are pregnant or have higher nutrient requirements. Public health officials conservatively estimate that such dietary deficiencies cost more than $120 billion each year in healthcare costs and lost productivity.[22]

All nutrients are not created equal

Mineral deficiencies affect billions of poor populations around the world with conditions like iron deficiency related anemia, vitamin A-related blindness, and selenium deficiency related cancers.[23] Even in well-fed wealthy nations, government surveys find that people do not consume sufficient amounts of vitamins and minerals for optimal health.[24]

Some nutritionists and crop scientists have suggested that taking mineral supplements or fortifying staple foods with additional nutrients is sufficient to compensate for a diet that is low in major nutrients. Clearly, supplements and fortification have a role to play in improving public health.

But nutritionists have also begun to understand that the form in which humans consume these nutrients is often more important than the quantity they consume. That is, getting vitamin C or iron or lycopene from a pill doesn't yield the same benefits to our bodies and health as consuming the same amount of vitamin C or iron or lycopene in the form of a carrot or serving of spinach or sun-dried tomato.[25] Supplements may not be as "bioavailable," typically contain no fiber, and do not also provide a myriad of phytochemicals and related nutrients found only in the whole food.

A recent article in the American Journal of Clinical Nutrition looking at the benefits of whole-grains in reducing heart disease suggested that it isn't the fiber or additional nutrients or phytochemicals in whole-grain that confer protection against heart disease, but the combination of the three which act "in synergy with each other" when eaten as part of a whole food. "The health benefit results from consuming a variety of whole grains, or the phytochemical-rich portions of them," the authors wrote, "but not from consuming the endosperm alone," [26] cereal fiber from the endosperm, or wheat bran alone." Consider that the purified vitamin C from an apple (a form equivalent to vitamin C supplements) confers only 0.4 percent the antioxidant benefit—and anti-cancer benefit—present in the same apple. (And the apple with skin had about double the benefit of the apple[27] without skin.)

And there are likely thousands of such health-conferring phytochemicals in any given fruit or vegetable, including those that we think are important, those that we don't think are important (but are), and many not yet even recognized.[28]

2. More Food, Fewer Nutrients

Early evidence of declining nutritional quality

In the last hundred years, every new agricultural or food processing innovation—whether the pasteurization of milk or the rise of frozen foods or the invention of chemical fertilizers—has prompted critics to suggest that the change has compromised the nutritional quality of our food. In the last century, the increasingly scientific and chemical-based efforts to raise crop yields prompted a new round of criticism that our more abundant food supply was actually more deficient. As far back as the early 1900s, Rudolf Steiner suggested that "a lot of things have diminished in their nutritive value," partly due to the early adoption of chemical fertilizers.[29] In fact, since the middle of the 20th century, researchers looking at British and American data have found that the nutrient content of those nations' food supplies have steadily declined.[30]

Modern equipment and chemical inputs have helped farmers maximize yields by assuring that crops always have enough nutrients to support optimal growth rates and face little competition from weeds, insects, and plant diseases.

In the middle of the 20th century, R.A. McCance and E.M. Widdowson, two British nutritionists who tracked changes in the nutrient content of the British food supply, suggested that the future of their nation was threatened by food processing, neglect of manuring, and the disappearance of crop rotations.[31] A reanalysis of this British government data found "marked reductions" of 7 minerals in 20 fruits and 20 vegetables from the 1930s to the 1980s, concluding that "in every sub group of foods investigated there has been a substantial loss in their mineral content."[32] These historical analyses invited critics who challenged the reliability of old data and measuring techniques; many aspects of sampling, handling, and assaying for nutrients have changed over the decades and in some cases methods are not well-documented.

Another analysis of British data, also criticized for not controlling for moisture content or separating raw from cooked foods, reported even more dramatic findings: spinach's potassium content dropped by 53 percent, its phosphorus by 70 percent, its iron by 60 percent, and its copper by 96 percent; a person would have had to eat three apples in 1991 to supply the same iron content as one in 1940; and the iron content of meat products declined by an average of 54 percent.[33] (The work is one of the few studies to look at meat and dairy products. As such, the double-digit declines in the nutrient quality of meat and dairy products are some of the first indications that consumption of less nutrient-dense animal feed grains and forages has a measurable impact on the animals eating them, and perhaps secondarily, on people consuming the meat and milk from such animals.)

Most recently, two teams—one in Britain and another in the United States—reexamined this data with particular attention to statistical rigor, adjusting for moisture content, throwing out suspicious data, and separating raw and cooked foods, as some earlier assessments had neglected to do. In 2005, White and Broadley looked at a half century of data for British fruits, vegetables and nuts and found that "the average concentrations of copper, magnesium and sodium in the dry matter of vegetables and the average concentrations of copper, iron and potassium in the dry matter of fruits available in the UK have decreased significantly between the 1930s and the 1980s."[34]

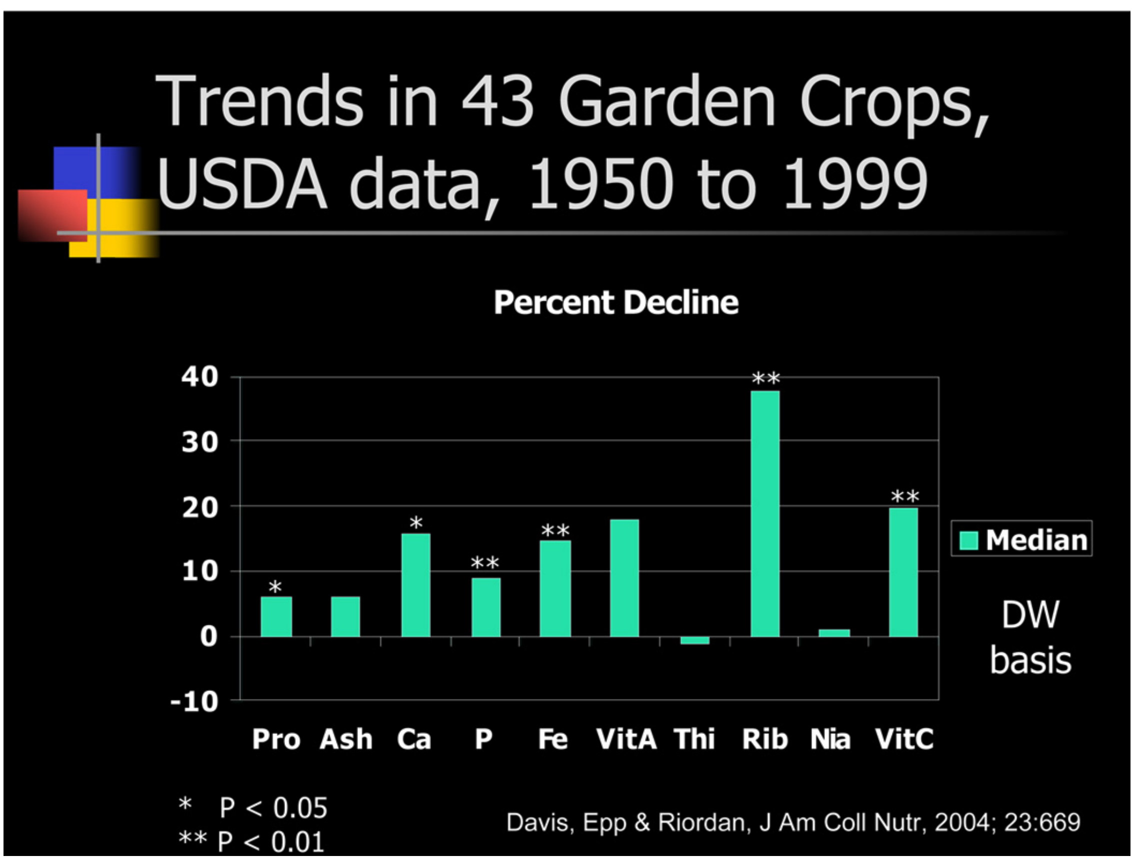
The year before, Davis and colleagues at the Biochemical Institute at the University of Texas in Austin, studied 50-year changes in U.S. Dept. of Agriculture food composition data for 13 nutrients in 43 garden crops—foods that were once commonly grown in home gardens and now are commonly bought at food stores, from turnip greens to strawberries, from sweet corn to cantaloupe. The team found declines in median concentrations of six nutrients from the 1950s to 1999, including a 6 percent decline for protein, a 16 percent decline for calcium, a 9 percent decline for phosphorus, a 15 percent decline for iron, a 38 percent decline for riboflavin, and a 20 percent decline for vitamin C.[35] (See Figure 3.) Davis et al. didn't find any nutrients that increased in the last 50 years, although thiamin and niacin barely changed.[36]

Side-by-side evidence

Given potential problems with old nutrient content data, the most powerful evidence of a nutritional decline comes from more recent studies that have grown older varieties and newer varieties—or low- and high-yield varieties—side-by-side under comparable agronomic conditions (same soil, planting method, fertility levels, harvest timing and method). These studies, including experiments with wheat, broccoli, and red raspberries, all show a correlation between increasing yield and decreasing nutrient content.[37]

For instance, a team of Department of Agriculture researchers ran a similar comparison of the micronutrient concentrations of 14 varieties of

Figure 3

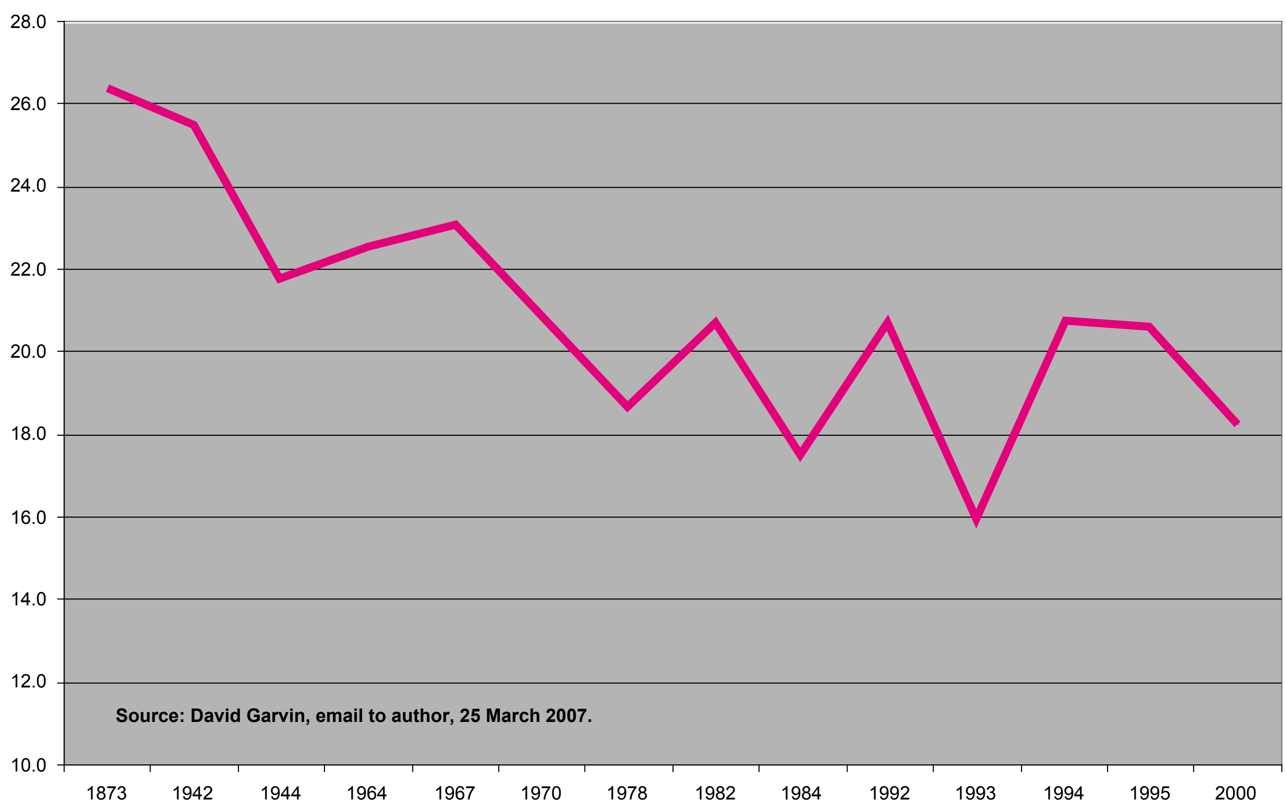


wheat introduced between 1873 and 2000, a period during which the amount of grain a typical American wheat farmer harvested per acre more than tripled. But the researchers found that the average micronutrient content of the harvested wheat declined dramatically, concluding that "genetic gains in the yield of US hard red winter wheat have tended to reduce seed iron, zinc, and selenium concentrations."[38] Iron content dropped by about 28 percent, while zinc dropped by about 34 percent and selenium by about 36 percent, over the 130-year period. (See Figure 4.) In other words, the amount of wheat farmers harvested from a given field increased by about 1 percent each year, the amount of these micronutrients in the harvested grain declined by .16 to .38 percent each year.[40] Such changes are no surprise, given that most of the focus in hard red wheat breeding has been on raising gluten (a form of protein) content, which makes the grain more conducive to baking. At the same time, the increase in total gluten and protein levels has come at the expense of protein quality assessed from the perspective of human nutrition—that is, the protein has a less beneficial suite of amino acids.[41]

Researchers at Washington State University found a similar relationship for modern and historical soft white wheat varieties and wrote that "plant breeders, through selection of low ash content in soft white wheat cultivars, have contributed to the decreased mineral nutrient in modern wheat cultivars."[42] Looking at 63 spring wheat cultivars grown between 1842 and 2003, they found declines in mineral concentration for all eight minerals studied, with an 11 percent decline for iron, 16 percent decline for copper, 25 percent decline for zinc, and 50 percent decline

Figure 4

Declining Zinc Content of Wheat Varieties Grown Between 1873 and 2000.



for selenium.[43] Put another way, the researchers found that, to get their recommended daily allowance of nutrients, people would have to eat many more slices of bread today than people had to eat in the past. (See Figures 5 and 6.) It is interesting to note that the Washington State researchers did not find a similar decline for hard red wheat, in contrast to the Department of Agriculture study mentioned above; the Washington State researchers suggest this points to the possibility of breeders increasing both yield and nutritional content simultaneously.[44]

In another example, Mark Farnham at the U.S. Vegetable Laboratory and colleagues grew out 43 cultivars of broccoli in the late 1990s and found a strong negative correlation between calcium and magnesium levels and head weight; that is, the higher the yield in terms of broccoli head harvested per plant (which is closely correlated with yield per acre), the lower the calcium and magnesium concentrations.[45] "It is possible that when breeders aim for a broccoli phenotype similar to that of 'Marathon' [the standard high-yielding variety], they select against high mineral concentration," the researchers concluded.[46] The researchers also noted that although certain high-yield varieties might have lower concentrations of these micronutrients, a given field of the high-yield crop—or a larger, denser head of the high-yield broccoli—may still produce more total calcium and magnesium.[47] The relevance of this advantage for consumers, who purchase most food based on weight, is debatable. (See "Measuring Nutrient Quality.")

Figures 5 & 6. Bread Alone?

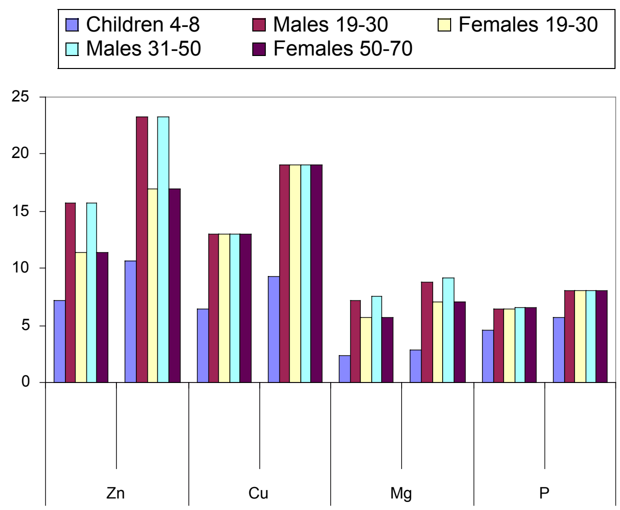


Figure 5

Estimated number of slices of bread required to meet the Recommended Dietary Allowance (RDA) levels for zinc, copper, magnesium, and phosphorus, with flour from both modern cultivars (denoted 'Top 7 Modern') and historical cultivars with high levels of nutrient content (denoted 'Top 7 Historical'). Each slice is equivalent to 50g whole wheat flour.

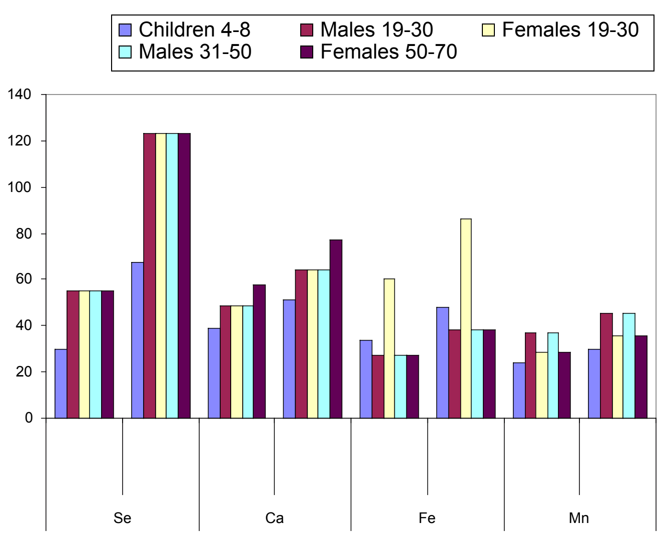


Figure 6

Estimated number of slices of bread required to meet the Recommended Dietary Allowance (RDA) or Adequate Intake (AI) levels with flour from both modern cultivars (denoted 'Top 7 Modern') and historical cultivars with high levels of nutrient content (denoted 'Top 7 Historical'). RDA was used for iron and selenium. AI was used for calcium and manganese. Each slice is equivalent to 50g whole wheat flour.

Finally, in an early experiment, researchers examined the effect of mycorrhizae on the amount of phosphorus taken up by red raspberry plants. They found a symbiotic relationship between mycorrhizae and phosphorous uptake, as many studies had previously demonstrated, but in addition, they showed that the higher the yield of berries, the lower the concentrations of nitrogen, calcium, magnesium, copper, boron, and zinc. Statistically significant reductions were noted in six out of the nine nutrients studied.[48]

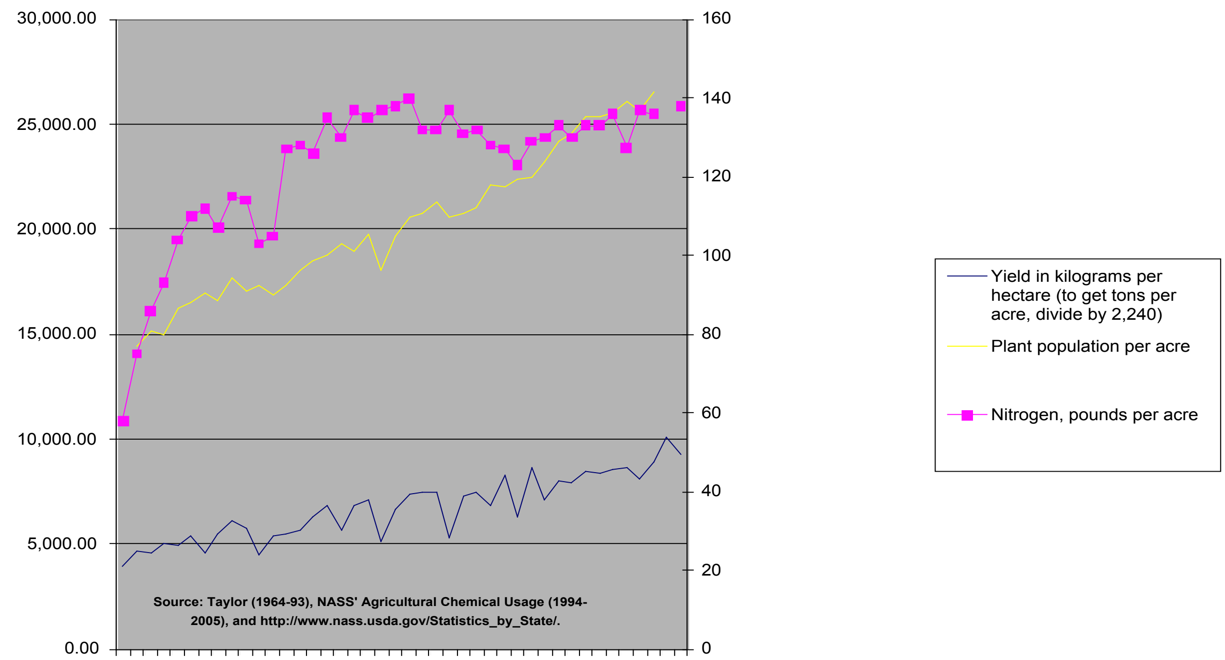
Measuring Nutrient Quality

Most nutritionists agree that the most pertinent measure of nutrient quality, or nutritional quality, is the amount of nutrients per calorie, sometimes called "nutrient density." This measure is superior to nutrients per pound or by volume, since many foods have a high water content. For instance, a comparison of the nutrient quality of orange juice and orange juice concentrate that doesn't take into account water content would deem the concentrate several times more nutritious. But measuring nutrients per dry weight or per calorie would consider the juice nutritionally identical to the concentrate. For the purposes of this report, nutrient quality refers to nutrients per calorie, or on the basis of dry weight.

From the perspective of the shopper, however, the most practical measure is probably nutrients per moist weight or purchased weight, since the price of food often depends on its weight. In this sense, the orange juice has only one-third the nutrients as the concentrate and it might be worth paying more for the concentrate than the diluted natural product. Some scientists point out that although in recent decades the nutrient content might have declined per head of lettuce or grain of wheat, the larger yields of these crops mean that we are still getting more total micronutrients per harvested acre. Farnham of the U.S. Vegetable Laboratory notes, for instance, that although the concentration of calcium and magnesium in a given higher-yielding head of broccoli may be lower, the larger size and weight of modern broccoli heads means each one probably has more total calcium and magnesium.[49] Still, most people don't eat an entire head of broccoli at once. Or, as Stephen Jones, a wheat breeder at Washington State University, counters, "People eat bread by the slice, not by the acre."[50]

Figure 7

Corn yield, nitrogen use, and plant population per acre, 1964-2005 [54]



3. Explaining Nutrient Decline

Redesigning plants

In a 1981 review in Advances in Agronomy, the soil scientist and plant nutritionist Wesley Jarrell suggested the presence of a "dilution effect" to describe the decline in the nutritional content of crops as farmers pushed crop yields higher.[51] Jarrell pointed to extensive evidence that the widespread adoption of yield-enhancing methods like fertilization and irrigation may decrease nutrient concentrations.[52] (See Figure 7.)

Although the process still isn't completely understood, it appears that crops redesigned for one goal—higher yields—are less capable of meeting other goals, including warding off disease, resisting drought, and accumulating vitamins and minerals. (See Figure 8.) Breeders and farmers seem to be generally aware of this phenomenon, although it gets little mention in the plant science literature; when it does get mentioned, it is typically dismissed as inconsequential. [53]

This tradeoff isn't surprising when you consider the plant's eye view, to borrow a term from journalist Michael Pollan. From the perspective of most plants, modern agriculture offers a sort of resource bonanza, with an abundance of nutrients, water, and other resources that would never be found in nature. This setting will tend to encourage rapid growth—the development of fleshy and watery stems, leaves, and grain—but will detract from the production of defense compounds (phytochemicals) and the prudent accumulation of micronutrients.[55] (Consider the "managed stress" strategy of vineyard and orchard managers, who will intentionally deprive their fruit of water towards the end of the season to increase the concentration of essential nutrients and flavor-conferring phytochemicals.) To put such consequences in human terms, think of a

Figure 8.

What Factors Affect Nutrient Levels in Crops

Decrease Nutrient Levels

Genetic
Select crop varieties only for yield, while not assessing nutrient content.

Environmental
Heavy fertilizer and irrigation leads to atrophied roots, which cannot accumulate as many micronutrients.

Plants respond to excess nutrients by putting more energy into starch and low-quality storage proteins, and less into absorbing micronutrients and synthesizing phytochemicals.

Close plant spacing reduces the amount of soil and soil nutrients available to each plant.

Pesticide use discourages plants from synthesizing phytochemicals.

Increase Nutrient Levels

Genetic
Choose crop varieties with higher nutrient levels.

Environmental
Slow-release fertilizers like compost and manure encourage more robust root systems.

These fertilizers also offer a more balanced range of micronutrients.

Reduced pesticide use encourages phytochemical production.

Restrictive irrigation reduces the moisture content of crops.

person at an all-you-can eat buffet. Many will tend to overeat the items they are most fond of, leaving less room for healthier items. As a result, such individuals will grow, but not necessarily in ways consistent with good health.

More yield, less everything else

Crop breeders were partly responsible for shifting the plant's attention away from nutrient accumulation. As breeders selected for crops that yielded more ears of corn per acre, larger tomatoes, or more beans per pod, the crops devoted less energy to other activities, including growing roots, absorbing minerals, and synthesizing vitamins. Think of this as the no-free-lunch principle of crop breeding. The tradeoff is well-documented.

- In corn and wheat plants, the higher the yield, the lower the protein content.[56]

- At the Illinois Longterm Corn Experiment, which has been testing popular corn varieties for more than 100 years, researchers have found that "Among recent commercial corn hybrids, increased yields have further reduced total protein levels."[57] A separate study found that protein in corn plants decreased about 0.3 percent every decade of the 20th century, while starch increased by 0.3 percent each decade.[58]

- Soybeans with higher yields have a lower oil and protein content.[59]

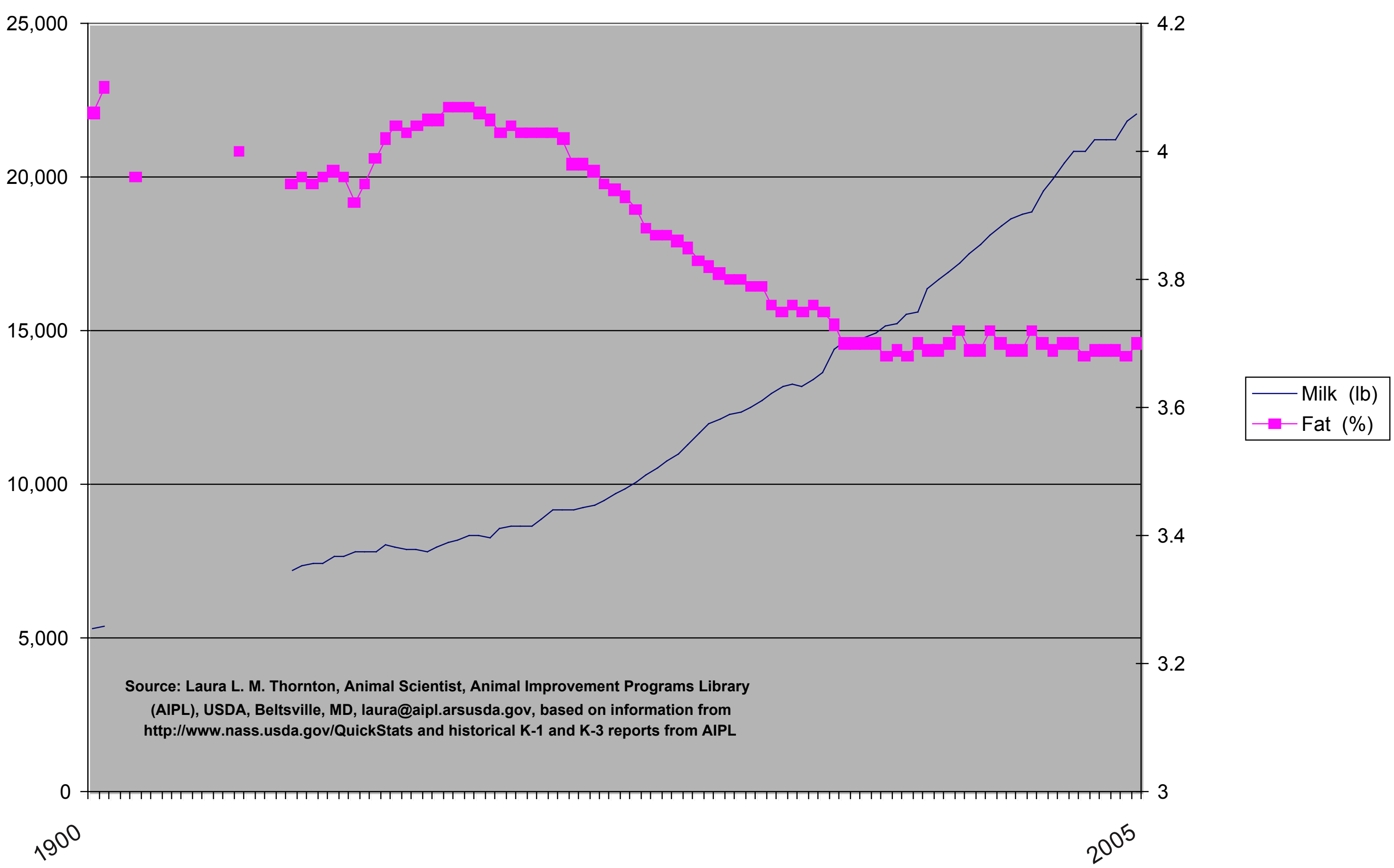
- Higher tomato yields (in terms of harvest weight) not only correlate with lower vitamin C, but also lower levels of lycopene (the primary color of tomatoes) and beta-carotene (a vitamin A precursor);[60] as one report noted, "University of California...breeders spent several years trying to select high-yielding progeny with elevated levels of vitamin C...but yield levels were not acceptable in the high-vitamin C lines;"[61]

- Studies from dairy production, including from cows and goats, show that animals that yield a higher volume of milk, produce milk that is less concentrated with fat, protein and other components;[62] or, as one dairy researcher stated matter-of-factly, "It is known that the greater the volume of milk yielded, the lower the concentration of milk constituents."[63] (See Figure 9, "Historical changes in milk yield per cow, and percent fat and protein,1900-2005.")

Plants are thrifty. They partition energy where they get the most benefit, which isn't the same as the most benefit for the person or animal eating the plant. For instance, when given an excess of nitrogen, grains tend to store it in the form of storage proteins, which are of lower nutritional value for humans than other grain proteins.[64] (Certain nutrients, like selenium and chromium, are not essential for plants, but important for humans, while zinc, copper, and iron are needed in trace amounts for plant growth, and are also essential for humans.[65])

Figure 9

Historical changes in milk yield per cow, and percent fat and protein, 1900-2005



Since water and carbohydrates make up the bulk of a bushel of corn or a peck of cucumbers, or a hundred-weight of potatoes, plants pushed to increase yield typically do so by accumulating even more water and starch. This ends up pushing down—or diluting—the concentration of many nutrients. In tomatoes, for instance, higher harvest weight correlates with lower dry matter content.[66] One study from 1943 showed that the larger a red cabbage, of the same age, the lower the concentration of vitamin C.[67] Research on lettuce suggests that the heavily fertilized plant takes on more water in an attempt to maintain osmotic balance and to keep the accumulating nitrates dissolved in the cell tissue.[68]

It is likely that certain nutrients and certain crops are more susceptible to this tradeoff than others. For instance, fruits and vegetables like strawberries, melons and sweetcorn that naturally have a high moisture content may be more likely to take on water that will dilute nutrient levels. In the Department of Agriculture research on 14 wheat varieties, copper did not show a significant decline, and the authors suspect that it is a micronutrient that is less susceptible to being bred out in favor of yield; at the same time, the wheat yield at the Manhattan, Kansas, test site was lower and zinc, selenium, and iron showed less of a decline than the higher-yielding field at Hutchinson, Kansas.[69] In broccoli, for instance, the yield-nutrient trade-off does not hold for certain phytochemicals, because breeders selecting for darker green florets—a popular characteristic for shoppers—inadvertently selected for higher levels of antioxidants that cause the florets to be green.[70] Researchers suggest that these increases were likely unintentional, since none of the varieties were developed as high-iron or high-protein crops. Within most crops, there is a wide variability of nutrient content across different cultivars. In addition, environmental conditions, whether poor soils, drought, or excessive heat, will tend to exacerbate this genetic trade-off. (See Our Changing Food System: “Prematurely Picked Produce and a Changing Climate.”)

Our Changing Food System:
Prematurely Picked Produce and a Changing Climate

Of course, changes in crop breeding and how farmers fertilize their fields aren’t the only thing that has altered the nutrient quality of our food. The average food item now travels at least 1,500 miles from the farm to our plates and might endure long times in storage and transport. Most commercial fruit, including tomatoes, is picked green and ripened artificially. Produce picked early doesn’t develop sunlight-related nutrients such as anthocyanins and polyphenols—compounds that give fruit their color and flavor, and which protect humans that ingest them against DNA damage, brain cell deterioration and cancer.[71] Blackberries picked “green” contain 74 mg of anthocyanins, compared to 317 mg in ripe ones (per 100 grams fresh weight).[72] Apples and apricots picked green had no vitamin C, but significant concentrations of the vitamin when picked half or fully ripe.[73]

Processed foods that tend to be less nutrient-dense have become more ubiquitous. In the case of bread and other cereals, refining—turning whole wheat into white flour or brown rice into white rice—eliminates 50-96 percent of the fiber, vitamin and mineral contents, much deeper losses than has been found in unprocessed crops.[74] Studies have even found that the rising atmospheric levels of carbon dioxide associated with climate change (levels are about 30 percent higher than at the beginning of the industrial revolution and are on target to double within the next century) tend to dilute crop tissues, sometimes spurring crop growth, but making the crops less healthy for animals and humans. More than a hundred studies have shown that increased atmospheric carbon levels tend to reduce the nitrogen “in seeds in both wild and crop species,”[75] while dozens of greenhouse experiments show that CO2 enrichment also causes significant decline in zinc, iron, phosphorus, potassium, magnesium, and other micronutrients.[76]

Faster growth, less time to accumulate nutrients

Some researchers suggest that faster-growing, shorter-stature crops have fewer opportunities to move nutrients from the stalks and leaves and other parts into the harvestable portion at the end of the season. Yes, breeders have increased the harvestable part of the plant (the fruit, seed, or grain) as a share of the plant's total biomass—boosting what is known as "the harvest index." But those unharvestable parts of the plant are essential to providing nutrients to the harvestable part as the season ends, since when seeds start to develop and mature, nutrients in the vegetative part of the plant are remobilized to fill out fruit, nuts, and grains.[77] "If you have much vegetative tissue from which to remobilize nutrients to the developing seeds, this may contribute to higher mineral concentrations in the older varieties," said Garvin, author of the wheat seed study discussed above.[78]

The pace of growth might also play a role. A study of 63 Brassica varieties, including broccoli, cauliflower, kale, and Brussels sprouts, found that early maturing broccoli varieties had about one-tenth to one-quarter the glucosinolates, an important phytochemical, as late-maturing varieties, although this relationship wasn't found for other phytochemicals in those broccoli varieties.[79] As Davis summed it up, "Either way, modern crops that grow larger and faster are not necessarily able to acquire nutrients at the same, faster rate, whether by synthesis or by acquisition from the soil." Faster growing plants and animals also seem to be less fit and have shorter lifespans, as demonstrated by high-producing dairy cows that have higher rates of mastitis, heavy laying hens that suffer from calcium deficiencies, and studies showing that animals on a restricted diet, in terms of total calories, tend to live longer and suffer fewer illnesses than animals on a more abundant diet.[80] (See Appendix 3.)

Fast food for plants

Just as the form in which humans get their food affects how they absorb nutrients (think of the difference between getting sugar from drinking a soda or from eating a banana), the form in which plants get their nutrients seems to play a role in their nutrient concentrations.

Mechanical technology, like the aerial application of fertilizer and pesticides, has allowed farmers to cover more ground and push yields higher, but has done so, in many cases, at the expense of soil and environmental quality.

Most farmers fertilize primarily with three major nutrients—nitrogen, phosphorus and potassium (NPK)—there is some evidence that conventional soils tend to develop deficiencies in many other nutrients.[81] One long term study started in Nova Scotia in 1990 that grew a variety of crops with standard NPK fertilizer or with compost found that, although equal quantities of crop were removed from the fields each year, the conventional plots had higher or equal levels of P and K, while the organic plots had higher levels of calcium, magnesium, manganese, copper, zinc, and other trace minerals.[82] And certain formulations of synthetic fertilizers can also alter the acidity and other chemical properties of the soil, making other nutrients less available.[83] At the same time, herbicides and pesticides have also been found to disrupt the ability of plants to absorb or synthesize certain nutrients.[84] A recent study estimated that widespread pesticide use and other soil contaminants are reducing yields of some crops in the United States by one-third by impairing symbiotic nitrogen fixation.[85]

Plants that grow on a steady, slow-release diet in the form of manure, compost, or nutrients bound up in decomposing organic matter accumulate higher nutrient concentrations than plants that receive larger pulses of soluble chemical fertilizer.[86] For instance, three independent studies showed that when compost and manure were the main source of phosphorus, the ratio of zinc to phytate (a substance that inhibits zinc digestion) was substantially higher than when the plants received phosphate salts.[87] An animal feeding experiment comparing the bioavailability of zinc and iron in diets with "traditionally" grown sorghum (no fertilizer or pesticides) with "improved" material (grown with recommended amounts of fertilizer and pesticides), showed that the improved grain resulted in the lowest values for weight gain and for iron and zinc contents of the animal's bones.[88]

In a survey of the literature that included not just studies that compared organic and conventional farming, but a wide range of farming and fertilization techniques, Kirsten Brandt, a senior lecturer at the School of Agriculture, Food and Rural Development at the University of Newcastle, concluded that "In terms of levels of compounds indicated as positive for health, the composition of plants that obtain much of their nutrients from slowly released sources such as plant residues or compost, tend to differ from those provided large amounts of easily available mineral fertilizers." Specifically, Brandt found that plants nurtured on the slowly released sources like plant residues and compost—fertilizers more likely to be used in organic farming systems—had higher levels of ascorbic acid (vitamin C); lower levels of nitrate; lower levels of total nitrogen (often expressed as "protein"); higher proportion of essential amino acids in protein; higher zinc to phytate ratios (on tropical soils); and higher levels of phytochemicals.[89]

More recently, researchers at the University of California at Davis's Long-Term Research on Agricultural Systems reported dramatically higher levels of two common phytochemicals in organic tomatoes compared to conventional tomatoes: the level of quercetin (the most common flavonoid in the human diet and the major flavonoid in tomatoes) was 79 percent higher, and kaempferol was 97 percent higher.[90] Most importantly, the organic plots built up significantly higher soil organic matter levels, which actually prompted the researchers to reduce compost additions in the final years. Yields didn't suffer, and flavonoid levels continued to increase. "Flavonoid content in tomatoes seems to be related to available N," the researchers concluded. "Plants with limited N accumulate more flavonoids than those that are well-supplied….overfertilization (conventional or organic) might reduce the health benefits from tomatoes."[91]

The power of organic matter

Nutrients that are bound up in organic matter seem to help boost crop nutrient levels partly by making nutrients available over more of the season and partly by stimulating healthy root growth: the fungi, bacteria and other soil microorganisms that depend on organic matter help plant roots function better.[92] One survey found that mycorrhizal treatment of a range of crops can increase copper, selenium, and zinc uptake by roughly 30 percent.[93]

Roots, in general, are a neglected area of agricultural research, partly because their location below the soil makes them difficult to study. Still, there is some indication that modern efforts to raise crop yields have compromised crop roots. (See "Are We Neglecting Our Roots?") And organic matter might help boost nutrient levels in crops partly by helping to foster healthy roots. Researchers at the Michael Fields Agricultural Institute in Wisconsin, working in conjunction with USDA/ARS National Soil Tilth Lab, have looked at several dozen corn farms in the Midwest and found that conventionally grown corn actually had a higher percentage of diseased roots than organic corn—26 percent of the corn root nodes in the conventional system were diseased, almost twice as much root disease as the 15 percent in the organic system.[94] (The highest levels of disease—30 percent—were seen in conventional corn planted after corn; the lowest levels—14 percent—were seen in corn following organic soybeans. See Figures 10 and 11.) The chief researcher, Walter Goldstein, suspects that lack of crop rotations and lower organic matter levels allow root diseases to build up in the soil and ultimately lead to less effective nutrient absorption. As a result, over the long-term, it took considerably more nitrogen to grow a given bushel of corn conventionally, because the plants were using considerable energy and nutrients to replace unhealthy roots. This additional nitrogen, however, *Figures 10 and 11*

Root disease in conventional and organic corn, and other differences from the Michael Fields Institute-University of Wisconsin trials. [97]

Figure 10

Root Disease 2000-2002 averaged across fertilization treatments:

Conventional = 26% n = 47

Organic = 15% n = 32

level of P = ***

Conventional corn after corn or soybeans = 22% n = 24

Organic corn after soybeans or forages = 13% n = 28

level of P = ***

Conventional corn after corn = 30% n = 9

Organic corn after soybeans = 14% n = 14

level of P = ***

Figure 11

	Conventional *(corn-corn, soybean-corn)*	**Organic** *(soybean-corn, alfalfa-corn, alfalfa + grass-corn)*	**% Organic/ Conven-tional**	**Level of P**
number of fields	27	53		
grain yield (t/ha)	7.2	7.9	110	NS
corn roots (t/ha)	5.9	5.0	85	**
root disease (%)	22	15	68	**
kg root/kg grain	1.2	0.7	58	*
total N uptake kg/ha	227	186	82	**
kg N uptake/ton grain	32	25	78	*
N min from organic matter (kg/ha)	211	207	98	NS
kg N min/ton grain	29	28	95	NS
total organic N in topsoil (t/ha)	5	5.6	112	***
total N mineralized (%)	4.2	3.7	88	

Are We Neglecting Our Roots?

Well-fertilized and well-watered plants have less incentive to grow lots of roots, since most of the nourishment they need is readily available.[98] From the plant's eye view, scouring the soil becomes a cost rather than a benefit, so a large root system would be selected against in a standard breeding program carried out under conventional high-input conditions. For instance, in contrast to plants grown under low levels of phosphorus, which develop more resilient plant architecture, including a more efficient and drought-tolerant root system, plants grown with an oversupply of phosphorus develop a much smaller root system.[99] The poorly developed, shallow root systems of some modern crops may be sufficient to absorb the major nutrients the plant needs to grow, particularly when farmers apply copious amounts of fertilizer. But they may be less capable of absorbing secondary nutrients. Consider these other observations:

A recent study found that pesticides commonly applied to legume crops, like this western alfalfa field, can reduce the natural fixation of nitrogen by bacteria that colonize the roots of legumes, and reduce yields by as much as one-third.

A survey of heirloom and modern wheat varieties grown in Australia showed that the ratio of root biomass to shoot biomass was about 20 percent higher in the older varieties.[100]

Modern varieties of alfalfa, which has long had a reputation for being a deep-rooted, drought tolerant plant, have smaller root systems than older varieties, particularly when grown in well-irrigated settings.[101]

In soybeans, the plant shuts down nodulation when there is ample nitrogen in the soil, since it has no reason to invest in fixing its own nitrogen.[102]

As the number of plants in a given field has doubled, as it has in corn grown in the United States over the last fifty years, the amount of soil available to each plant is reduce by half.[103] Average nutrient levels in the soil would have to double for the plant to remain equally well-nourished. Modern corn plants respond to the stress of close spacing—and the resulting shortage of nitrogen—by producing less protein (a nitrogen-rich compound) than when they are planted less densely.[104]

didn't end up in the grain.[95] "If you have a rooting system that is compromised due to root diseases, which is the case for most of American agriculture," said Goldstein, "how can you expect that plant to pick up fine nutrients?"[96]

Just as organic matter in the soil can help buffer crops against weather extremes as it absorbs and retains excess water in wet periods and absorbs and releases water in dry periods, this same buffering quality may hold for nutrient extremes. For instance, Rodale Institute's three-decade-long field trials have shown that nutrients in organic form—whether compost or manure or decomposing organic matter—serve as a late season repository of nutrients, a finding confirmed by other studies.[105] Plants, like any growing thing, need essential nutrients throughout their lives, which makes a continuous and available form of nutrients like organic matter superior. In contrast, conventional fertilizer is applied in the form of a soluble salt, which yields an early growth response, but is not retained for later in the season when plants are typically moving nutrients from the growing tissues (stalks and leaves) into harvestable tissues (fruits, nuts, and seeds). Rodale has shown that compared with crops fertilized with chemical nitrogen, the organic plants can have 2-3 times the amount of nitrogen in the stalk at the end of the season. In a tortoise-beating-the-hare sort of way, this results in higher protein content in the harvested grain, higher levels of biologically available protein, as well as higher levels of two amino acids: methionine and tryptophan. [106]

A nutritional advantage for organic farming?

Since several of the standard practices in agriculture, especially heavy use of chemical fertilizers, have been implicated in reducing the nutrient quality of our crops, organic farming is one approach that can help reverse the trend toward lower nutrient concentrations. (Crop breeding can also play a role, although few crop breeders are currently focused on increasing nutrient levels. See Appendix 3.) But is the higher price often paid for organic produce justified by higher nutritional value and relative absence of chemical and drug residues?[107]

Organic farming appears to increase the density of certain minerals, vitamins, and antioxidants in many fresh fruits and vegetables by marginally reducing levels of starches, sugars, and water in harvested crops, by increasing production of plant phytochemicals, and through physiological changes that lead to smaller average cell sizes.

In 2002, the Soil Association, the United Kingdom's primary regulatory body for organic farming, published a report assessing all existing research on food quality, human health and organic farming. The report disregarded many studies that were lacking in sample size or analytical rigor, and acknowledged that more research is needed on the impact of farming technique on the quality of the resulting food. "While there are many factors that can influence the nutrient contents of crops," the report concluded, "the method of farming is also shown to be a strong influence.[108] Specifically, the report found sufficient evidence to conclude that animals show a preference for organically grown crops, animals fed on organically grown crops show improved health and reproduction, and that organically produced crops generally show higher levels of vitamins, minerals and phytochemicals.[109] Organic crops contained significantly more vitamin C, iron, magnesium, and phosphorus and significantly less nitrates than conventional crops, as well as lower moisture content by about 20 percent (something that by itself boosts nutrient concentrations).[110] There were non-significant trends showing less protein, but higher quality protein in terms of digestibility and completeness in organic foods compared to conventional foods.[111] (Researchers have also found considerably higher levels of phytochemicals in organic produce, due partly to the higher concentrations of micronutrients in the soil, which are the building-blocks of these compounds. See Appendix 2.)

More recently, several side-by-side planting experiments have confirmed these findings. For instance, a study at Washington State University compared the mineral content of wheat grown organically and in a conventional system, and found that the organic crops had higher concentrations of copper (16 percent), magnesium (5 percent), manganese (3 percent), phosphorus (7 percent), and zinc (8 percent).[112] (See Table 2.)

Table 2 Mean mineral content (mg/kg) of wheat grown in organic and conventional systems

System	N	Ca	Cu	Fe	Mg	Mn	P	Zn	Ash
Organic	70	339	2.78	28.63	971	45.1	2845	17.05	1.42
Conventional	70	349	2.4	29.24	929	43.6	2650	15.79	1.4
Org/conv.		0.97	1.16	0.97	1.05	1.03	1.07	1.08	1.01

Source: Kevin Murphy, Washington State University, email to author, 27 March 2007; N refers to the number of genotypes compared (35 genotypes per location). This was for two locations in Pullman in 2005. The researchers are still waiting on 2006 results and will repeat this experiment in 2007.

The Rodale Institute Farming Systems Trial is among the longest studies directly comparing the nutritional quality in organic and conventional crops. Started in 1981, the experiment grew corn, soybeans, wheat, tomatoes, peppers, and carrots in side-by-side plots that were either managed conventionally (managed completely with chemical fertilizer and pesticides), or organically (fertilizing with compost, manure, and cover crops, and controlling pests with rotations or biological controls). The experiment tracked not just yield, soil quality, energy use, and carbon emissions, but also the nutritional quality of the harvested crops, and the researchers found the organic crops had higher levels of nitrogen, phosphorous, potassium, calcium, magnesium, sulfur, iron, manganese, boron, copper, and zinc. "Pretty much all of the minerals we've looked at," said Paul Hepperly, Rodale's research manager. (See Table 3.)

Table 3 Nutrient levels of oats grown at Rodale Institute under different farming systems in 2003.[113]

System	N %	P	K	Ca	Mg	Mn ug/g	Fe	Cu	B
Manure	3.89	0.32	2.17	0.43	0.20	48	92	6	12
Legume	3.01	0.27	2.10	0.37	0.18	47	94	7	9
Conventional Chemical	3.07	0.26	2.05	0.39	0.18	41	74	4	7
% Diff Manure to Conventional	26.71	23.08	5.85	10.26	11.11	17.07	24.32	50	71.43
% Diff Legume to Conventional	-1.99	3.84	2.44	-5.4	0	14.63	27.03	75	28.57

Note: Manure and Legume Systems are organic with and without manure applications. Conventional is a corn and soybean row crop system without cover crops using herbicides, fungicide, and fertilizer, according to Pennsylvania State University recommendations for the previous 22 years. Major nutrients (N, P, K, Ca and Mg) were 6 to 27 percent higher under the legacy of the organic system. Minor nutrients (Mn, Fe, Cu, B, Al, and Na) were -17 percent to 287 percent higher for organic. Each reading came from 8 samples.

Reinforcing the suspected connection between soil organic matter levels and crop nutrient levels, Hepperly and his team found that while soil organic matter in the organic treatments increased by approximately 30 percent over the 27 years of the experiment, the nutrient content of the crops increased by a similar amount.[114] "It's proportional. When you increase organic matter in soil, you get higher mineral content in crop products," said Hepperly. (Although the results are not yet finalized, Rodale is now in the final year of a 3-year feeding study with the two crops, in collaboration with the University of Wisconsin, that is "showing significant difference in the quality of the food and how it affects the animal's health and behavior," according to Hepperly.)

Will organic always be more nutritious?

Some observers of the organic industry are concerned that the nutritional advantage of organic food could be eroded if organic farmers develop higher-input systems that produce yields comparable to nearby conventional, chemical-intensive farmers. Several ongoing studies—by

Jones et al. and Preston Andrews at Washington State University—hope to show that organic farming, coupled with plant breeding that places equal weight on nutrient density and yields, can reverse the decline in nutrient content in major crops like wheat, apples, and strawberries, and match or even exceed nutrient densities of five decades ago. Others, like Rodale's Hepperly, argue that organic farming can already match conventional yields without compromising nutrient levels as long as farmers continue to encourage well-balanced soils that are rich in organic matter. Research on systems and genetics that can increase nutrient density while sustaining good yields will benefit all farmers—organic or otherwise—hoping to raise high quality, nutrient-rich crops. (See "Lessons for Growers and Agricultural Scientists.")

The body of evidence supporting this nutritional advantage of organically grown foods is rapidly growing; The Organic Center will release in the fall of 2007 a database including more than 80 published studies comparing the nutritional quality of organic and conventional foods. And while this organic advantage remains controversial, many researchers interviewed for this report suggested that relatively straightforward and inexpensive experiments could either confirm, dispute or refine this conclusion.

Organic food will not always be more nutrient dense than conventional foods. Organic fruit that is picked green would likely have lower levels of most nutrients than the same conventional fruit picked at optimal ripeness. In addition, there are combinations of weather and growing conditions that tend to increase the nutrient content of a conventionally grown crop, while reducing the nutrient density of nearby organic crops. In years when these conditions prevail, conventional crops may, on average, match or exceed the nutrient density of organic crops.

Consider a hypothetical farm growing organic and conventional strawberries in adjacent fields. In a typical season, the organic plot might yield 10 to 15 percent less volume of berries, but produce fruit that has 20 percent to 30 percent higher levels of several nutrients and tastes better as a result. But what would happen in a more erratic growing year, with lots of rain early on and excessive drought later in the season? The conventional plot might lose enough fertilizer to leaching to reduce growth and result in a more open canopy. On the organic field, however, the wet spring will have less of an impact on fertility levels and leaching, because of differences in soil quality and the forms of nitrogen in the system. Weeks later, as summer approaches and the weather turns hot and dry, soil on the conventional field will dry out more quickly than on the organic field, and there will be less water stored in the rootzone. Yields will suffer, but likely result in higher nutrient density. The more open canopy will also result in more direct sunlight falling on the strawberries, which can cause sunscald and trigger the production of phytochemicals by the plant to help protect the skin of the berries—raising total antioxidant content.

Increasing soil organic matter is a necessary step in improving soil quality. Recent science has highlighted potential linkages between soil quality and food nutritional quality, raising the hope that both conventional and organic farmers may one day be able to enhance nutrient density just by incrementally improving soil quality.

In the organic plot, with its slow-release nutrients that aren't leached to the same degree by the rain, and its higher levels of soil organic matter that tends to hold moisture and provide a buffer against drought, the plants will thrive. The relatively more lush plants will more fully shield the berries from antioxidant-producing sun, and produce bigger berries that have lower levels of nutrients and antioxidants than in normal years, or than the conventional berries harvested nearby.

Such exceptions will arise occasionally, but in most years, and under most conditions, prevailing evidence seems to demonstrate that organically grown produce will be more nutrient dense than nearby conventional produce, especially if conventional farmers are striving for maximum yields and rapid growth. Conventional farmers working with exceptionally rich soils will be able to sustain nutrient concentrations farther up the yield curve, but eventually, if they keep pushing yields higher, they will start harvesting less nutrient dense crops.

It is important to acknowledge that nutritional quality is, to a large extent, defined by the dietary needs of the animals or people for which food is grown. In rich countries like the United States, people tend to consume more calories than they need. Our major health problems are rooted in excessive caloric, salt, and saturated fat intakes. Yet, we have inadequate intakes of vitamin and antioxidant-rich fruits and vegetables, and fiber. More nutrient-dense foods, and foods with higher levels of phytochemicals (e.g., whole grains, fruits and vegetables) are just what the doctor ordered for millions of Americans in need of more nutrients, despite higher caloric intake.

In countries with many people living in poverty and suffering from an absolute shortage of food, increasing overall calorie intake will be more important than increasing the availability of micronutrients and phytochemicals.[115] And, yet, in these same settings, organic farming tends to offer an advantage by raising yields as well as the amount of nutrients per calorie compared to subsistence farming with little of the fertilization, pesticides, and infrastructure of chemical-intensive farming. According to Brandt, "Based on the scientific evidence, at least in developing world settings, only organic methods have demonstrated the ability to improve both yield and nutritional quality at the same time." [116]

Advice for Growers and Agricultural Scientists

Encourage root growth:
Farmers and agricultural extensionists should consider ways to improve root growth in their crops, including using some organic forms of fertilizer (compost, manure, cover cropping) or making chemical fertilizer available in smaller doses throughout the season.

Encourage phytochemical production:
Farmers, scientists, and agricultural extensionists should look for ways to increase the phytochemical content of crops. Techniques to consider include lowering nitrogen levels, allowing plants to mature a bit more slowly and reach maturity somewhat smaller than now the case, and by reducing pesticide use and increasing use of biological controls.

Breed crops for nutrient quality:
Crop and livestock breeders, agricultural researchers, and seed companies should begin to monitor crop nutrient levels as an important variable when developing new breeds of crops. They should also begin a systematic effort to increase the nutrient levels of crop varieties by drawing on existing natural variation among cultivars. Organic growers favor certain crop varieties for disease resistance and flavor, and these same varieties often have higher nutrient and phytochemical content. Crop breeders, seed companies and farmers should assess and catalogue these varieties, since they might be useful in crop breeding for all growers.

Encourage high yields, but not maximum yields:
Farmers and agricultural researchers should reconsider the strategy to maximize yields in any given season. Whether using excess fertilizer and water or growth hormones and antibiotics, efforts to maximize yield for both crops and livestock lead to shorter lifespans, greater health problems, and reduced taste and nutrient levels in the final food products.

Practice restraint with irrigation and fertilization:
Vintners and fruit growers speak of "managed stress" in the vineyard and orchard as a way to maximize flavor, nutrients and phytochemicals in their crops. This involves a more restrained irrigation and fertilizer regime that encourages robust root systems and efficiency in nutrient uptake and synthesis. It will also result in tastier more nutritious crops that consumers will be willing to pay a premium for.

APPENDIX 1.

Nutrient Deficiency in the U.S. Population

Some nutritionists and crop scientists argue that any decline in nutrient content isn't significant because most healthy Americans do not show signs of nutrient deficiencies, clinical or otherwise. Still, it isn't clear if our health is less than it would be if we consumed more micronutrients, as scientists still grasp exactly what it is in fruits and vegetables that so strongly promote good health. A 2002 review of the scientific literature by the Produce for Better Health Foundation found numerous studies showing reduced risk for cancers, cardiovascular disease, stroke, diabetes, bone disease, birth defects, and a range of severe and less severe conditions when people consumed higher amounts of fruits and vegetables.[117] The greatest benefits were often for individuals who consumed more than the recommended daily servings of these foods; for instance, a recent report from the Nurses' Health Study and Health Professionals' Follow-Up Study found a 4 percent lower risk of coronary artery disease for each 1 serving per day increase in fruit and vegetable intake, even when this intake exceeded the five servings per day recommendation.[118] In lieu of more servings, consuming fruits and vegetables that have higher concentrations of micronutrients and phytochemicals will deliver more health benefits.

And, at least according to the standards set by the U.S. government, a substantial proportion of Americans are nutrient deficient. The following table, Table 4, "Nutrient Intakes From Food Compared to Estimated Average Requirement (EAR) for 8,940 Individuals, 2001-2002," compiled by Chuck Benbrook of The Organic Center, shows the pervasiveness of inadequate nutrient intake throughout the U.S. population. Moreover, the minimum nutrient requirements set by the government do not consider the larger amounts of nutrients needed by individuals fighting off illness or disease, as well as the millions of individuals who are pregnant or otherwise have higher nutrient requirements.

Table 4, Nutrient Intakes From Food Compared to Estimated Average Requirement (EAR) for 8,940 Individuals, 2001-2002

Nutrient	Population Groups	EAR	Percent of Group With Intake Less Than EAR	Mean Intake	10th Percentile Intake	10th Percentile Intake as Percent of EAR	50th Percentile Intake	50th Percentile Intake as Percent of EAR
Vitamin A (RAE[2])	Children 1-3	210	<3	532	330	157%	512	244%
	Males 9-13	445	13	670	418	94%	643	144%
	Males 19-30	625	59	615	288	46%	559	89%
	Females 19-30	500	58	487	249	50%	458	92%
	Females 71+	500	38	600	349	70%	559	112%
	All Persons 1+[3]		44	600				
Vitamin E (mg Alpha-tocopherol)	Children 1-3	5	80	4	2.4	48%	3.7	74%
	Males 9-13	9	97	6	4.4	49%	5.9	66%
	Males 19-30	12	89	8.1	4.8	40%	7.6	63%
	Females 19-30	12	>97	6.2	3.4	28%	5.8	48%
	Females 71+	12	>97	5.6	3.3	28%	5.1	43%
	All Persons 1+		93	6.7				
Thiamin (mg)	Children 1-3	0.4	<3	1.2	0.85	213%	1.17	293%
	Males 9-13	0.7	<3	1.78	1.31	187%	1.74	249%
	Males 19-30	1	3	2.01	1.25	125%	1.93	193%
	Females 19-30	0.9	8	1.48	0.94	104%	1.44	160%
	Females 71+	0.9	12	1.27	0.87	97%	1.21	134%
	All Persons 1+		5	1.6				
Riboflavin (mg)	Children 1-3	0.4	<3	1.97	1.33	333%	1.94	485%
	Males 9-13	0.8	<3	2.51	1.7	213%	2.43	304%
	Males 19-30	1.1	<3	2.55	1.56	142%	2.44	222%
	Females 19-30	0.9	5	1.8	1.06	118%	2.19	243%
	Females 71+	0.9	<3	1.74	1.11	123%	2.02	224%
	All Persons 1+		<3	2.18				
Niacin (mg)	Children 1-3	5	<3	13.5	8.9	178%	13.2	264%
	Males 9-13	9	<3	22.5	15.6	173%	22	244%
	Males 19-30	12	<3	29.4	19.6	163%	28.5	238%
	Females 19-30	11	5	20.2	12.9	117%	19.7	179%
	Females 71+	11	13	16.1	10.5	95%	15.2	138%
	All Persons 1+		<3	21.9				
Vitamin B_6 (mg)	Children 1-3	0.4	<3	1.34	0.89	223%	1.3	325%
	Males 9-13	0.8	<3	1.81	1.23	154%	1.76	220%
	Males 19-30	1.1	<3	2.36	1.42	129%	2.24	204%
	Females 19-30	1.1	23	1.54	0.87	79%	1.47	134%
	Females 71+	1.3	49	1.44	0.84	65%	1.32	102%
	All Persons 1+		14	1.81				
Folate (DFE[4])	Children 1-3	120	<3	416	254	212%	369	308%
	Males 9-13	250	<3	644	424	170%	619	248%
	Males 19-30	320	6	696	366	114%	641	200%
	Females 19-30	320	14	519	291	91%	491	153%
	Females 71+	320	21	452	272	85%	418	131%
	All Persons 1+		8	554				

Nutrient	Population Groups	EAR	Percent of Group With Intake Less Than EAR	Mean Intake	10th Percent-ile Intake	10th Percent-ile Intake as Percent of EAR	50th Percent-ile Intake	50th Percent-ile Intake as Percent of EAR
Vitamin B_{12} (µg)	Children 1-3	0.7	<3	4.51	2.79	399%	4.38	626%
	Males 9-13	1.5	<3	6	3.98	265%	5.84	389%
	Males 19-30	2	<3	6.41	3.48	174%	5.8	290%
	Females 19-30	2	9	4.27	2.09	105%	3.87	194%
	Females 71+	2	*	4.18	1.92	96%	3.59	180%
	All Persons 1+			5.28				
Vitamin C (mg)	Children 1-3	13	<3	92.1	41	315%	84	646%
	Males 9-13	39	8	80.2	41	105%	75	192%
	Males 19-30	75	37	116.2	37	49%	97	129%
	Females 19-30	60	40	82.3	31	52%	70	117%
	Females 71+	60	40	81.6	27	45%	72	120%
	All Persons 1+		31	91.8				
Phos- phorus (mg)	Children 1-3	380	<3	1065	721	190%	1044	275%
	Males 9-13	1055	9	1431	1066	101%	1399	133%
	Males 19-30	580	<3	1658	1097	189%	1612	278%
	Females 19-30	580	4	1160	717	124%	1136	196%
	Females 71+	580	5	946	650	112%	918	158%
	All Persons 1+		5	1304				
Magnesium (mg)	Children 1-3	65	<3	188	132	203%	185	285%
	Males 9-13	200	14	250	193	97%	246	123%
	Males 19-30	330	55	328	213	65%	317	96%
	Females 19-30	255	64	235	136	53%	226	89%
	Females 71+	265	82	213	142	54%	203	77%
	All Persons 1+		56	265				
Iron (mg)	Children 1-3	3	<3	11	6.8	227%	10.5	350%
	Males 9-13	5.9	<3	17	11.6	197%	16.4	278%
	Males 19-30	6	<3	19.2	11.2	187%	18	300%
	Females 19-30	8.1	15	13.9	8.5	105%	13.4	165%
	Females 71+	5	<3	12.3	8	160%	14.2	284%
	All Persons 1+		5	15.3				
Zinc (mg)	Children 1-3	2.5	<3	8.3	5.6	224%	8	320%
	Males 9-13	7	<3	13	9.3	133%	12.8	183%
	Males 19-30	9.4	6	14.5	10.1	107%	14.2	151%
	Females 19-30	6.8	13	10.3	6.4	94%	9.8	144%
	Females 71+	6.8	36	8.2	5.2	76%	7.6	112%
	All Persons 1+		12	11.6				
Copper (mg)	Children 1-3	0.34	<3	0.76	0.49	144%	0.74	218%
	Males 9-13	0.54	<3	1.16	0.9	167%	1.14	211%
	Males 19-30	0.7	<3	1.59	1.09	156%	1.52	217%
	Females 19-30	0.7	11	1.13	0.68	97%	1.08	154%
	Females 71+	0.7	14	0.95	0.67	96%	0.91	130%
	All Persons 1+		5	1.24				

Nutrient	Population Groups	EAR	Percent of Group With Intake Less Than EAR	Mean Intake	10th Percent-ile Intake	10th Percent-ile Intake as Percent of EAR	50th Percent-ile Intake	50th Percent-ile Intake as Percent of EAR
Selenium (µg)	Children 1-3	17	<3	65	45	265%	64	376%
	Males 9-13	17	<3	103	77	453%	102	600%
	Males 19-30	45	<3	131	89	198%	127	282%
	Females 19-30	45	4	99	57	127%	93	207%
	Females 71+	45	<3	75	54	120%	73	162%
	All Persons 1+		<3	102				
Carbo-hydrate (g)	Children 1-3	100	<3	204	143	143%	198	198%
	Males 9-13	100	<3	309	229	229%	264	264%
	Males 19-30	100	<3	366	239	239%	355	355%
	Females 19-30	100	<3	273	181	181%	268	268%
	Females 71+	100	<3	189	135	135%	186	186%
	All Persons 1+			274				
Protein (g/kg body weight)[5]	Children 1-3	0.87	<3	4.38	3.08	354%	4.31	495%
	Males 9-13	0.76	<3	2	1.32	174%	1.95	257%
	Males 19-30	0.66	<3	1.38	0.97	147%	1.36	206%
	Females 19-30	0.66	5	1.15	0.75	114%	1.12	170%
	Females 71+	0.66	11	0.95	0.65	98%	0.92	139%
	All Persons 1+		3	1.51				

Source: All data derived from "What We Eat in America, NHANES 2001-2002" (USDA Agricultural Research Service, September 2005); except where noted below.

Data in Columns "% of EAR Intake at 10th Percentile" and "% of EAR Intake at 50th Percentile" calculated by the Organic Center.

[1]Sample Size: Children 1-3: 798, Males 19-30: 552, Females 19-30: 465, Females 71+:405, All Persons 1+:8940

[2]RAE= Retinol Activity Equivalents. 1 RAE= 1 _g retinol=12 _g Beta Carotene=24 _g Alpha Carotene

[3]"Percentage computed as weighted average of estimates for gender/age subgroups comprising the composite group."

[4]DFE= Dietary Folate Equivalent; 1 DFE= 1 _g food folate = 0.6 _g of folic acid from fortified food.

[5]Sample Size: Children 1-3: 798, Males 19-30: 535, Females 19-30: 457, Females 71+: 345, All Persons 1+: 8637.

**"Comparison to EAR for ages 50 and older not presented because 10-30 percent of older people malabsorb food bourne vitamin B12. This age group is advised to meet the vitamin B_{12} requirement mainly by consuming foods fortified with vitamin B12 or a supplement containing it."*

APPENDIX 2.

Why Farmers and Consumers Should Worry

Apart from the worrying fact that crops with lower nutrient concentrations are less nutritious, there are certain other results of this decline that might concern consumers, farmers, and public health officials.

Fitness of Crops

There is evidence that the same techniques that farmers use to push up crop yields, including high amounts of chemical fertilizers and irrigation, can also make crops more susceptible to insect pests, disease, and extreme weather. As noted above, when crops have a more limited supply of resources, they choose a defensive path, growing more slowly and devoting more energy to producing defensive phytocompounds. In fact, experiments at the Danish Institute of Agricultural Sciences showed that plants grown under high-nutrient levels were more susceptible to diseases, and theorized that organic plants have "more intrinsic resistance" to disease than conventionally grown ones, even when the same cultivar is used.[119] (In any case, organic farmers do tend to favor disease-resistant varieties, which have higher concentrations of defense compounds.[120]) A study on processing tomatoes found that nitrogen fertilization increased total yield but not marketable yield, because of a marked increase in unripe, misshapen, and other unmarketable fruit.[121] (The highest fertilization rate resulted in less concentrated ripeness, more phytosanitary problems and an increase of viral damage incidence on fruits.) High nitrogen supply also worsened some important processing characteristics such as pH, soluble solids, glucose and fructose content, as well as reducing sugar/total solids ratio.[122]

Crops grown this way also tend to direct less energy to their root systems, making them less able to deal with drought. An indirect consequence of organic fertilization with large amounts of green manures and compost is to confer a higher tolerance for adverse weather events, like floods and droughts, since the fertilizers enhance the moisture-buffering organic matter content of the soil. The Rodale Institute's long-term cropping trial has shown its organic and manure-treated crops fare better in drought years than crops grown with chemical fertilizers, partly because of the more extensive root systems and partly because of the greater water-holding capacity of the soils. (This advantage should become more important as climate change causes more erratic conditions for farmers.)

Livestock pushed to gain weight more rapidly or produce more milk and eggs suffer similar consequences. Modern laying hens sometimes suffer from a condition known as "cage layer fatigue," caused in part by insufficient calcium, despite the best efforts of the farmer to supplement their feed.[124] Dairy cows that are pushed to produce more milk with hormone injections, high-energy feed, and breeding, typically survive for an average of about two lactations, as opposed to cows raised mostly on grass, which often last four or more lactations, based on interviews with dairy experts.[125]

Impacts on taste

Part of what gives foods their flavor and aroma are the same nutrients and phytochemical compounds that protect plants against disease (or protect the humans who consume those plants). For instance, tomato varieties that score highest in flavor tests have high levels of several phytochemicals and phytochemical breakdown products.[126] And if research shows that as yields increase, production of these compounds decrease, it's likely there would be a related decrease in flavor. The quest for higher yields might have other impacts on taste if it produces plants with higher water content.

Published studies that have analyzed the sensory appeal of organic fruits and vegetables compared to their conventional counterparts find that organic fruits and vegetables tend to score higher in taste because they are sweeter than conventionally grown foods.[127] Vegetable scientists suggest that these improved flavors result from the greater nutrient density of organic produce.[128] (Interestingly, because the protective antioxidants in plant foods are mostly bitter, acrid, or astringent, the primary strategy has been to breed them out of cultivars over generations and replace them with varieties that were blander and had more sugar.[129] This removal of the plants' natural protection mechanisms also made crops more vulnerable to pests and encouraged pesticide use.[130]) Conventional farming methods produce bigger fruits and vegetables partly by accumulating more water, diluting the concentrations of both vitamins and natural flavors. A National Agricultural Library search in 2004 of published studies that compare the flavor and aroma of older and newer varieties of food turned out 34 abstracts. Although the individual articles haven't all been analyzed in detail, there is some support for the hypothesis that newer varieties tend to have less taste and aroma.[131] One study comparing the fragrance in 121 heritage roses with 185 modern roses found a correlation between year of introduction of roses and how good they smell; that is, older varieties have a more intense and pleasing fragrance.[132]

The surest way for a person to assure adequate intakes of vitamins, minerals and antioxidants is to include several fruits and vegetables in daily diets. The brighter the color, the higher the likely antioxidant concentration in fruits and vegetables. It is also important to consume a significant share of each day's fruits and vegetables in a relatively unprocessed form.

In particular, taste surveys for apples, strawberries, and tomatoes showed that tasters generally preferred the organically raised crops, despite the fact that they were often smaller.[133] An evaluation of organic and conventionally grown Golden Delicious apples over four years at Washington State University found that the organic apples often outscored the conventional apples in terms of flavor and eating quality. The organic apples were either firmer or always as firm as the conventional and integrated apples, and ratios of soluble solids (sugar) content to acidity (tartness), an indication of sweetness (a preferred trait among growers and consumers), were most often highest in organic fruit based on blind taste tests. This taste advantage held even after six months' storage.[134] Interestingly, there was little difference in yields between the two systems, indicating that something about the way the trees were tended determined the taste.

Phytochemicals

Some researchers suggest that, of all the measures of nutrient quality, concentrations of phytochemicals have the potential to differ the most between organic and conventional foods.[135] (See Table 5.) Produced by plants primarily to ward off pests and disease, these compounds also happen to be beneficial to human health.[136] A recent survey suggested that organic fruits and vegetables contain nearly one-third more antioxidants than conventionally grown produce, "because plants on organic farms not only more fully engage their defense mechanisms, they tend to grow more slowly."[137] Another review suggested that "on the basis of currently available evidence… organically grown vegetables will tend to have 10-50 percent more secondary or 'plant defense related' compounds than conventionally cultivated vegetables."[138] This phytochemical advantage seems to extend not just to organic fruits and vegetables, but also prepared foods. Organic catsups contained significantly more—50 percent more—of the carotenoid lycopene than conventional catsups.[139] *(See Table 5.)*

Table 5. Review of Recent Studies Comparing Phytochemical Levels in Organic and Conventional Foods

Study	Experiment Material	Parameters Analyzed	Findings
Asami et al., 2003	Marionberry, strawberry, corn	Total phenolics (TP), ascorbic acid (AA)	Increased TP and AA in organic and sustainable practices
Carbonaro and Mattera, 2001	Peach, pear	Polyphenoloxidase activity (PPO), TP	Increased TP and PPO activity in organic fruit
Carbonaro et al., 2002	Peach, pear	PPO activity, TP, AA, citric acid, (CA), α-tocopherol (TH)	Increased TP and PPO activity in organic fruit; AA and CA higher in organic peaches, α-TH higher in organic pear and lower in peach
Grinder-Petersen et al., 2003	Human excretion metabolites following organic vs. conventional diets	Quercetin (Q), kaempferol (K), hesperetin (H), naringenin, isorhamnetin	Organic foods had higher Q, trends of higher K and lower I; Higher urinary excretion of Q and K in organic diet
Häkkinen and Törrönen, 2000	Vaccinium berries, strawberry	Q, K, ellagic acid, p-coumaric acid	No consistent difference between organic and conventional techniques
Ren et al., 2001	Qing-gencai, Chinese cabbage, spinach, welsh onion, green pepper	Antioxidant and antimutagenic activity, flavonoids (Q, K, H, caffeic acid, myricetin, quercitrin, hesperitin, apigenin, baicalein)	Higher antioxidant activity in organic spinach, onion, cabbage, qing-gen-cai, no difference in green pepper; antimutagenic activity higher in organic samples; generally higher flavonoids in organic samples.

Adapted from Alyson E. Mitchell and Alexander W. Chassy, "Antioxidants and the Nutritional Quality of Organic Agriculture," unpublished comminque.

Organic farmers might select crop varieties with greater natural resistance to diseases and pests; these may also be the varieties that synthesize the most secondary defense compounds.[140] But this isn't the only suspected cause of the phytochemical advantage. Research has shown that treating plants with pesticides reduces the plant's ability to produce phytochemicals either by directly disrupting plant physiology or by reducing the factors that encourage plants to produce these compounds in the first place.[141] Plants produce many of these compounds to protect themselves against attack from insects, disease and other damage. Therefore, plants subjected to more stress—insect infestations, fungal attacks, drought—will generally accumulate higher levels of these compounds. (Consider that wine grapes produced in the damp eastern United States contain much higher concentrations of the anti-aging compound resveratrol than grapes produced in balmy California.[142]) On the other hand, when insecticides or fungicides take pressure off of the plant's own defense system, the plant produces less of these compounds.[143] Moreover, plants generally synthesize these phytochemical compounds during the maturation process—late stages of the growing season when fruit or other harvestable portions are forming and ripening. Because organically raised plants may have a greater repository of these compounds to draw on—due to higher micronutrient concentrations in their tissues—their fruit will have higher concentrations of these phytochemicals.[144]

APPENDIX 3.

Natural Variation in Nutrient Levels in Major Crops and Efforts to Raise These Levels With Crop Breeding

Since the decline in the nutritional quality of our major food crops is the result of both crop breeding and changes in farming practices, reversing this trend will require changes in both breeding and farming strategies.

The good news is that considerable variation exists in nutrient content in different varieties of a given crop (See Table 6.) In addition, some crop breeders believe the genetic tradeoffs between yield and nutritional quality aren't inevitable. Based on their experience with wheat, both Garvin and Jones suggest that careful breeding can increase yields while maintaining high nutrient content.[145] *(See Table 6)*

But any decline won't be reversed automatically. Increasing mineral micronutrients has not been at the top of breeders' priority lists. For instance, as Jones notes, in the case of hard red winter wheat, the breeder is primarily focused on yield and protein- (or gluten-) content of the grain. This crop is mostly destined for bread making, so these are the qualities that will allow the millers and bakers to produce a good product and the qualities that the grower will get paid for. "If money were available for breeders to tackle increasing mineral micronutrients, they undoubtedly would direct some effort that way," he said.[152] Juvick, the brassicas expert who showed the wide variation in phytochemical content in those crops, has continued limited work on developing broccoli lines with improved nutrient content and health promotion, but echoed Jones's sentiment: "There has been no support for conducting a significant breeding program to develop finished varieties."[153]

Linda Pollak at USDA-ARS, located at Iowa State University's campus in Ames, knows of few public breeding efforts at American universities focused on increasing nutrient content, including breeding apples for higher vitamin C, carrots for vitamin A, soybeans for

Table 6

Existing Variation in Nutrient Content of Selected Crop Species

Copper: *Concentrations in spinach and onion shoots differed by 50 percent between cultivars; apples and strawberry varieties differed by 2-fold, potato cultivars by 4-fold, and cranberry cultivars by up to 16-fold.*[146]

Iron: *Common beans showed a 2.6-fold variation, apples and strawberries showed 20-60 percent variation, plum showed an 8-fold variation, and cranberry varieties showed a 20-fold difference.*[147]

Zinc: *Threefold variation in concentrations in beans, 6.6-fold variation in peas, fourfold variation among cassava, and 19-fold variation in yam. 12-fold among leaves of spinach, 19-fold among the shoot of cabbage.*[148]

Similarly large ranges have been found for iodine, magnesium, calcium, selenium.[149]

Phytochemicals: One study of 63 varieties of broccol*i, cabbage, kale, cauliflower and Brussels sprouts varieties found a substantial variation both within and between subspecies in terms of carotene, tocopherol, and ascorbate content.*[150] *In a related study, the content of glucosinolates—a class of chemicals primarily found in crucifers that exhibit anticancer properties—varied by 2- to 3-fold in Brussels sprouts, 6-fold in cabbage, and 2-fold in cauliflower and kale.*[151]

lower linoleic acid (which promotes rancidity), and corn with higher fiber and slower-released starch (to reduce obesity, diabetes and certain cancers in Hispanic populations).[154] Pollak and colleagues are leading an effort, "reframe plant breeding," to improve the nation's nutrition and health, and a workshop was recently held to form a national coordinating committee among plant breeders, which Pollak hopes will "help to communicate the importance of plant breeding to our food, fiber and energy system to those with power to stop or reverse the reductions [in nutrient levels] we've been experiencing lately." [155]

Laura L. M. Thornton, an animal scientist with the USDA's Animal Improvement Programs Laboratory, who has observed the "antagonistic relationship" between milk production and the fat, protein, and other components of that milk, said, "Because there was such a long focus on increasing production, and premiums were not offered for higher components, there was little interest until the last 10 years or so in maintaining higher fat and protein levels. . . Dairymen are now beginning to breed for moderately framed cows rather than the humongous cows seen in the last many years, because the extremely framed cows don't have the longevity or productive life of more moderately framed cows."[156] Thornton notes that, in certain breeds like Brown Swiss and Jersey cows, the decrease in fat and protein content has been much smaller. Moreover, the growing production of high-quality cheese in America is creating a market for milk with higher fat, protein, and micronutrient content.[157]

On the international level, HarvestPlus is a global alliance of research institutions and agricultural development agencies, including the Worldbank's Consultative Group on International Agricultural Research, that have come together to breed and disseminate crops for better nutrition.[158] HarvestPlus hopes that biofortification," or breeding crops with higher nutrient content, will result in a more permanent and lower-cost solution than fortifying foods or providing mineral supplements to deficient populations.[159] In the case of rice, HarvestPlus' results already show that by selective breeding, iron content in polished rice can be increased by a factor of two to four.[160] One study, recently published in the Journal of Nutrition, demonstrated a 20 percent increase in iron blood stores attributable to the consumption of biofortified high-iron rice.[161] (The most famous and controversial effort was using genetic engineering to raise vitamin A content of rice, yielding a so-called "golden rice."[162])

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