4 Facts and Myths of Feeding the World with Organic Farming Methods

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4.1 INTRODUCTION

During the past few years, two issues have somewhat dominated the future of world agriculture. The first is that the world population that has passed 7 billion people in 2011 is expected to reach more than 9 billion by 2050. Even more daunting, while the world population is expected to increase by about 30%, food production, particularly cereals, is expected to increase 70% or more because of increasing prosperity that is resulting in changing diets that include more meat, eggs, and dairy products. At the same time, an increasing number of people think our global food system is rapidly approaching, if not already in, a condition of crisis, and a conversion to sustainable agriculture is required. For many of these concerned individuals, synthetic nitrogen fertilizers, irrigation, pesticides, and loss of genetic diversity that have been so important in increasing food production during the past 50 years are not sustainable, and a conversion to more sustainable farming systems is necessary.

For the 50 years between 1961 and 2011, world population increased from 3 billion to 7 billion, but cereal production increased even faster from about 875 million tonnes (Mt) to almost 2500 Mt (FAOSTAT 2012). Therefore, the agricultural community did a remarkable job of increasing food production at a rate faster than population growth, and while there was still a segment of the population that was malnourished, the world food situation improved considerably during this period. Much of the increased cereal production during this 50-year period was due to a doubling of irrigated land from about 140 to 280 million ha and an increase in synthetic N fertilizer from about 9 to 100 Mt (Smil 2011).

Organic agriculture, generally considered as a more sustainable system, has grown rapidly in the past few years. From 1999 to 2010, organic agriculture increased almost fourfold from 11 to 37 Mha. While this is still a tiny portion of the world's cropland, its rapid growth is occurring in more than 100 countries (IFOAM 2012).

While some believe that more sustainable systems like organic farming can produce enough food to feed the world, others believe that the use of synthetic nitrogen fertilizer is absolutely essential. This paper will look at some of the facts and myths of organic farming methods.

4.2 ORGANIC FARMING

As defined by IFOAM (2012), organic agriculture is a production system that sustains the health of soils, ecosystems, and people. It relies on ecological processes, biodiversity, and cycles adapted to local conditions, rather than the use of inputs with adverse effects. Organic agriculture combines tradition, innovation, and science to benefit the shared environment and promote fair relationships and a good quality of life for all involved. IFOAM (2012) further elaborates that organic farming is based on four principles, as follows:

1. *Health:* Organic agriculture should sustain and enhance the health of soil, plant, animal, human, and planet as one and indivisible.
2. *Ecology:* Organic agriculture should be based on living ecological systems and cycles, work with them, emulate them, and help sustain them.
3. *Fairness:* Organic agriculture should build on relationships that ensure fairness with regard to the common environment and life opportunities.
4. *Care:* Organic agriculture should be managed in a precautionary and responsible manner to protect the health and wellbeing of current and future generations and the environment.

Few people, if any, would find fault with these principles. Many, however, would say that, with the present and growing number of people, without inputs, especially irrigation and synthetic N, food production needs simply cannot be met. Even though the land area devoted to organic agriculture has grown almost fourfold in the past

10 years to 37 Mha (IFOAM 2012), it represents only about 2.7% of the 1381 Mha of the cropland estimated by FAO (FAOSTAT 2012).

4.2.1 Soil Productivity of Organic Farming

Numerous literature reviews have been conducted to compare soil productivity and crop yields of organic fields with those of conventional production fields. Not surprisingly, the conclusions drawn by different authors have sometimes varied. Edmeades (2003) reviewed the results of 14 long-term experiments conducted in North America and Europe, all of which had yield data for more than 20 years. The yields from plots treated with balanced chemical fertilizer were similar to those from plots treated with applications of manure when the nutrient rates were equivalent. Edmeades (2003) concluded that only after a very large amount of manure has been applied for a very long time, which may result in significantly higher soil organic carbon, can any additional benefit of manure be observed. Higher soil organic carbon can have beneficial effects on water infiltration and storage, and on soil biological properties that can increase yields of some soils under some conditions. For a specific site, application of manure can result in higher, similar or lower yield compared with chemical fertilizer applications, depending on the previous soil organic C pool, soil management, soil type, rate and frequency of chemical and organic fertilizer application, rainfall and irrigation amounts, and other factors (Edmeades 2003; Lal 2006; Diacono and Montemurro 2010; Miao et al. 2010). Edmeades (2003) stated that it cannot be assumed that the long-term use of manures will enhance soil quality—defined in terms of productivity and potential to adversely affect water quality—in the long term relative to applying the same amounts of nutrients as fertilizer. However, the most important point to be gained from the Edmeades review is perhaps the fact that the input of nutrients of either fertilizers or manures had very large effects (150% to 1000%) on soil productivity as measured by crop yields. Clearly, high yields require high inputs of nutrients.

Badgley et al. (2007) stated that the principal objections to the proposition that organic agriculture can contribute significantly to the global food supply are low yields and insufficient quantities of organically acceptable fertilizers. They carried out an extensive review of the literature specifically to evaluate, and dispel, these claims. For comparing yields, Badgley et al. (2007) compared yields of organic versus conventional or low-intensive food production for a global dataset of 293 examples and estimated the average yield ratio (organic/nonorganic) of different food categories for the developed and developing world. They reported that for most food categories, the average yield ratio was slightly less than 1.0 for studies in the developed world and greater than 1.0 for studies in the developing world. Badgley et al. (2007) also reviewed 77 studies where leguminous cover crops were grown to supply nitrogen to soils and concluded that the amount of nitrogen potentially available from fixation by leguminous crops used as fertilizer could replace the amount of synthetic fertilizer currently in use without adding any additional cropland. In drawing these conclusions, they assumed that the cover crops could be grown between normal cropping periods. This assumption is clearly not valid for much, if not most, of the cropland in the world.

Seufert et al. (2012) reviewed 66 studies representing 62 study sites that reported 316 organic-to-conventional yield comparisons on 34 different crop species. Their analysis was restricted to (1) organic systems defined as those with certified organic management or noncertified organic management, following the standards of organic certification bodies; (2) studies with comparable spatial and temporal scales for both organic and conventional systems; and (3) studies reporting sample size and error or information where these could be estimated. Seufert et al. (2012) stated that, overall, organic yields are typically lower than conventional yields, but the differences were highly contextual, depending on system and site characteristics, and range from 5% lower organic yields (rain-fed legumes and perennials on weak-acidic to weak alkaline soils), 13% lower yields (when best organic practices are used), to 34% lower yields (when the conventional and organic systems are most comparable). Under conditions with good management practices, however, they found that organic systems can nearly match conventional yields for particular crop types. For example, organic fruits and oilseed crops showed slightly lower, but not statistically significant, yields of 3% and 11%, respectively, when compared to conventional crop yields. In contrast, organic cereals and vegetables had significantly lower yields of 26% and 33%, respectively. Seufert et al. (2012) stated that part of the yield response could be explained by differences in the amount of N input received by the systems. Most of the N in organic materials is only slowly available and often over multiple crops, whereas N fertilizer is readily available. Therefore, Seufert et al. (2012) stated that organic systems appear to be N limited, whereas conventional systems are not.

de Ponti et al. (2012) conducted a similar study to that of Seufert et al. (2012) in that they compiled and analyzed 362 published organic–conventional comparative crop yields. They began their review with the hypothesis that the yield gap between organic and conventional agriculture increases as conventional yields increase. The stated rationale behind the hypothesis of de Ponti et al. (2012) was that when conventional yields are high and relatively close to the potential or water-limited level, nutrient stress, as per definition of the potential or water-limited yield levels, must be low, and pests and diseases well controlled, which are conditions more difficult to attain in organic agriculture. They showed that organic yields of individual crops are on average 80% of conventional yields, but variation was substantial having a standard deviation of 21%. They further stated that relative yields differed between crops with soybean, some other pulses, rice, and corn scoring higher than 80% and wheat, barley, and potato scoring lower than 80%. Most regions had relative yields fairly close to the overall average, but Asia and Central Europe had comparatively higher relative yields and Northern Europe had lower relative yields. In Denmark and The Netherlands, countries with very intensive agricultural systems, they found the gap between organic and conventional yields somewhat larger. de Ponti et al. (2012) concluded that the findings gave some support to their hypothesis that the organic–conventional yield gap is higher when conventional yields are high, but that the relationship and hence the evidence underpinning were not strong.

Although studies that compare yields of organic and conventional systems are of interest, it is clear that high yields are dependent on high inputs and the inputs must be available to the crop. From a theoretical viewpoint, there is every reason to believe that a well-managed organic crop can yield as much as a conventional crop as long as sufficient N, P, and other nutrients are supplied and pests are controlled. The reason that producers using conventional practices often have higher yields is generally because they have more options for supplying nutrients and controlling insects and diseases and can often react more timely. To feed a growing world population that is also becoming more prosperous resulting in diets that include more meat, dairy products, and eggs that generally require more grain and other feeds for animals, it is time to accept and promote various types of crop production. The National Research Council (2010) states that there are four goals required for a sustainable agricultural system. These are achieving sufficient productivity, enhancing the natural-resource base and environment, making farming financially viable, and contributing to the wellbeing of farmers and their communities. A combinative organic–conventional system has many advantages. Miao et al. (2010) reviewed a number of long-term experiments. A large number of agricultural experiments were initiated around the world beginning in the 1800s. Lawes and Gilbert established the Broadbalk plot in 1843 in Rothamsted, England (Rothamsted Research 2006). In the United States, the Morrow Plots were established in 1876 on the campus of the University of Illinois, Urbana; the Sanborn Field plots were started in 1888 on the campus at the University of Missouri, Columbia; and the Magruder Plot was initiated at Oklahoma State University in 1892. These plots are still active today, although some of them have been modified substantially. A number of other stations have also been in existence for more than 50 years, and several of these are listed by Miao et al. (2010). Miao et al. (2010) concluded from their review that chemical fertilizer alone is not enough to improve or maintain soil fertility at high levels, and the soil acidification problem caused by overapplication of synthetic N fertilizers can be reduced if more N fertilizer is applied as nitrate relative to ammonium- or urea-N fertilizers. Organic fertilizers can improve soil fertility and soil physical properties and result in high yields. However, long-term applications of organic fertilizers at high rates can lead to more nitrate leaching and accumulation of phosphorus. Stewart et al. (2000) discussed the ratio of N and P in manure compared with that in major crops. They stated that maize (*Zea mays*) and wheat (*Triticum aestivum*) require approximately five times as much N as P, and that the ratio of N to P in manure is only about 2.5 to 1. Thus, if sufficient manure is added to supply N needs, there is often a high accumulation of P. Even when manure supplied only part of the nutrients in a 15-year study in China by Zhang et al. (2009), there was a very high buildup of available P in the soil at the end of the study. Enriched P in the soil may be lost through runoff, or leached in soils with low P retention or in situations of organic P leaching, leading to water pollution (Edmeades 2003).

Organic fertilizers, when properly used, can provide adequate soil fertility for maximum yields. For over 4000 years, Chinese farmers managed to produce modest crop yields and maintain soil fertility using traditional farming practices, emphasizing integrated and efficient utilization of different strategies of crop rotation, intercropping, all possible resources of organic manures aiming at the most complete recycling of nutrients (e.g., animal waste, human excreta, cooking ash, compost, and dredged canal sediments, etc.), and green manures (Wittwer et al. 1987; Ellis and Wang 1997; Gao et al. 2006; Yang 2006). A Chinese farming proverb says "Farming is a joke without manuring." Many ancient Chinese publications mention

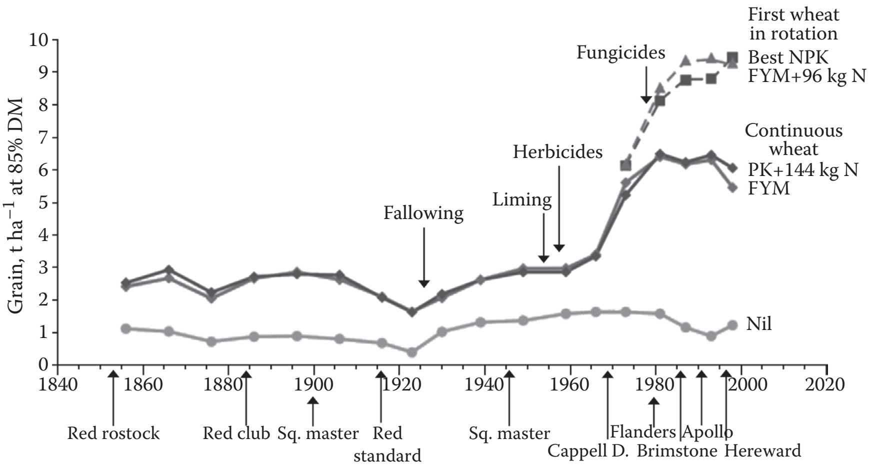

FIGURE 4.1 Mean yields of wheat grain on Broadbalk plots from 1852 to 1999 treated with NPK fertilizers, farmyard manure (FYM), FYM+N, or no fertilizers showing the effects of changing cultivars and management practices. (From Rothamsted Research. Guide to the classical and other long-term experiments, datasets and sample archive. Lawes Agricultural Trust Co. Ltd., 2006. Available at http://www.rothamsted.bbsrc.ac.uk/resources/LongTermExperiments.pdf, accessed March 1, 2012.)

the application of human and animal wastes to the land. For example, according to Yang (2006), Han Feizi (280–233 BCE) stated that human excreta must be applied to restore and improve soil fertility. King (1911) stated that "one of the most remarkable agricultural practices adopted by any civilized people is the centuries-long and well-nigh universal conservation and utilization of all human waste in China, Korea and Japan, turning it to marvelous account in the maintenance of soil fertility and in the production of food." However, these traditional agricultural practices could not produce enough food to meet the demand of a fast-growing population started around 1800. Today, the world population is 7 billion and expected to reach 9.2 billion by 2050. Therefore, as will be discussed later, the production of adequate food and fiber without the use of chemical fertilizers does not appear feasible. Miao et al. (2010) concluded that well-managed combination of chemical and organic fertilizers can overcome the disadvantages of applying a single source of fertilizers and sustainably achieve higher crop yields, improve soil fertility, alleviate soil acidification problems, and increase nutrient-use efficiency compared with only using chemical fertilizers (Figure 4.1). Of course, the combined use of organic wastes and chemical fertilizers is not an approved practice for organic farming.

4.2.2 Safety of Organic Crops Compared to Crops Produced with Chemical Fertilizers

Many people feel that safety is greater with organic than with conventional foods, primarily because of the precautionary principle followed in the formulation of organic regulations and in the assessment of food safety. Organic farming practices and regulations promote high standards of product safety. Organic foods are generally produced using lower nitrogen applications that potentially reduce nitrate concentrations. Pesticides are banned, so no pesticide residues are present. For organic meat and animal products, there are a number of rules directed toward a high status of animal welfare, care for the environment, restricted use of medical drugs, and the production of healthy products without residues of pesticides or drugs. Most developed countries have safeguards for assuring food safety, but a growing number of consumers still feel that there is enough risk for them to prefer organic foods. In developing countries, there are generally less safeguards both in applying pesticides and other chemicals to growing crops and in testing products being sold in the markets. Therefore, if recommendations and regulations for producing organic foods are properly followed and enforced in developing countries, they may very well be safer than conventionally produced food products.

Even though most developed countries have programs to ensure food safety, many people are still concerned. This seems particularly true in Europe where a number of countries show concern about food safety. Public worries relate mainly to specific agri-food-environment problems that have been recently encountered, and the following were noted by Hansen et al. 2002:

- Discovery of animals with bovine spongiform encephalopathy (BSE)
- Increased occurrence of salmonella in meat and eggs
- Increased occurrence of campylobacter in meat
- Finding of listeria in some dairy products
- Increased occurrence of dioxins in food and feed
- Excessive amounts of pesticides, antibiotics, additives, etc., in food
- Presence of toxic fungi in stored foods
- Pollution of drinking water with pesticides and nitrate
- Organic food products contaminated with genetically modified organisms (GMOs)
- Deception in sale of conventional foods as organic products

Although most food is safe, there is always some risk regardless of whether the food is produced according to organic standards or with conventional practices. Organic foods, by the very fact that they are produced without being subjected to many of the practices and chemicals that conventional foods are subjected, have several advantages from the food safety perspective. The growers of organic foods are also exposed to fewer chemicals, and this is probably of greater importance in developing countries than developed countries. Many countries have strict regulations and procedures for applying pesticides and other chemicals to crops that provide adequate protection, but this is not true in all countries. Also, the proper use of pesticides requires following the label as to how and when they are to be applied. Failure to follow the prescribed procedures will certainly result in more risk associated with foods produced under conventional practices. Ultimately, the consumer makes the final decision based on personal choices including availability and cost factors.

4.2.3 Quality of Organic Crops Compared to Crops Produced with Chemical Fertilizers

Organic products are those that are produced under controlled cultivation conditions in accordance with the provisions of the regulations on organic farming and its supplementary statutory provisions or the guidelines of the various recognized farming associations (IFOAM 2012). Organic foods can be divided into plant products and animal products. Organic plant products such as fruits, vegetables, and grains are grown without using conventional methods to fertilize or control pests. Organic animal products such as eggs, dairy products, meat, and poultry are produced without the use of antibiotics or hormones. Organic food can also be divided into fresh and processed products. Fresh organic foods are harvested directly from organic farms, such as fruits, vegetables, grains, eggs, milk, meat, and honey. Processed organic foods are food products like breakfast cereals, snack foods, canned foods, and drinks, which are completely or partially made of organic ingredients.

Both fresh and processed organic foods can be easily found today on market shelves. By reading the label of the products, organic food can be distinguished from others. In countries where organic standards are established, qualified organic foods are clearly labeled as meeting the standards. Based on the IFOAM definition (IFOAM 2012), certified organic products are those that have been produced, stored, processed, handled, and marketed in accordance with precise technical specifications (standards) and certified as "organic" by a certification body. In the United States, for example, the Organic Foods Production Act (OFPA) and the National Organic Program (NOP) assure consumers that organic agricultural products meet the prescribed standards during production, processing, and certification. Though organic farming is practiced on every continent, North America and Europe have comprised most of the global demand for organic food, while most organic production in Africa and Latin America is for export.

The growing awareness of health issues and the increased concern of environmental issues have resulted in a higher percentage of the public to focus on food quality. This in turn has increased attention paid to organic farming because products from organic farming are often perceived as having higher quality. Various rationales that consumers use when purchasing organic foods have been identified by Hughner (2007). Among all motives, including concerns for the environment, food safety, and animal welfare, the concern of health is the primary reason that consumers buy organic foods. In general, health-concerned consumers believe organic foods are more nutritious and of better quality. Several studies also found taste among the most important criteria in organic food purchases (Magnusson et al. 2001). They suggested that people buy organic food because they believe it is somewhat better than conventional food. They believe organic farms grow more nutritious and better tasting food from healthier soil with healthier agronomic methods. Numerous studies confirm that many people believe that organic foods are healthier than conventionally produced foods and that they are produced in a more environmentally compatible manner (Folkers 1983).

Although it is clear that consumers who purchase organic foods think these are better than those produced using conventional practices, there is little or no scientific basis to support their views. Studies about organic food nutrition started soon after organic farming came into being. Woese et al. (1997) reviewed numerous studies that had been published dating back to 1924. More recently, several reviews of comparative studies have been published (Worthington 2001; Williams 2002; Magkos et al. 2003). Since then, more studies on organic food quality had been published, and meta-analysis provided better comparisons. Meta-analysis is a statistical technique for combining the findings from independent studies, the validity of which is highly dependent on the quality systematic review. As more studies on organic food quality had become available in the past decade, meta-analysis was used more often in organic food quality reviews to give complete coverage of available studies.

Numerous research studies have been conducted on organic food quality. However, there is a major challenge on how to define food quality concepts and methods for determination (Kahl et al. 2012). The concepts of food quality and evaluation methods developed as the knowledge of food science expanded and new measuring technology became available. Now, sensitivity of analytical methods to measure nutrients has been increased. Taking plant-based organic food as an example, most of the early studies only evaluated dry matter, total sugars, and mineral contents. Secondary metabolites, with the exception of vitamin C and polyphenolic substances, were seldom included in these studies (Worthington 2001; Williams 2002; Magkos et al. 2003), but have received more attention in recent studies (Brandt et al. 2011).

Whether organic food has higher quality than conventionally produced food is highly dependent on how organic food quality is defined and determined. Food quality can be classified into the following fields: sensory properties, nutrition and health, authenticity and traceability, and specific organic properties (Willer and Kilcher 2012). The last two fields, however, are specific to organic food quality, so only sensory properties and nutrition and health can be used to compare the quality of organic foods and conventional foods. For both fresh and processed food, studies carried out on the sensory difference in terms of taste, smell, texture, and appearance showed a wide variety of results. In some studies, significant differences were found while other studies did not detect any differences (Willer and Kilcher 2012). Even though information on sensory differences is limited and inconclusive, more research is needed because taste and other sensory factors play an important role in purchasing decisions of consumers (Hughner et al. 2007).

Most of the data reported has been from plant products because information on organic animal products is vague and less sufficient. Early research was limited to dry matter; crude protein content; vitamins A, B_1, B_2, and C; minerals; and trace elements. Results indicated that organic plant products including leafy, root, and tuber vegetables contain more dry matter, but there was no significant difference between organically and conventionally produced fruits and fruit vegetables (Magkos et al. 2003). Due to lower nitrogen availability, organic fruits and vegetables generally have lower crude protein content but higher quality protein in some vegetables. Although the majority of comparisons on vitamins and mineral elements revealed no significant difference, Worthington (2001) reported that organic fruits and vegetables contained significantly more iron, magnesium, phosphorus, and vitamin C than conventionally produced ones. However, no general statement could be drawn because there was insufficient data for carbohydrate, protein, and other vitamins.

More recently, Brandt et al. (2011) concluded that organic crops contain significantly higher levels of secondary metabolites (compounds that are believed to protect people against a range of diseases including obesity) than conventionally grown crops.

High nitrogen availability generally results in increased protein synthesis. Thus, when N fertilizers are added to fields where grain crops are produced, these grain crops often, but not always, have higher crude protein than organically grown crops. Magkos et al. (2003) reported that organically produced grains had higher concentrations of some of the essential amino acids, but there was no clear picture. Data for comparisons of vitamins, minerals, and trace elements were too limited to draw any conclusions. More recently, Dangour et al. (2009) surveyed 52,471 articles, identified 162 studies (137 crops and 25 livestock products), and selected 55 as having data of satisfactory quality for further comparisons. From an analysis of the data from these selected studies, they concluded that conventionally produced crops had a significantly higher content of nitrogen, and organically produced crops had a significantly higher content of phosphorus and higher titratable acidity. No evidence of a difference was detected for the remaining 8 of 11 crop nutrient categories analyzed. Analysis of the more limited database on livestock products found no evidence of a difference in nutrient content between organically and conventionally produced livestock products.

4.3 LIMITATIONS OF ORGANIC FARMING

The previous sections have shown that organically grown crops can be similar to those produced using chemical fertilizers, and at least equal or superior in terms of quality and safety. The real question with regards to organic agriculture is to what extent the food and fiber needs of the world population can be produced without the use of chemical fertilizers. The world population is presently 7 billion and expected to reach 9.2 billion by 2050. Protein consumption is essential for humans, and the concentration of N in protein is approximately 16%. Smil (2002) states that published recommendations for ideal protein requirements were 3–4 g/kg of body weight for infants, 1.5–3 g for teenagers, and 0.3–1 g for adults. Smil (2011) estimated that global consumption of N contained in food was 30 Mt and essentially all of this is excreted. Furthermore, since more than 50% of people on all continents, except Africa, now live in cities, most of this waste is released directly into sewers. Most of the sewage water is either released to streams or coastal water and little is ever recycled for crop production. Therefore, a tremendous quantity of N is lost from human consumption, and there are also large losses of N each year from animals. These losses must be balanced by inputs to sustain the system. There are natural ways for providing N for crops that have been long known. Von Liebig (1840) listed three ways: (1) recycling of organic wastes (mainly crop residues and animal wastes); (2) crop rotations including N-fixing leguminous species; and (3) growing leguminous cover crops and plowing them under as green manures. While all of these can provide N to growing crops, only the N fixed from N_2 in the atmosphere by symbiotic bacteria associated with leguminous crops is added. Other sources of added N for crop production are atmospheric deposition and irrigation waters from aquifers. Ladha et al. (2005) estimated that additions to crop production from atmospheric deposition and biological N-fixation were 24 and 33 Mt, respectively. They also estimated leaching, runoff, and erosion losses, and they estimated ammonia volatilization losses from soil and vegetation as 37 and 21 Mt, respectively. These estimates indicate that losses are slightly greater than inputs from natural sources, and the differences would likely be even greater if only cropland was considered. Much of the N in crops, particularly grain crops, is removed from the crop land and is not recycled. Therefore, at the present time, additional inputs of N are essential for producing adequate food and fiber for the growing population.

In 1909, Fritz Haber, a German scientist, developed a process that takes N_2 from the air and synthesizes it to ammonia that can be used by plants or transformed into other N compounds that they can use. Within 4 years, Carl Bosch, an engineer for Germany's largest chemical company, developed the process commercially and was named the Haber–Bosch process. Haber was awarded the Nobel Prize in Chemistry in 1918, and Bosch shared the Nobel Prize in 1931 for industrializing the Haber invention. Without this synthesized N, many scientists do not think the population could have grown to today's level. Ladha et al. (2005) stated that 50% of the human population relied on N fertilizer for food production. Smil (2002) stated, "the Haber–Bosch synthesis provides the very means of survival for about 40% of humanity; that only half of today's population could be supplied by prefertilizer farming with overwhelmingly vegetarian diets; and that traditional cropping could provide today's average diets to only about 40% of the existing population." Since Smil made that statement, the world population has increased almost a billion people, calorie intake has increased, and the percent of protein coming from animal products has increased. During the first decade of the new century, world population increased by about 16%, while cereal production increased by about 20%. Maize, of which about 65% is fed to animals, increased by more than 35% (FAOSTAT 2012). Cereal production is extremely important because cereals provide a large part of people's food. The Worldwide Institute (2011) reported that, on average, people consume 48% of the world's grain supply directly, roughly 35% becomes livestock feed, and 17% is used to make ethanol and other fuels. The Worldwatch Institute (2011) further stated that humans get about 48% of their calories from eating grains directly. This has declined only slightly from 50% over the past 40 years. However, as incomes rise, the percent drops dramatically as people change diets to consume more meat, milk, eggs, and other foods that require more grain to produce. Because of projected increases in population and rising incomes, it is projected that cereal production will need to increase by 50% to 70% by 2050.

Ladha et al. (2005) estimated that during 2001 and 2002, about 60% of global N fertilizer consumed was used for cereal production. Specifically, three cereals (rice, wheat, and maize) accounted for about 56% of the N fertilizer used (IFA 2002). Norman Borlaug, the Nobel Laureate known as the father of the Green Revolution, developed short-straw wheat varieties that were credited for saving countless lives in Asia. However, he credited N fertilizers with much of the success because without added N, production would have been significantly less. Figure 4.2 shows how cereal production increased between 1961 and 2010, and also how the amount of N fixed by the Haber–Bosch process has increased. Although the Haber–Bosch process was first commercialized in 1913, it was not widely used for fertilizer until following

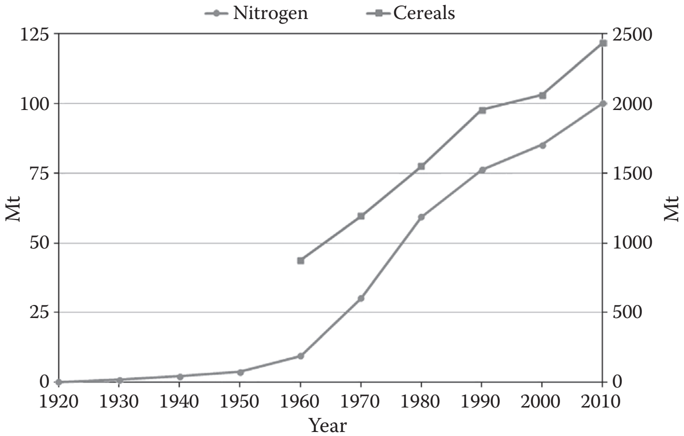

FIGURE 4.2 Nitrogen fixed by Haber–Bosch process (Mt, left axis) and world production of cereals (Mt, right axis). (N data from Smil, V., *World Agric* 2:9–1, 2011. Cereals data from FAOSTAT. Food and Agriculture Organization of United Nations, Rome, 2012. Available at http://faostat.fao.org, accessed April 3, 2012.)

World War II. During both World War I and World War II, the process was used to make N for bombs. Following World War II, many of the facilities that made bombs during the war were converted to N fertilizer plants, and this was the beginning of a major expansion of the use of fertilizers. The data shown in Figure 4.2 clearly show how closely cereal production has been linked with ammonia synthesis. Assuming that the N concentration of cereals is 1.8%, there was about 45 Mt of N contained in the cereals produced in 2010. Much, if not most, of this N will not be recycled through the crop production system. Therefore, while synthetic N fertilizer appears essential, some believe that the world's population can be fed without using N-based fertilizers. Nielsen (2005) makes this argument and also believes that the problems created by the use of synthetic fertilizers have outnumbered their benefits. He challenges two claims: (1) that the human-invented process of fixing nitrogen caused a global population explosion, and (2) without nitrogen-based fertilizers, we would not be able to feed the world. He points out that the population explosion was already advanced and well on the way when nitrogen-based fertilizers were introduced, and while the use of fertilizers may have supported the explosion, even this is doubtful. Nielsen (2005) stated that the world could be fed without using N fertilizers. He argued that this could be done by prudent organic farming, improving irrigation efficiency, improving the environment for nitrogen-fixing organisms, healing the soil that has been destroyed by using N-based fertilizers and other agricultural chemicals, and changing our food consumption habits. Even if this is possible, it is certainly not feasible because the reality is that the trends are in the opposite direction. In 1961, the number of calories per capita for the world population was 2201 compared to 2798 in 2007, and calories from meat were 110 and 218, respectively (FAOSTAT 2012). A more striking example is China. In 1961, China was in a period of famine, and the number of calories per person was only 1469, of which only 29 were from meat. Today, China is a rapidly developing economic power, and in 2007, the number of calories per capita was 2981, and 420 were from meat (FAOSTAT 2012). Therefore, it is most likely that if the world population becomes more prosperous, the demand for grain and other feeds to produce more meat and animal products will increase that will require more nitrogen. Unless synthesized ammonia is used, the only other feasible method to add additional N to the crop production system is by growing leguminous crops and incorporating them into the soil so the N can be used for growing nonleguminous crops such as cereals. This would, however, require enormous amounts of added cropland. Most leguminous crops, even when grown in favorable areas, will generally not supply more than 100 to 150 kg N ha^{-1}, so this would almost double the land requirement for cereal production, which is not a feasible alternative.

4.4 NEED FOR BETTER MANAGEMENT OF N FERTILIZERS

It is apparent to most that crop production in the future will continue to depend largely on the application of N fertilizer that is produced by the Haber–Bosch process. At the same time, there is increasing awareness that along with the benefits of this amazing and important process that has played such an important role in food production, there is a real potential that the environment can be seriously affected. A few, including Nielsen (2005), have expressed great concern over the large use of N fertilizer and went so far as to state that the Haber–Bosch process was a "fantastic invention—or was it?" Townsend et al. (2003) also expressed great concern about human health effects of a changing global nitrogen cycle. They stated that changes to the global nitrogen cycle affect human health well beyond the associated benefits of increased food production, and that many intensively fertilized crops become animal feed, helping to create disparities in world food distribution and leading to unbalanced diets, even in wealthy nations. Townsend et al. (2003) suggested that the net public health consequences of a changing N cycle are largely positive at lower levels, but they eventually peak and then become increasingly negative as our creation and use of fixed N continues to climb (Figure 4.3). Based on the conceptual model shown in Figure 4.3, Townsend et al. (2003) postulate that low to moderate increases in fertilizer use in developing countries will improve food availability and overall nutrition with only minor elevated losses of reactive N to the environment. Ladha et al. (2005) stated that about 60% of the global N fertilizer is used for producing the world's three major cereals: maize, wheat, and rice. These three cereals account for almost 90% of all cereals (FAOSTAT 2012). Figure 4.2 shows the world production of cereals increased almost three times between 1961 and 2009 (FAOSTAT 2012), but the amount of atmospheric N_2 fixed as ammonia that was almost entirely used for the production and use of N fertilizer increased about 10 times during the same time period (Smil 2011). Assuming the average N content of cereals to be 1.6%, the amount of N removed with all cereals in 1961 was approximately 14 Mt compared to about 40 Mt in 2009. In contrast, about 10 Mt of N was fixed in 1961 compared to about 100 Mt in 2009. This clearly indicates that much of the N added as fertilizer is not utilized directly by the plants. Although this fact has been recognized for many years, it is still not entirely clear where the N that is not used by the plants ends

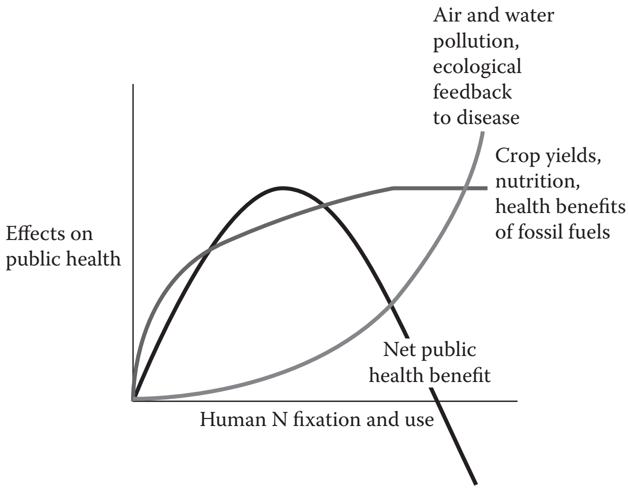

FIGURE 4.3 Conceptual model of the overall net public health effects of increasing human fixation and use of atmospheric N_2. (From Townsend, A.R. et al., *Ecol Environ* 1:240–248, 2003.)

up and what affect it has on the environment and public wellbeing. Galloway and Cowling (2002) estimated that for every 100 kg of N fertilizer used for producing crops, only 14 kg N was actually consumed by humans when they ate the products directly, which would represent a vegetarian diet (Figure 4.4a). They further estimated that if the cereals produced were fed to animals and the meat produced was consumed by humans, only 4 of the 100 kg N added as fertilizer was actually consumed by humans (Figure 4.4b).

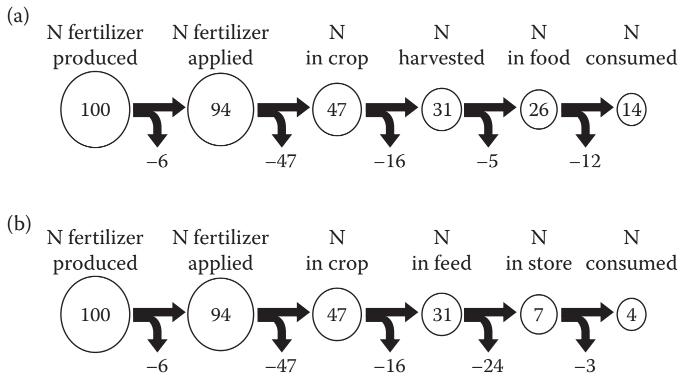

FIGURE 4.4 Fate of N fertilizer produced by the Haber–Bosch process from the factory to the mouth for (a) vegetarian diet and (b) carnivorous diet. (From Galloway, J.N., and E.B. Cowling, *Ambio* 31:64–71, 2002.)

Ladha et al. (2005) estimated that synthetic fertilizers supplied approximately 84 Mt of N, or about 45% of the total N input for global food production in 2005. They estimated other inputs to crop production as 33 Mt from biological nitrogen fixation, 16 Mt from recycling of N from crop residues, 20 Mt from atmospheric deposition, and 24 Mt from irrigation water. However, it is important to remember that the N from crop residues and much of that from irrigation water was not newly introduced to the system, but recycled within the system. Ladha et al. (2005) estimated that the amount of N removed by the harvested crop was almost equal to the amount of N added as fertilizer, but that 37 Mt was lost to the environment by leaching, runoff, and erosion; 21 Mt by ammonia volatilization from animal wastes, soil, and vegetation; 14 Mt from denitrification; and 8 Mt from nitrous oxide and nitric oxide emissions.

Although the losses discussed above are large and may be causing serious disruptions in ecosystem functions, much research has been conducted in recent decades to improve nitrogen use efficiency. There is also increasing awareness among producers, as well as the public, that practices must be developed and used that better synchronize the supply and requirement of N fertilizer for crop production. While more improvement is needed, nitrogen use efficiency has improved significantly in recent years. The use of synthetic N as fertilizer began in earnest following World War II, and the results were astonishing. The positive results, coupled with the low cost of the product, led farmers to apply more and more N. Although studies showed that as the amount of N added increased there was less increase in yield for each added increment, the guideline was to continue to add N until it was evident that additional N would not lead to a further increase in yield. There was no thought at the time among most scientists and producers that there were negative environmental effects associated with excess N additions. However, things began to change when scientists such as Rachel Carson (1962) in *Silent Spring* and Barry Commoner (1971) in *The Closing Circle* began raising concerns about chemicals used in crop production. Commoner was particularly concerned about nitrates in groundwater and their potential for causing methemoglobinemia (commonly known as blue-baby syndrome) in infants. Also, the US Environmental Protection Agency (EPA) was created in 1970. These concerns became great enough that scientists began seriously considering the effects of agricultural chemicals and practices on the environment, and particularly how they affected air and water quality and human health. This change is clearly reflected with the data shown in Figure 4.3. Between 1964 and 1976, the rate of N fertilizer applied per unit area of corn in the United States increased almost threefold while yield increased by about 50%. Since 1976, the average rate of N fertilizer has actually declined slightly, while the yield has increased almost every year and is almost two times higher. These data show that nitrogen use efficiency has greatly increased, and assuming the N content of corn grain is 1.6%, the amount of N removed with the grain is essentially equal to the amount of N applied as fertilizer. Therefore, the percentage of N fertilizer used for crop production that is lost to the environment has been significantly reduced in recent years. Europe has also made significant progress, but other areas such as China (Miao et al. 2010) have increased N fertilizer use so rapidly and to such high levels that serious environmental concerns are being raised.

4.5 INTENSIFICATION OF ANIMAL AGRICULTURE AND TRANSLOCATION OF NUTRIENTS

During the past 50 years and continuing today, there has been a dramatic increase in the concentration of animals into Concentrated Animal Feeding Operations (CAFOs). Beef animal feedlots with less than 1000 head of capacity comprise the vast majority of US feedlots but market a relatively small share of fed cattle. In contrast, lots with 1000 head or more of capacity comprise less than 5% of total feedlots but market 80% to 90% of fed cattle (USDA 2012). Feedlots with 32,000 head or more of capacity market around 40% of fed cattle, and some feedlots have a one-time capacity of 100,000 or more. Beef animals are usually fed only about 140 days, so 60,000 to 75,000 beef animals are commonly fattened annually in a 30,000-capacity feedlot. Similarly, dairy cows are becoming increasingly concentrated. In 2000, 10.5% of milk production was from dairy farms with more than 2000 cows, and this grew to 23.4% by 2006 (MacDonald et al. 2007). Poultry animals have long been highly concentrated, and swine are also increasingly being concentrated. An even more important factor is that more and more of these large operations are located in areas far removed from where most of the grain and other feed stuffs fed to these animals are produced, so massive amounts of feeds are transported into the area by trucks and trains. This has led to the translocation of millions of tons of N and P from areas where crops are produced to areas where animals are fed. Most of the N and P fed to animals are excreted and remain in the area as manure, and there is often not enough cropland to efficiently utilize the manure. On average, about 12 Mt of N and 2 Mt of P have been used as fertilizer every year in the United States for the past few decades, and approximately 40% of these nutrients are applied to corn and 40% to 50% of the corn is fed to animals. Because more and more of the corn fed to animals is being fed in areas far removed from where the corn was grown, and often in areas where there are limited amounts of cropland, these nutrients are not being recycled. The 12 Mt of N comes from atmospheric N_2 and the 2 Mt of P comes from mines. Thus, huge amounts of N and P are added to the environment each year, some of which damages surface and groundwater supplies and increases greenhouse gases. The disconnect between the location of nutrients used for production of grain crops, and where the nutrients ultimately reside in the environment after excretion by both humans and animals, is a growing and serious concern. In retrospect, it is clear that there was not enough thought given to the total system as needed, and this lack of a systems approach is still evident today. Recycling of nutrients should be a high priority, and this is the foundation of organic farming. Therefore, while much more attention should be given to the recycling of nutrients, organic farming as defined by IFOAM (2012) cannot meet the food and fiber needs of the world according to many scientists as discussed above. Norman Borlaug, the Nobel Peace Prize Laureate, credited for saving more human lives than any man in history by being the father of the "Green Revolution," saving countless millions of people from hunger in India and other countries, responded to a reporter that stated that a lot of people claim organic food is better for human health and the environment than conventionally grown food by stating, "That's ridiculous. This shouldn't even be a debate. Even if you could use all the organic material that you have—the animal manures, the human waste, the plant residues—and get them back on the soil, you couldn't feed more than 4 billion people. In addition, if all agriculture were organic, you would have to increase cropland area dramatically, spreading out into marginal areas and cutting down millions of acres of forests" (Borlaug 2009).

4.6 INTEGRATING THE USE OF ORGANIC MATERIALS, BIOLOGICAL PROCESSES, AND CHEMICAL FERTILIZERS

Crop yields, particularly cereals, must continue to increase to support a growing and more prosperous world population that is demanding more meat, dairy products, eggs, and other products requiring more animal feeds. At the same time, serious concerns are increasing about the effect that the heavy use of synthetic nitrogen, phosphorus fertilizers, and pesticides (Galloway and Cowling 2002; Townsend et al. 2003; Pimentel et al. 2005; Ladha et al. 2005) is having on the environment and perceived health issues. While organic production is growing and seen by some as a solution, most scientists believe that food and fiber needs can only be met by continued high use of fertilizer and pesticide inputs. The primary question is not whether high yields can be produced from organic systems. Pimentel et al. (2005) stated that various organic agricultural technologies have been used for about 6000 years to make agriculture sustainable while conserving soil, water, energy, and biological resources. They also reviewed results from 1981 to 2002 of the Rodale Institute farming systems trial conducted in Kutztown, PA. They concluded that there were many benefits from organic technologies. Soil organic matter and nitrogen were higher in the organic farming systems and helped conserve soil and water resources during drought years. Fossil energy inputs were about 30% lower than for conventionally produced corn. Labor inputs averaged about 15% higher but were more evenly distributed over the year. Regarding yields, they concluded that depending on the crop, soil, and weather conditions, organically managed crop yields on a per-hectare basis can equal those from conventional agriculture, although it is likely that organic cash crops cannot be grown as frequently over time because of the dependence on cultural practices to supply nutrients and control pests. In an earlier study conducted in California, Sean et al. (1999) found that nitrogen deficiency and weed competition were the two primary problems associated with organic farming. Pimentel et al. (2005) acknowledged that the favorable geographical soil characteristics present at the Rodale Institute farm may not be universally applicable.

Unfortunately, there has been too much conflict between people supporting use of synthetic fertilizers and those that use only organic materials. There are several reasons this has happened, but it is important that both sides become more fully informed. Many users of organic products believe that synthetic fertilizers are anthropogenic substances. Although synthetically fixed ammonia is produced by human activities, there is absolutely no difference in an NH_4^- ion formed in the soil from synthetically fixed ammonia and one that is formed from ammonia added with manure or from biologically fixed nitrogen. Likewise, phosphorus ions taken up by plants are the same regardless of their source. In contrast, many of the pesticides used in conventional agriculture are anthropogenic substances, and supporters of organic foods can make a more valid case for concern. From a nutrient standpoint, however, plants cannot distinguish between sources when taking up ions such as N and P. This is highly important because there are ample studies showing that, in many cases, current nutrient practices are not sustainable and more efficient management systems are needed. A review of long-term experiments conducted around the world indicated that chemical fertilizer alone is not enough to improve or maintain soil fertility, and the soil acidification problem caused by overapplication of synthetic N fertilizer can be reduced if more N fertilizer is applied as NO_3^- relative to ammonium- or urea-based N fertilizers (Miao et al. 2010). Organic fertilizers can improve soil fertility and quality, but long-term application of high rates can also lead to nitrate leaching, and accumulation of P, if not managed well. The review by Miao et al. (2010) clearly showed that well-managed combinations of chemical and organic fertilizers can overcome the disadvantages of applying single sources of fertilizers and sustainably achieve higher crop yields, improve soil fertility, alleviate soil acidification problems, and increase nutrient-use efficiency compared with only using chemical fertilizers.

A major disadvantage of relying on organic materials as a source of N and P for crop production is that enough material is added to supply adequate N, and P accumulations are common that can result in excessive amounts of P in runoff water causing eutrophication. The primary reason for this is that the N/P ratios of freshly excreted animal manures are about 3 to 3.5, and the ratio decreases to about 2 for aged manure (Stewart et al. 2000). Furthermore, the N in manures is not as readily available to plants as the P, so relatively large amounts of P can accumulate in soils when manures are added to supply N. Also, most crops require a higher ratio of N to P than is present in manures. For example, maize and wheat plants require approximately five times as much N as P. Therefore, the use of N fertilizer in combination with manure can result in more balanced soil fertility and reduce the threat of P pollution (Figure 4.5).

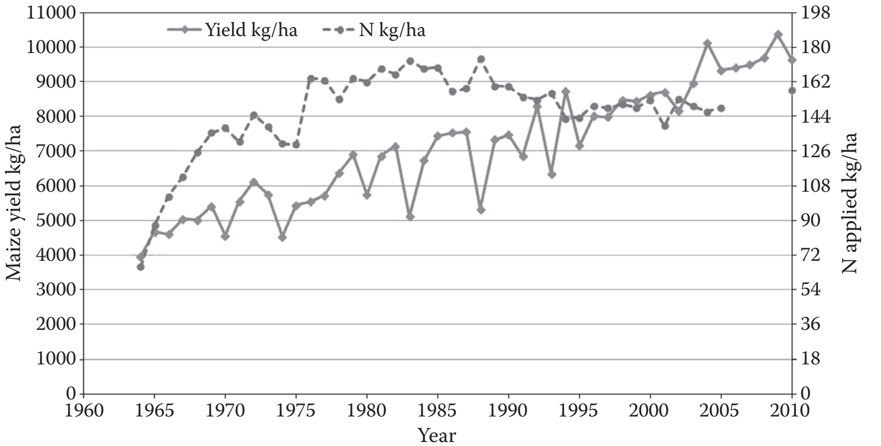

FIGURE 4.5 Amounts of nitrogen applied to maize in the United States to grain yield. (Data from National Agricultural Statistics Service, 2012.)

The use of manure and other forms of organic wastes should be highly encouraged and practiced. As already discussed, there is growing concern about the changes to the global nitrogen cycle being caused by synthetic N fertilizers and the effect this might have on human health and the environment (Townsend et al. 2003). The recycling of as much N as feasible could reduce the need for synthetically produced N substantially. Perhaps as important, or even more so, is the recycling of P. Unlike N, which has no limit to the amount that can be synthesized as long as an energy source is available, commercial P fertilizer is manufactured from phosphate rock obtained from underground mines and is a finite resource. As recent as 1950, about 80% of the P used for fertilizer globally was from organic sources, whereas about 90% today comes from phosphate rock (Cordell et al. 2009). Although the amount of phosphate rock present globally is not known, the supply is finite. Cordell et al. (2009) estimated that peak production of phosphate rock known to be economically available for mining and processing would occur between 2030 and 2040; more recent estimates have been revised upward (Jasinski 2011). Compared to the estimate of about 16 billion Mt by Jasinski (2011), the International Fertilizer Development Center estimated reserves as 60 billion Mt and would be sufficient for 300 to 400 years (Syers et al. 2011). Regardless of the amount, the fact that phosphate rock is a finite resource and an element that is essential for food production requires recycling for long-term sustainability. Cordell et al. (2009) estimated that only one-fifth of the phosphorus mined in the world is consumed by humans as food.

4.7 CONCLUSIONS

While the production and sales of organically grown foods continue to increase at significant rates, they still account for only about 2% to 3% of the total. There is ample evidence showing that the yields of organically grown crops can be as high, or even higher, than conventionally grown crops. Although consumers of organic products generally consider the quality to be higher and also safer, the scientific evidence to support these views is limited at best, particularly in developed countries. While there is every reason to think the production of organic foods will continue to increase, there is little likelihood that it will ever be a major source of the world's total food supply. With a few exceptions, agricultural scientists suggest that world food needs can only be met with the use of commercial fertilizers, and that even with their use, the task will be challenging in view of increasing world population and changes in diets that increase the demand for grain. At the same time, an increasing number of scientists believe that changes in the global nitrogen cycle are becoming so serious that major changes must be made in the fixation and use of atmospheric nitrogen. Many long-term experiments have shown that the combined use of organic materials and commercial fertilizers results in the highest yields and the best soil quality. Therefore, every effort should be made to recycle nutrients to the fullest extent feasible. This will not be easy because commercial fertilizers have historically been relatively inexpensive, easy to use, highly concentrated, free of weed seed, and of known composition of single or multiple nutrients. In contrast, organic materials such as manure are highly variable in terms of moisture, concentration and availability of nutrients, kind and number of weed seed, ease of handling, and uniformity of spreading. Many producers chose, and were often encouraged by scientists, industry representatives, extension workers, and other change agents, not to use organic materials even when they were available because they felt the short-term benefits of using commercial fertilizers were the best.

ABBREVIATIONS

BSE: bovine spongiform encephalopathy
CAFOs: concentrated animal feeding operations
GMOs: genetically modified organisms
Mt: million tonnes
NOP: National Organic Program
OFPA: The Organic Foods Production Act
EPA: US Environmental Protection Agency

REFERENCES

Badgley, C., J. Moghtader, E. Quintero, E. Zakem, M.J. Chappell, K. Avilés-Vázquez, A. Samulon, and I. Perfecto. 2007. Organic agriculture and the global food supply. *Renew Agr Food Syst* 22:86–108.

Borlaug, N. 2009. Norman Borlaug on organic farming. http://www.coyoteblog.com/coyote_blog/2009/03/norman-borlaug-on-organic-farming.html (verified June 6, 2012).

Brandt, K., C. Leifert, R. Sanderson, and C.J. Seal. 2011. Agroecosystem management and nutritional quality of plant foods; the case of organic fruits and vegetables. *Crit Rev Plant Sci* 30:177–197.

Carson, R. 1962. *Silent Spring.* Houghton Miffin Publishers, Boston, MA.

Commoner, B. 1971. *The Closing Circle: Nature, Man, and Technology*. Knopf Publishers, New York.

Cordell, D., J.-O. Drangert, and S. White. 2009. The story of phosphorus: global food security and food for thought. *Global Environ Change* 19:292–305.

Dangour, A.D., S.K. Dodhia, A. Hayter, E. Allen, K. Lock, and R. Uauy. 2009. Nutritional quality of organic foods: a systematic review. *Am J Clin Nutr* 90:680–685.

De Ponti, T., B. Rijk, and M.K. van Ittersum. 2012. The crop yield gap between organic and conventional agriculture. *Agr Syst* 108:1–9.

Diacono, M. and F. Montemurro. 2010. Long-term effects of organic amendments on soil fertility: a review. *Agron Sustain Dev* 30:401–422.

Edmeades, D.C. 2003. The long-term effects of manures and fertilizers on soil productivity and quality: a review. *Nutr Cycl Agroecosyst* 66:165–180.

Ellis, E.C. and S.M. Wang. 1997. Sustainable agriculture in the Tai Lake Region of China. *Agric Ecosyst Environ* 61:177–193.

FAOSTAT. 2012. Food and Agriculture Organization of United Nations. Rome. http://faostat.fao.org (verified April 3, 2012).

Folkers, D. 1983. Biologischer anbau von obst und gemüse—die einstellung der Bundesbürger. *Ernährungsumschau* 30:B36.

Galloway, J.N. and E.B. Cowling. 2002. Reactive nitrogen and the world: 200 years of change. *Ambio* 31:64–71.

Gao, C., B. Sun, and T.L. Zhang. 2006. Sustainable nutrient management in Chinese agriculture: challenges and perspective. *Pedosphere* 16:253–263.

Hansen, B., H.F. Alrøe, E.S. Kristensen, and M. Wier. 2002. Assessment of food safety in organic farming. Danish Research Centre for Organic Farming (DARCOF) Working Paper no. 52, Post Box 50, DK-8830 Tjele, Denmark. http://orgprints.org/00000206 (verified April 10, 2012).

Hughner, R.S., P. McDonagh, A. Prothero, C.J. Shultz, and J. Stanton. 2007. Who are organic food consumers? A compilation and review of why people purchase organic food. *J Consum Behav* 6:94–110.

IFA. 2002. Statistics, 2nd edn. International Fertilizer Industry Association. http://www.fertilizer.org/ifa (verified April 3, 2012).

IFOAM. 2012. International Federation of Organic Agriculture Movements. www.ifoam.org. (verified April 3, 2012).

Jasinski, S.M. Phosphate rock. 2011. In: *Mineral Commodity Summaries.* United States Geological Survey, United States Government Printing Office, Washington, DC.

Kahl, J., T. Baars, S. Bügel, N. Busscher, M. Huber, D. Kusche, E. Rembiałkowska, O. Schmid, K. Seidel, B. Taupier-Letage, A. Velimirov, and A. Załęcka. 2012. Organic food quality: a framework for concept, definition and evaluation from the European perspective. *J Sci Food Agric* 92:2760–2765.

King, F.H. 1911. *Farmers of Forty Centuries: Organic Farming in China, Korea, and Japan*. Dover Publications, Inc. Mineola, NY, USA.

Ladha, J.K., H. Pathak, T.J. Krupnik, J. Six, and C. van Kessel. 2005. Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. *Adv Agron* 87:85–156.

Lal, R. 2006. Enhancing crop yields in the developing countries through restoration of the soil organic pool in agricultural lands. *Land Degrad Dev* 17:197–209.

MacDonald, J.M., E.J. O'Donoghue, W.D. McBride, R.F. Nehring, C.L. Sandretto, and R. Mosheim. 2007. Profits, Costs, and the Changing Structure of Dairy Farming. Economic Research Report No. (Err-47), USDA Economic Research Service, Washington, D.C.

Magkos, F., F. Arvaniti, and A. Zampelas. 2003. Organic food: nutritious food or food for thought? A review of the evidence. *Int J Food Sci Nutr* 54:357–371.

Magnusson, M.K., A. Arvola, U. Hursti, L. Aberg, and P. Sjoden. 2001. Attitudes towards organic foods among Swedish consumers. *Br Food J* 103:209–227.

Miao, Y., B.A. Stewart, and F. Zhang. 2010. Long-term experiments for sustainable nutrient management in China. A review. *Agron Sustain Dev* 31:397–414.

National Agricultural Statistics Service. 2012. Quick Stats. http://www.nass.usda.gov/QuickStats/Create_Federal_All.jsp (verified June 6, 2012).

National Research Council. 2010. *Toward Sustainable Agricultural Systems in the 21st Century.* The National Academies Press, Washington, D.C.

Nielsen, R. 2005. Can we feed the world? Is there a nitrogen limit of food production? http://home.iprimus.com.au/nielsens/nitrogen.html (verified April 3, 2012).

Pimentel, D., P. Hepperly, J. Hanson, D. Douds, and R. Seidel. 2005. Environmental, energetic, and economic comparisons of organic and conventional farming systems. *BioScience* 55:573–582.

Rothamsted Research. 2006. Guide to the classical and other long-term experiments, datasets and sample archive. Lawes Agricultural Trust Co. Ltd., available at http://www.rothamsted.bbsrc.ac.uk/resources/LongTermExperiments.pdf (verified March 1, 2012).

Sean, C., K. Klonsky, P. Livingston, and S.T. Temple. 1999. Crop-yield and economic comparisons of organic, low-input, and conventional farming systems in California's Sacramento Valley. *Am J Altern Agric* 16:25–35.

Seufert, V., N. Ramankutty, and J.A. Foley. 2012. Comparing the yields of organic and conventional agriculture. *Nature* 485:229–232.

Smil, V. 2002. Nitrogen and food production: proteins for human diets. *Ambio* 31:126–131.

Smil, V. 2011. Nitrogen cycle and world food production. *World Agric* 2:9–1.

Stewart, B.A., C.A. Robinson, and D.B. Parker. 2000. Examples and case studies of beneficial reuse of beef cattle by-products. In *Land Application of Agricultural, Industrial, and Municipal By-Products.* J.F. Power and W.A. Dick, eds., 387–407. SSSA Book Series 6, Soil Science Society America, Madison, WI, USA.

Syers, K., M. Bekunda, D. Cordell, J. Corman, J. Johnston, A. Rosemarin, and I. Salcedo. 2011. *Phosphorus and Food Production*. UNEP Year Book. United Nations Environmental Program, Nairobi, Kenya.

Townsend, A.R., R.W. Howarth, F.A. Bazzaz, M.S. Booth, C.C. Cleveland, S.K. Collinge, A.P. Dobson, P.R. Epstein, E.A. Holland, D.R. Keeney, M.A. Mallin, C.A. Rogers, P. Wayne, and A.H. Wolfe. 2003. Human health effects of a changing global nitrogen cycle. *Ecol Environ* 1:240–248.

USDA. 2012. Cattle: Background. Economic Research Service, Washington, DC. http://www.ers.usda.gov/briefing/cattle/background.htm (verified April 14, 2012).

Von Liebig, J. 1840. *Chemistry in Its Application to Agriculture and Physiology.* Taylor & Walton, London.

Willer, H. and L. Kilcher (Eds.). 2012. *The World of Organic Agriculture—Statistics and Emerging Trends.* Research Institute of Organic Agriculture (FiBL), Frick, and International Federation of Organic Agriculture Movements (IFOAM), Bonn.

Williams, C.M. 2002. Nutritional quality of organic food: shades of grey or shades of green. *Proc Nutr Soc* 61:19–24.

Wittwer, S., Y. Youtai, H. Sun, and L. Wang. 1987. *Feeding a Billion: Frontiers of Chinese Agriculture*. Michigan State University Press, Michigan, USA.

Woese, K., D. Lange, C. Boess, and K.W. Bögl. 1997. A comparison of organically and conventionally grown foods—results of a review of the relevant literature. *J Sci Food Agric* 74:281–293.

Worldwatch Institute. 2011. Grain harvest sets record, but supplies still tight. August 12, 2011. http://worldwatch.org/node/5539 (verified April 14, 2012).

Worthington, V. 2001. The nutritional quality of organic versus conventional fruits, vegetables, and grains. *J Altern Complement Med* 7:161–173.

Yang, H.S. 2006. Resource management, soil fertility and sustainable crop production: experiences in China. *Agric Ecosyst Environ* 116:27–33.

Zhang, H., B. Wang, M. Xu, and T. Fan. 2009. Crop yield and soil responses to long-term fertilization on a red soil in southern China. *Pedosphere* 19:199–207.