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Food, Fuel, and Plant Nutrient Use in the Future

Predictions of a world population of nine billion by 2050 necessitate careful stewardship of current food, fuel, and plant assets; a major part of that challenge involves managing what is beneath the surface. (Photo by Colette Kessler, USDA Natural Resources Conservation Service.)

Abstract

Current conditions and future trends show that adequate food production will require increases in the use of fertilizer nutrients. With a growing population, dwindling arable land, and an increased demand for *biofuels,*[1] the world cannot count on an expansion of harvested area to fill the demands. Scientists and food producers need to look at the way land is currently used to feed the world's growing population and look into the best practices for how to move forward.

To meet global food demand, the use of genetics to improve crop productivity, promote soil conservation and management, and use nutrients efficiently is necessary. The key to these endeavors lies in supporting research and development in these areas.

This paper looks at the background leading to the current situation and addresses the resulting requirements as world food production develops during the next 40 years. Because of various circumstances, grain production will need to increase by approximately 50% during the next four decades. Current U.S. growth rates in cereal yields should meet 2050 demands, but greater cereal yields per unit land area require increases in fertilizer nutrient use, advances in genetics, and improved soil and crop management technologies.

Other topics in this paper include issues dealing with *cellulosic* biofuel production. According to projections, land availability is not a constraint to biofuel production, and the United States has the capabilities to decrease

[1] Italicized terms (except genus/species names and published material titles) are defined in the Glossary.

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dependency on imported oil. Efficient land use is a key, and cover crops will play a significant part in this process. In the United States, however, the removal of the three primary plant nutrients—nitrogen, phosphorus, and potassium—has been increasing, and there is a need for increased fertilizer use and more recovery and recycling from farm and nonfarm systems. Continued advances in nutrient use efficiency will moderate increased nutrient demand.

Future food, fiber, and fuel demands will not be met by expanding cropland area. The authors use data to analyze factors influencing crop production now and indications of what is to come. With a growing population and increased demand for food and fuel, research regarding nutrient use, recovery, and recycling is crucial.

Introduction

The world's population is expected to increase to 9.2 billion people by 2050. But it is estimated that the annual population growth rates are decreasing considerably from 1.2% for the 1990–2010 period to 0.8 and 0.4% for the 2010–2030 and 2030–2050 periods, respectively (Table 1). The growth rates are different for developed and developing countries, as shown in Table 1.

The question of how to feed mankind by 2050 is a very important one and brings many concerns to policymakers and researchers alike. Three major components deserve special attention based on the world's current food system: estimation of food needs, availability of land to grow food, and the nutrients that are required to increase world food production. One model on which to base projections for future food demands is cereal production, because cereals are used not only as a main human source of energy but also in feeding animals that will be consumed as meat and dairy products.

The United States is and will continue to be a major producer of food for the world in the form of cereals and animal production. Increasing food demands and shrinking agricultural land in the United States and other parts of the world necessitate an analysis of this problem. Moreover, the stress put on food production by increasing oil prices significantly challenges the agricultural system. Bioenergy has been identified as a major component in developing alternative energy sources in the United States to achieve some level of energy independence. But the use of cereals in the production of bioenergy has created concerns of competition due to the increased demands of cereals to feed the world.

Increasing population and demand for cereals for food and feed, increasing use of cereals and other agricultural products for bioenergy, and limited land resources require increasing yields on current agriculture land or using land with limited and/or decreased nutrients. Historically it has been documented that to increase crop yields the use of fertilizers and other nutrient sources must also increase, even though fertilizer use efficiency has improved in recent years. Therefore, the objective of this paper is to obtain a better understanding of the factors influencing future fertilizer nutrient requirements and availability.

Table 1. Differences in population growth and annual population growth rate between developed and developing countries (UN 2007)

	Population (billion)						Average Annual Growth Rate (%)				
	1950	1970	1990	2010	2030	2050	1950–1970	1970–1990	1990–2010	2010–2030	2030–2050
World	2.54	3.70	5.29	6.91	8.32	9.19	1.99	1.74	1.21	0.82	0.41
Developed countries	0.81	1.01	1.15	1.23	1.26	1.25	0.96	0.59	0.32	0.06	−0.09
Developing countries	1.72	2.69	4.14	5.68	7.06	7.94	2.41	2.08	1.41	0.96	0.49

This, in turn, would support recommendations to identify future policy implications and research requisites. The authors have addressed the issues in the following sections using a target of year 2050:

- Population Dynamics. Estimation of population in developed and developing countries that needs to be fed by 2050.
- Food Needs to Sustain the World Population. Increased food demand associated with consumption patterns of cereals needed as food and feed, and the impact on U.S. grain production.
- Impact of Energy and *Biomass* Production. Demand of cereals for biofuels as well as the land availability in the United States, and the potential that the production of second-generation biofuels presents, with two scenarios and the impact on environmental issues.
- Land Use and Productivity. The worldwide demands for land to grow food considering space and soil quality and the need for increased yields based on historical yield increases since 1950.
- Applied Nutrients and Nutrient Availability. Historical nutrient use of nitrogen (N), phosphorus (P), and potassium (K) and crop removal in the United States, current soil fertility status and trends, future nutrient requirements, and availability of fertilizer raw materials.
- Conclusions and Recommendations.

Population Dynamics

From the early 1960s, the world annual population growth rate of slightly more than 2% has decreased by 50% to current levels of slightly more than 1% (UN 2007). Projections to 2050 show global population growth rates will decrease again by 50% to approximately 0.5% per year. Whereas annual growth rates in all nations will decrease by 2050, those in developing nations will still be higher (0.5%) than those in industrialized nations (-0.1%) (Table 1) (UN 2007). In developing countries, most of the decline in population growth rates is related to improved education, economic development, and increased agricultural productivity primarily in South and East Asia, an area that represents nearly 50% of the total world population (UN 2007). Population growth rates are projected to remain high in sub-Saharan Africa where poverty, suppressed economic opportunity, and low agricultural productivity will continue to persist during the next 40 years (Bruinsma 2009; FAO 2010).

Despite declining world population growth rates, total world population will still increase nearly 35% to more than 9 billion people by 2050 (UN 2007). Currently, approximately 80 million people worldwide are added annually, which will slowly decline during the next four decades to an estimated 40 million people per year. Total population will remain relatively constant at approximately 1.25 billion in the developed countries because of their low and declining population growth rate (Table 1). Therefore, most of the population growth will occur in the developing countries. In the least developed countries (e.g., countries in sub-Saharan Africa), populations will more than double to 1.8 billion in 2050. Although population growth in the remaining developing countries will be less rapid, population will increase from 4.5 billion to 6.1 billion in 2050. It is interesting to note that population in developed nations will decrease from 32% of total world population in 1950 to approximately 13% by 2050 (calculated from data in Table 1).

Food Needs to Sustain the World Population

The factors determining future global food demand include changes in population (food demand), per capita energy consumption, and diet composition reflecting changes in prices. In addition to large projected increases in population by 2050, world food consumption per capita also will continue to increase during the next 40 years; it is, however, projected to stabilize at approximately 3,100 kilocalories (kcal)/capita/day by 2050, an increase of 300 kcal from current consumption (FAO 2006). The largest increases in food consumption will occur in developing countries where 30 years ago per capita consumption was approximately 2,100 kcal and is projected to increase to approximately 3,000 kcal/capita/day by 2050. In contrast, food demand in developed countries will increase only slightly from current levels of 3,400 kcal and remain constant at approximately 3,540 kcal/capita/day. These increases in caloric intake primarily reflect increases in the consumption of meats.

Whereas per capita consumption (in kcal) is projected to stabilize during the next 40 years, diet composition will change substantially. World consumption of cereals for food (kilograms [kg]/capita/year [yr]) is not projected to increase over current levels; per capita consumption of animal products (meat and dairy), however, will expand by more than 30% from current consumption levels through 2050 (Figure 1). Cereal consumption (all uses) will increase by approximately 10% during the same time period, which represents an increase in cereals used for feed grain. In developed countries, per capita consumption of food cereals is expected to remain at current levels, but consumption of animal products will exhibit a modest 8% increase during the next 40 years (Figure 1). Total cereal consumption in developed countries will increase by 12.5%, most of which represents an increase in cereals used for animal feed.

In contrast, substantial changes in diet will continue to occur in developing countries (Figure 1). Although per capita cereal consumption for food will remain stable, consumption of

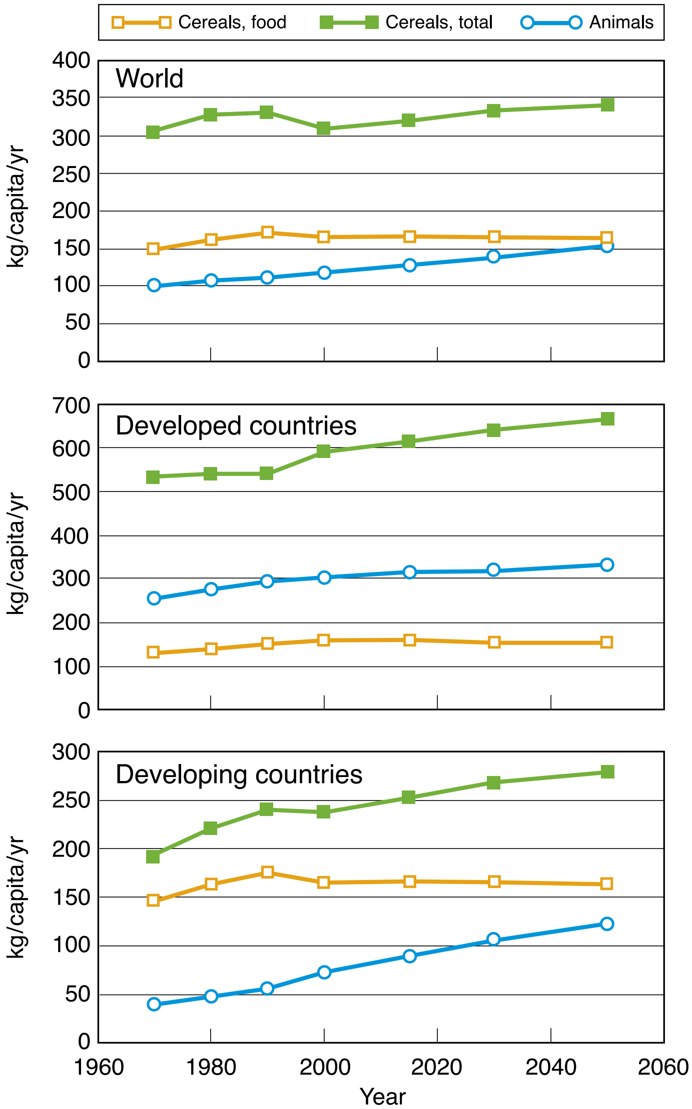


Figure 1. Actual and projected changes in per capita annual cereal and animal (meat + dairy) product consumption from 1970 to 2050. Total cereal consumption represents cereals used for food and animal feed (FAO 2006).

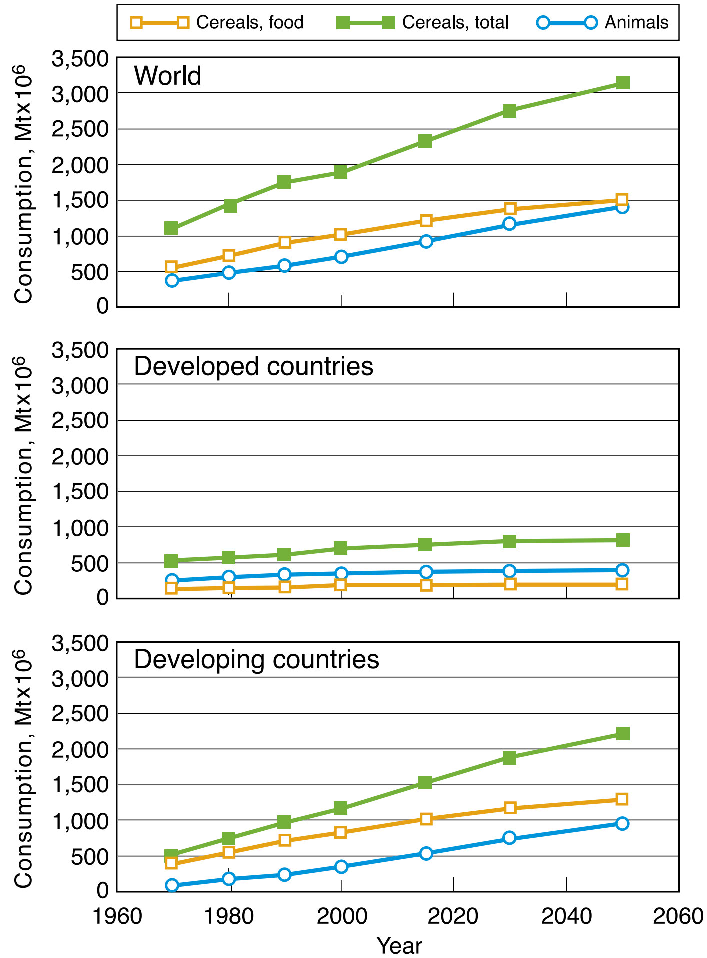


Figure 2. Actual and projected annual consumption of cereals and animal products (meat + dairy) from 1970 to 2050 (Mt = metric tons). Total consumption represents cereals used for food and animal feed (FAO 2006).

animal products will increase by 70% from current levels to those expected in 2050. Per capita cereal consumption for all uses will increase approximately 17%, which again reflects additional use of cereals for animal feed. Most of the increase in consumption of animal products is related to increased meat consumption in China, India, and several other countries in South and East Asia (Evans 2009).

Although increases in per capita consumption and changes in diet composition are important indicators of future food demand (especially in developing countries) (Figure 1), food consumption measured across an increasing population better illustrates future food needs. Thus, annual consumption in million metric tons (MMt) is calculated by multiplying annual per capita consumption (Figure 1) by the projected population (Table 1) for a given year. In the developed countries, annual consumption of cereals remains level during the next four decades, whereas total cereal and animal product consumption will increase by 17% and 13%, respectively (Figure 2). In contrast, annual consumption of food cereals, total cereals, and animal products in developing countries during the next 40 years will increase 59, 89, and 173%, respectively. Annual consumption worldwide shows that food and total cereals will increase by 47% and 65%, respectively, from current levels to 2050, whereas global animal product consumption (meat+dairy) will double (97% increase).

A number of assessments of global food demand and supply have documented that current food supply is sufficient to meet demand, despite the fact that approximately 900 million or 12% of the world population is undernourished (FAO 2010; IFPRI 2002; Rosen et al. 2008). A large proportion of these people reside within a subset of 32 nations (primarily sub-Saharan Africa) wherein approximately 40%

(29 to 72% range) of the population is undernourished (<2,200 kcal/capita/day). In these countries, the current population of 580 million likely will increase to 1.4 billion by 2050. Inequitable food distribution perpetuated by ongoing issues (distressed economies, troubled education systems, poor agricultural productivity, and possible internal conflicts) will continue to require substantial food aid to meet future population growth and accompanying food demand.

Since the 1800s, as scientific measures affected agricultural production, cheap food combined with improved health contributed to population growth. Overall, the rate of growth in food exceeded the rate of population growth, and the relative price of food has declined over time (Federico 2005). Commodity programs in the United States (including land diversion programs) were actually designed to decrease excess supply (Gardner 1987). Currently, world food production is meeting food demand (USDA–ERS 2008). Historically, per capita cereal production has kept pace with population growth, although since the mid-1980s, population growth has exceeded cereal production (FAO 2008). These data show annual per capita cereal production worldwide decreased from approximately 370 kg to 350 kg/person, a decline of 5.7%. Dyson (1999) concludes that even though per capita cereal production increased slightly in developing countries, it was offset by declines in developed nations.

Alston, Beddow, and Pardey (2009) argue that the rate of growth in demand for agricultural commodities (stemming from population growth and economic growth in Asia as well as expansion of biofuel) has been faster than the rate of growth of agricultural supply, which has triggered an increase in agricultural commodity prices. The rate of growth of supply suffered from the decline in the rate of growth of agricultural productivity that was affected to a large extent by underinvestment in agricultural research. Regulatory burden has been another cause for the decrease in productivity and, in particular, slower development of new innovation. Graff, Zilberman, and Bennett (2009) argue that the European practical ban of genetically modified (GM) crops has slowed the development of this technology. Sexton and Zilberman (2011) argue that adoption of GM varieties in corn increased yields significantly, especially in developing countries, and lessened the increase in food prices that was associated with an increase in demand in developing countries. They suggest that added adoption of GM varieties in Europe and Africa would further increase food availability and significantly lower some of the recent increases in food prices. Thus, continued capacity to provide food to meet growing demands requires an increase in investment of research as well as regulatory policies that will enable implementation of new technologies.

Worldwide cereal yields have increased linearly by approximately 2,000 kg/hectare (ha) since 1960, which represents an average annual increase of 43.6 kg/ha (Figure 3). The increase in world cereal production since 1960 is primarily related to increased yield per unit of land area compared with increased land area cultivated for cereal production (Figure 3). In 2007, cereal production was approximately 2,350 MMt produced on approximately 700 million ha, which represents 3,350 kg/ha of total cereal grain yield.

Estimating future food consumption requires modeling of dynamic processes that affect the demand and supply of food. The data suggest that there are significant differences in demand and supply between developed and developing countries and that diet is changing across regions. Although these differences in consumption patterns exist, research on food demands suggests that common forces affect consumption patterns globally. Rising income levels within a range tend to change diets by increasing reliance on meats rather than grains. This growing demand for meat products strongly increases the demand for cereal. The recent economic growth in China was a driver behind the increased demand for grain in that country as well as the increase in the price of grain commodities globally (Hochman et al. 2011). Continued economic growth in the developing world, as well as population growth, is likely to increase the demand for food globally, but the exact estimation of future demand is subject to much uncertainty.

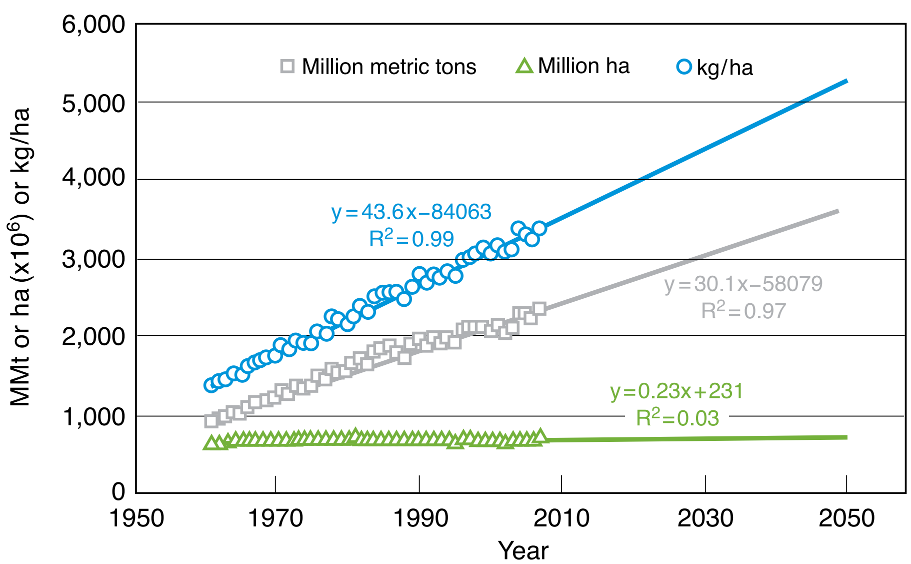


Figure 3. **Historical trends in cereal production (MMt), cereal yield (kg/ha), and cereal production area (million ha) (FAO 2008).**

Future supply is subject to uncertainties regarding future crop productivity, land use patterns, weather conditions, and policies. Lobell, Schlenker, and Costa-Roberts (2011) suggest that climate change may result in decreased yield because of susceptibility to heat. Agricultural systems may adapt, however, minimizing crop yield losses (Nelson et al. 2009). Intensive development and adoption of transgenic technologies can provide an avenue to increase yield and adapt to climate change, but it is constrained by regulatory requirements (Potrykus 2010; Sexton and Zilberman 2011) that may be modified in the future.

Thus rigorous prediction of food yields and consumption trends requires quantification of the processes that affect it. This is consistent with a recent analysis of Gitiaux, Reilly, and Paltsev (2011), who examined alternative yield growth models using data from 1961 to 2009 and showed that linear growth is quite limited in its ability to explain much of the variation in productivity growth. There is significant evidence that structural breaks, due to both technological and policy reasons, significantly affect the evolution of yields per acre. Yield estimation can improve by using Bayesian procedures or by identifying causal models that explain structural change and relate it to yield growth. These efforts are beyond the scope of this analysis, which will use a simple, linear projection to calculate food consumption in the future, recognizing its limitations and realizing that the contribution of this work is the qualitative implications rather than precise numerical predictions.

Since grains represent the majority of food consumed by the poor (directly) and the rich (indirectly through the consumption of livestock), future food use will be estimated by projecting cereal use (wheat, rice, corn, etc.). Several assumptions are required. First, without using sophisticated forecasting models, production and consumption are relatively equal (USDA–ERS 2008), which reflects low carryover or year-end cereal reserves. Second, the annual per capita cereal production remains constant at approximately 350 kg/person (FAO 2008). Although increases in income may lead to increased consumption of meats, and thus of grain per capita, declining efforts associated with modern life may decrease the demand for calories per capita (Deaton and Drèze 2009). This is somewhat higher than in Dyson (1999), who suggested that this amount may decrease to 330 kg/capita. Third, world agricultural land area used for crops remains relatively constant. And finally, cereal yields continue to increase at current rates (~40 kg/ha/yr) (Figure 3). As suggested earlier, there is much uncertainty about the evolution of yield per acre. Although climate change is likely to decrease yield both directly (Lobell, Schlenker, and Costa-Roberts 2011) and because of difficulties of adaptation (Zilberman, Zhao, and Heiman 2012), higher prices of food are likely to increase investment in agricultural research and intensify agricultural production. Furthermore, higher prices of food may increase pressure to streamline regulation of GMOs. Thus, existing trends are used as a starting point.

A calculation (350 kg/capita annual cereal demand times projected population) provides an estimated cereal consumption demand of approximately 3,400 MMt by 2050 (Figure 4). This represents a 45% increase in cereal consumption from 2007 (2,350 MMt) to 2050, whereas cereal production (kg/ha) will increase by 55% over the same period if yield increases continue at historical rates (Figure 3). Using an estimated 5,200 kg/ha cereal yield in 2050 (Figure 3) averaged over approximately 700 million ha results in approximately 3,650 MMt of cereal production by 2050. Using the same procedure, cereal production in 2025 is estimated to be approximately 2,825 MMt, which is similar to the estimate provided by Dyson (1999). These figures suggest that world grain production will meet world grain demand if the historical trend in yield increase can be maintained. Although there are many uncertainties in any analysis of future food demand, these data suggest that grain production will need to increase by approximately 50% during the next four decades, assuming current projected population growth and relatively constant agricultural land area.

Although the estimated growth in cereal demand cited earlier has been verified by other authors (Bruinsma

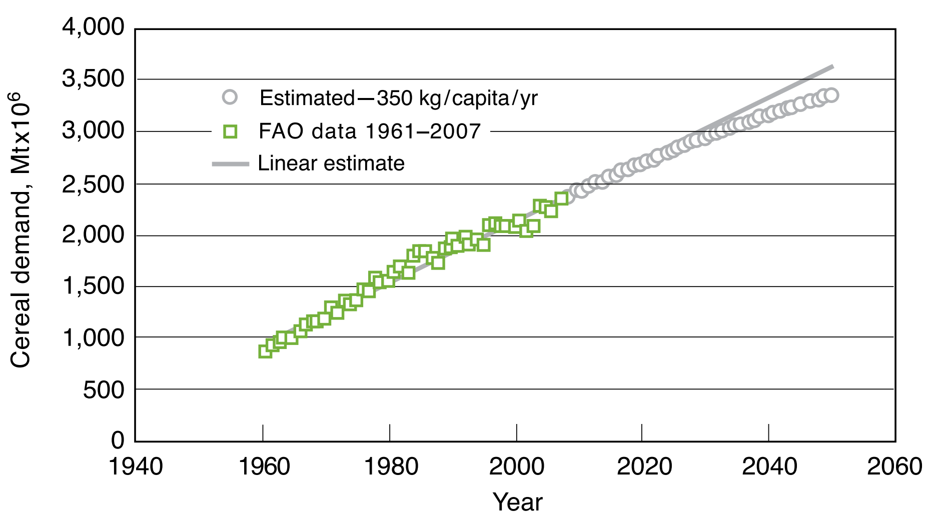


Figure 4. Estimated world cereal production demand. Open circles represent projected population multiplied by an estimated average annual per capita consumption of 350 kg. The open squares represent FAO (2008)-reported world cereal production (1961–2007). The linear estimate is taken from Figure 3 (y = 30.108x + 58079).

2009; FAO 2006; IWMI 2007; Ringler 2006), clearly wide variability in any estimate is likely due to uncertainties in estimating future population growth, diet composition, potential income, and nonfood crop use. While doubling of food production by 2050 has been widely communicated (Beachy 2010; Diouf 2009), it is important to distinguish between future food and cereal demand. In this analysis the focus is on future cereal demand, which includes cereals used for human consumption and animal feed. In contrast, future food demand includes projected growth in all plant and animal food sources. In this regard, the doubling of food production by 2050 is largely based on estimates of increased meat consumption driven by potential increases in personal income in China, India, and other East Asian countries. While studies question the estimated doubling of meat demand by 2050 in East Asia (Ma, Huang, and Rozelle 2004), estimates of total cereal demand in 2050 have been consistent and agree with Food and Agriculture Organization of the United Nations (FAO) data (FAO 2006, 2008).

Impact on U.S. Grain Production

Historically, North America and the European Union have been the major suppliers of grain to many food-poor nations. The United States is currently providing approximately 60% of world food aid (Shapouri and Rosen 2004) and meeting nearly 30% of cereal import needs (FAO 2008). Current U.S. exports are approximately 100 MMt, which represents 25% of total U.S. cereal production (FAO 2008; USDA–ERS 2008). Of the total world cereal production of 2,350 MMt in 2007 (Figure 3), 100 MMt of U.S. cereal exports represent approximately 4.3% of world cereal production. Assuming that global cereal grain production increases by 50% to approximately 3,500 MMt during the next four decades (Figure 4), and expecting the United States to maintain its share in global production, U.S. cereal production should increase by at least 50% as well, which implies that the United States will require production of 600 MMt by 2050.[2] Obviously, many factors influence commodity import-export projections; it is likely, however, that the dominant role of the United States in meeting world cereal grain demand will continue (USDA–ERS 2008).[3]

Currently in the United States, approximately 60 million ha are harvested for cereal production at an average yield of 6,500 kg/ha (Figure 5), which represents nearly 400 MMt of cereal production. Linear extrapolation of current growth in U.S. cereal production shows that cereal yield will be nearly 9,700 kg/ha by 2050. Maintaining current land area (60 million ha) in cereal production results in approximately 580 MMt of cereal production in 2050. Thus, the current growth rate in cereal yields should meet 2050 cereal demand, assuming current distribution of cereal grain use in the United States.

Unfortunately, agricultural land area has been decreasing at an annual rate of 0.15 million ha since 1960 (Figure 5). This trend is somewhat misleading, as the annual decrease from 1990 is approximately 0.54 million ha. This decrease is likely an overestimate because cereal cropland loss at this rate would result in approximately 35 million ha of cereal cropland in 2050. Lubowski and colleagues (2006) estimated approximately 0.40 million ha/yr of total cropland loss to predominately rural residential uses. Similarly, the USDA (2009) estimated nearly 0.5 million ha/yr of total cropland loss between 1982 and 2007. With approximately 70% of total U.S. cropland in cereals, annual cereal cropland loss would be 0.25–0.30 million ha. If the conservative estimate of 0.25 million ha/yr is used, then 10 million fewer ha of cereal cropland will be available in 2050. With approximately 50 million ha of cereal production, cereal yields need to increase to more than 11,600 kg/ha, compared with 9,700 kg/ha under current cereal yield increases on 60 million ha. To achieve an additional 2,000 kg/ha cereal yield by 2050, annual growth rate in cereal yield must

[2] Because income levels in Asia are lower, income elasticities of food demand in Asia are higher, and that will contribute to higher relative increases in their demand for food compared to the United States (Rosengrant et al. 2001).

[3] The increase in grain prices in the new millennium (from approximately $100 in the 1990s to approximately $150 between 2005 and 2012, with rapid increases) suggests increasing food scarcity, and thus the prediction of future demands that undervalue the recent trend of price increases may be somewhat conservative.

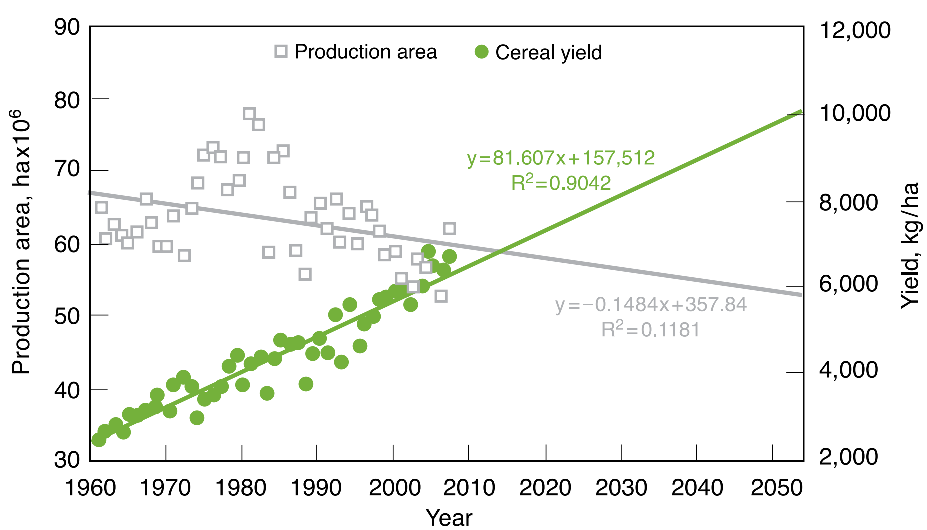


Figure 5. Historical and projected cereal yield and production area in the United States (FAO 2008).

be increased from 81 kg/ha/yr to approximately 123 kg/ha/yr. To achieve this increase, substantial advances in genetics and soil/crop management technologies will be required.

Impact of Energy and Biomass Production

A New World of Food and Fuel

This is a time of profound transition in how the world will be fed and fueled. At the root of the movement is the fact that the age of stable, cheap oil is over. The balance between oil supply and oil demand is tight enough that economic growth will put steady pressure on oil prices, magnifying any effects of speculation and threatened or actual loss of supply (IEA 2007). Unfortunately, it may be that low oil prices will remain low only during a recession. Thus we arrive at a potentially grim future described by the following painful cycle: recession leads to lower oil prices; lower oil prices promote economic recovery, thereby increasing oil demand; oil prices rise in turn, aborting the nascent recovery and returning us once again to recession. In short, not a pretty picture for an oil-dependent world.

Furthermore, because all energy carriers can be substituted to some degree, high and unpredictable oil prices will increase the price and volatility of all other energy carriers, including natural gas and coal. Increased energy costs are an important driving force behind recent worldwide increases in the cost of food and agricultural commodities (Anderson et al. 2008). The world has had cheap food in no small part because it has had cheap energy, led by cheap oil. The production, processing, and distribution of all agricultural and food commodities are intimately linked with the price of energy. For example, natural gas is the major feedstock for fertilizer-N production. Change in natural gas prices, therefore, can impact the cost of fertilizing many crops. Rising oil prices increase the cost of all field operations requiring diesel fuel, and rising coal and natural gas prices increase the cost of electricity. Therefore, the cost of processing and refrigerating food increases. It is clear that energy prices will not return to the low levels of the twentieth century. While new discoveries, and especially the drastic increase in known natural gas reserves, are likely to increase the supply of energy, demand for oil will continue to increase because of population and income growth. Much of the new natural gas resources can substitute for coal to help address climate change concerns. Furthermore, the new economics of oil and gas are subject to high degrees of uncertainty (Paltsev et al. 2011). Scarcity and anxiety in the fuel markets will spill over to food markets, amplifying uncertainties in these markets, threatening both total food production and prices.

The Promise of Biofuels

Is there a way to resolve this dilemma in which food prices rise along with energy prices? Are there ways that energy and food production can complement and not compete with each other? Cellulosic biofuels may help resolve these crucial questions. Plant matter—particularly cellulosic materials such as grasses, straws, and woody substances—are now much less expensive than oil on a dollars per megajoule (MJ) basis. Figure 6 shows the cost of cellulosic biomass in dollars per dry Mt plotted against the cost of oil in dollars per barrel. The dashed horizontal line represents the approximate price of large-scale sources of cellulosic biomass, which should be available at approximately $65 per Mt (Sokhansanj et al. 2009). (Some sources of cellulosic biomass are available at much lower prices.) The solid diagonal line shows where the price of the energy content of the biomass (essentially, the heat released when it is burned) is equal to the price of the energy content of the oil.

It is not possible to create or destroy energy, only to change its form. The goal of biofuel production is to convert the energy content of plant material into a form that can substitute for petroleum. Thus, when oil was cheap ($20 per barrel or less), it was only affordable to purchase the energy content of biomass. There was no economic margin left over to meet the cost of processing biomass to energy products. Now that oil is in a new, higher price range, it becomes

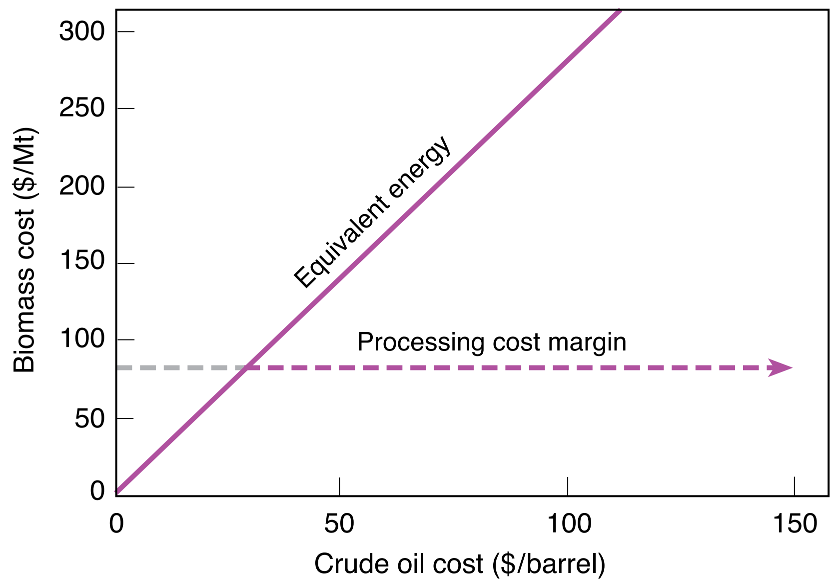


Figure 6. Cost of energy in plant biomass versus cost of energy in oil.

economically possible to convert biomass to petroleum substitutes (Dale 2008). Economic forces alone will tend to drive the use of plant matter to replace petroleum and other energy carriers. Plant matter can be burned to provide electricity or natural gas substitutes or processed to produce petroleum substitutes such as ethanol (a gasoline replacement) or biodiesel. First-generation biofuels such as ethanol from corn or sugarcane or biodiesel from soy oil will, over time, be decreased by second-generation biofuels made at a much lower cost and in much larger volumes from cellulosic materials (Dale 2008).

There is a large body of literature on the impact of biofuels—particularly first-generation biofuels such as ethanol from corn or sugarcane—on energy markets, food production, water use, land availability, and the environment (Khanna, Scheffran, and Zilberman 2010; Naylor et al. 2007). Learning by doing (Hettinga et al. 2007) has decreased the cost of corn ethanol substantially in the United States, and with the rising price of fuel, the economics of both corn and sugarcane ethanol have been improved.[4] The capacity of first-generation biofuel is limited, however, and the potential of second-generation biofuel must be unleashed to capture the much larger national security, economic, and environmental benefits (Greene 2004).

This section will explain briefly how cellulosic biofuels are different from first-generation biofuels and how these differences are important relative to the previously stated issues. The section concludes by explaining how cellulosic biofuel systems likely will be designed to coproduce animal feeds and also how they might be designed to recover and recycle mineral nutrients, an important focus of this report.

[4] Because of the instability of food prices, biofuel producers may be vulnerable during periods of high food prices and low fuel prices and may have to adjust their behavior accordingly (Hochman, Sexton, and Zilberman 2008).

Energy Markets

Grain-based biofuels are competitive with oil without subsidies when the price of a bushel of corn is less than approximately 5% the price of a barrel of oil. For example, without subsidies, corn-based ethanol competes well with $100-per-barrel oil when corn is $5 per bushel or less (Tyner 2008). Corn-based ethanol, however, probably will never supply more than approximately 10–15% of the U.S. gasoline market. There simply is not enough corn to produce more than that amount. In comparison, cellulosic biofuels can be competitive when oil is approximately $50 per barrel. When cellulosic ethanol technology matures, it will be possible to deliver ethanol to the pump at less than $2 per gallon (Laser et al. 2009). Worldwide, cellulosic biofuels can be produced in very large quantities. In the United States alone, there is sufficient cellulosic biomass to produce enough ethanol to replace all imported oil rather easily (USDOE/USDA 2005). The stranglehold that oil has over economic development and national security for many nations will only be broken when oil has serious competition as a provider of liquid fuels, and cellulosic biofuels are an essential part of that competition.

Water Use

Water is used for biofuels both to grow crops and to process them into fuels. Approximately 15% of corn is irrigated, perhaps drawing down water tables in some areas. Cellulosic biofuel crops, however, probably will not be irrigated, and most of the water used in crop production will be rain and snow. Plants use a process called *evapotranspiration* to take water from the soil, pass it through the plant, and release water vapors into the atmosphere. These water vapors can then form clouds and fall again as rain or snow somewhere else. Water recycling through evapotranspiration is a key part of the ecological function of plants. Biofuels do use some water (three to four gallons per gallon of fuel) in the *biorefinery* (the processing facility that converts crops to fuels), which is similar to the amount of water consumed per gallon of gasoline produced in oil refineries (Aden 2007).

Water requirements should not present a real problem for the expansion of cellulosic biofuels apart from isolated local exceptions in some watersheds because of excessive draw-down of important aquifers, or perhaps decreased flows of seasonal streams resulting from high-productivity energy crops. On a global basis, expansion of the water recycling and water purification ecosystem services provided by plants would seem to be a strong point in favor of biofuels, as long as irrigation from endangered aquifers or limited surface water supplies is avoided. Put bluntly, plant biomass production, particularly through nonirrigated perennial grasses and trees, is generally good for the environment and for human societies. Plants enhance both the quantity and quality of water available in the biosphere. The same thing cannot be said for the effects of oil production on water quality and quantity.

Net Energy

Many people have heard that corn ethanol has a negative "net energy" (Pimentel and Patzek 2005). Net energy is defined by these authors as the lower heating value of the fuel divided by the sum of all the fossil energy (coal, petroleum, and natural gas) required to produce the fuel. By this way of thinking, ethanol is a poor fuel because "it takes more energy to produce the ethanol than you get when you burn the ethanol in your car." But net energy, if misused, can become an irrelevant and misleading datum. Net energy analysis is founded on the idea that 1 MJ of petroleum is equivalent to 1 MJ of natural gas is equivalent to 1 MJ of coal. This is obviously untrue; otherwise people would not be paying so much more for 1 MJ of petroleum than for 1 MJ of coal (Dale 2008). The energy value of coal is simply not as useful or as versatile as the energy content of oil, so coal is less valuable.

Second, the net energy argument can be misleading if the net energy of ethanol is not properly compared with the net energy of gasoline. Calculated on the same basis, gasoline has a lower net energy than ethanol from corn (Farrell et al. 2006). Ethanol from cellulosics will have an even better net energy profile than ethanol from corn. More importantly, both corn and cellulosic ethanol produce more than 20 times more liquid fuel per unit of petroleum "invested" to make them than is produced in converting petroleum to gasoline. In essence, bioethanol stretches domestic petroleum supplies into the future by leveraging oil to make much more liquid fuel: ethanol.

A related concept called energy return on investment (EROI) is important and useful and should not be confused with net energy analysis, as net energy has commonly been understood and misused in the biofuels context. The EROI is a measure of the total useful energy output of a system divided by the total energy input required to produce that output. The "excess" energy (output minus input) is what is available to run the rest of society—education, cultural events, health care, and so on. It is obvious that all human activities require energy. The higher the EROI, the more activities not related to energy production can be undertaken by society. The EROI for corn ethanol is approximately 2:1, while sugarcane ethanol's EROI is approximately 10:1. Based on near future technology, cellulosic ethanol has an EROI of approximately 18:1 with the potential of 35:1 or so as technology improves (Hall, Dale, and Pimentel 2011).

A pioneering study (Heller, Keolian, and Volk 2003) showed that electricity production from biomass (plantation willow) produced 11 units of electrical energy for every unit of fossil energy consumed, an EROI of 11:1. It is customary, however, to account for electricity's higher energy quality by multiplying the electricity output by a factor of three, yielding an EROI of more than 30:1 for this system. If the willow had been converted to ethanol and electricity in a biorefinery (Laser et al. 2009), the overall EROI would have been at least 15:1. By way of comparison, bitumen oil from the tar sands has an estimated EROI of approximately 5:1 and deepwater oil's EROI is approximately 12:1 (Hall, Balog, and Murphy 2009). Thus, even in their current relatively underdeveloped state, cellulosic biofuels offer better EROIs than their highly developed fossil counterparts.

Land Availability

Large amounts of crop and forest residues (straws, forest thinnings, slash, etc.) are available for cellulosic biofuel production without any new land required. At least 1.5 billion tonnes of such residues are available worldwide annually (Kim and Dale 2004), enough to make approximately 560 billion liters of ethanol, almost the entire volume of gasoline consumed each year in the United States, or approximately 70% of the energy content of all U.S. gasoline.

Additionally, at least 400 million ha of former agricultural land are abandoned or unused (Campbell et al. 2009). It should be possible to produce an average of 4 Mt/ha/yr of cellulosic biomass on these lands with minimal inputs, enough to make approximately 750 billion liters of ethanol per year, roughly the energy equivalent of the annual amount of gasoline consumed in the United States. Furthermore, potential energy crops such as switchgrass and *Miscanthus* (crops grown specifically to capture solar energy rather than for their food or feed value) have received little agronomic attention to increase their yields. Significant yield gains should be expected, increasing the productivity of both abandoned and active agricultural lands for cellulosic biofuel production (Christian, Riche, and Yates 2008).

Finally, taking into account the likely land efficiency savings of coproducing animal feeds and cellulosic biofuels (see sections to follow), second-generation biofuel production may actually free up current agricultural land for other uses such as conservation and protection of biodiversity. Contrary to popular belief, land availability is not currently a constraint to biofuel production.

Food vs. Fuel: Adapting Agriculture for Large-scale, Second-generation Biofuel Production

It is important to distinguish between the impact of biofuel on final food prices in the United States, which is quite low (3%–4.5%) because commodities account for a small share of the final food price (Hochman et al. 2011), and the impact of biofuel on commodity food prices, which, however, is more substantial. Zilberman and colleagues (2012) suggest that biofuel contributed between 25% and 40% of the increases in corn and soybean prices for the period 2001–2008, which was less than the contribution of economic growth and more than the contribution of rising energy prices. Furthermore, the food price peak in 2008 was affected by various governments' inventory management policies. As a significant portion of commodity food production is allocated to biofuel, it contributes to rising food prices, yet this is not a major concern where supplies are ample and overall food prices are reasonable. Concerns about biofuel's contributions to food price inflation, however, are during periods of high food prices as in 2008.[5]

Second-generation biofuels are much less likely to impact food prices.

[5] Actually, one of the benefits of biofuel during periods of ample supply is that it raises agricultural commodity prices and rural incomes and decreases the need for commodity support programs.

In fact, this issue of food vs. fuel requires careful thinking because it offers potentially important synergies between food and biofuel production. Throughout the United States and much of the rest of the world, people do not actually "grow food." Instead, they grow animal feed and then consume the meat, milk, eggs, and so forth produced by the animals. Approximately 85–90% of the best U.S. agricultural land—more than 300 million ha of cropland and pasture—is used to feed animals, not directly to feed humans.

Animals, like humans, require two primary food components: protein and digestible energy (calories). Also, approximately 70% of the protein and calories fed to livestock is fed to dairy and beef cattle, and approximately 90 million cattle are raised in the United States, a nation of 300 million human beings (Dale et al. 2009). Cattle and other ruminant animals can use grasses or straws as a source of calories. Most such cellulosic materials are not very digestible, however, so in the United States the tendency has been to feed grains, primarily corn and corn silage, to cattle. Almost all soybean production, including the associated vegetable oil, goes to providing protein in animal diets.

The so-called pretreatment processes that "unlock" sugars (cellulose and hemicellulose) in cellulosic materials for conversion to ethanol and other biofuels may also unlock these sugars for digestion by ruminant animals (Dale 2008). The same facility that produces pretreated feedstock for biofuel production may be able to produce enhanced ruminant animal feeds. Furthermore, grasses and legumes such as alfalfa can be harvested in the early spring when their protein content is high (15–20%), and this protein, so-called leaf protein concentrate or LPC, can be recovered as animal feed using well-known technology (Pirie 1978). The residual cellulosic fiber left behind after the protein is removed is suitable for animal feed or biofuel production.

Additional feed protein also may be readily coproduced with biofuels via the spent yeast cell mass following the fermentation to produce fuels (Matthews et al. 2011). Therefore, it is likely that increased cellulosic biofuel production will be accompanied by large increases in quantities of ruminant animal feeds, leading to an increase in both protein and digestible energy. The effect of these two changes will be to use land more efficiently to meet both food (actually animal feed) and biofuel needs. Some possibilities for integrating animal feed and biofuel production and their land use consequences, including effects on greenhouse gas (GHG) production, are outlined in the following pages.

Winter *double crops* are annual grasses or legumes (e.g., winter rye or clover) planted in the fall after the corn or soybean crop is harvested, typically to provide a green animal feed in the spring and/or for soil improvement. Double crops increase soil fertility (by sequestering carbon), largely eliminate wind and water erosion, and significantly decrease leaching of nitrates and other pollutants. In spite of these positive environmental benefits, double crops are grown on much less than 10% of corn acres. This is largely due to the fact that they represent a cost to the farmer without much associated revenue. If double crops became a source of farmer revenue—for example, for LPC and/or cellulosic biofuel production—more double crops would undoubtedly be planted. The LPC could replace some soy meal protein, thereby freeing up land for additional biofuel production without impacting food supplies.

As mentioned earlier, the cellulosic fiber remaining after LPC production can replace some existing animal feeds or serve as a raw material for biofuel production. Furthermore, the presence of the double crop protects soil, thereby allowing increased removal of corn stover. These effects would increase the total biomass productivity per acre without decreasing food supplies. Another increase in land use efficiency might be to employ crop residues (e.g., corn stover and wheat straw) to produce improved ruminant feeds. Since roughly half of the corn plant is grain, this approach approximately doubles the per-acre productivity of land for animal feed.

Increased double cropping has already played a major role in meeting the elevated demand for feed associated with population growth. In particular, much of the increases of soybean acreage, which has doubled since 1990, is due to double cropping of soybean and grains, primarily in Argentina but also in Brazil. Much of this expansion was fueled by adoption of herbicide-tolerant varieties and was associated with adoption of low-tillage practices (Trigo and Cap 2003). This increase in supply produced sufficient output to meet the growing demand for soybeans in China (Sexton et al. 2009). Expanding double cropping in the United States may lead to higher productivity without increasing the ecological footprint of agriculture.

Double crops, leaf protein, and enhanced cellulosic animal feeds were recently analyzed for their potential to provide current levels of food (mostly animal feed) as well as significantly larger amounts of feedstocks for biofuel production (Dale et al. 2010). The analysis was based on 114 million ha (approximately 70% of U.S. cropland), assuming that one-third of U.S. corn and soybean land was used to produce a winter double crop. According to this analysis, total biomass (grain plus cellulosic biomass) increased 2.5 times over current levels. This is enough biomass to produce approximately 400 gigaliters (GL) of ethanol per year, roughly the energy equivalent of all imported petroleum used for gasoline production, while still providing all the food and feed currently produced on this acreage. This approach to integrated food and biofuel production also decreases total U.S. GHG emissions by approximately 700 teragrams (Tg) carbon dioxide ($CO2$) equivalents per year, roughly 10% of the total U.S. GHG emissions.

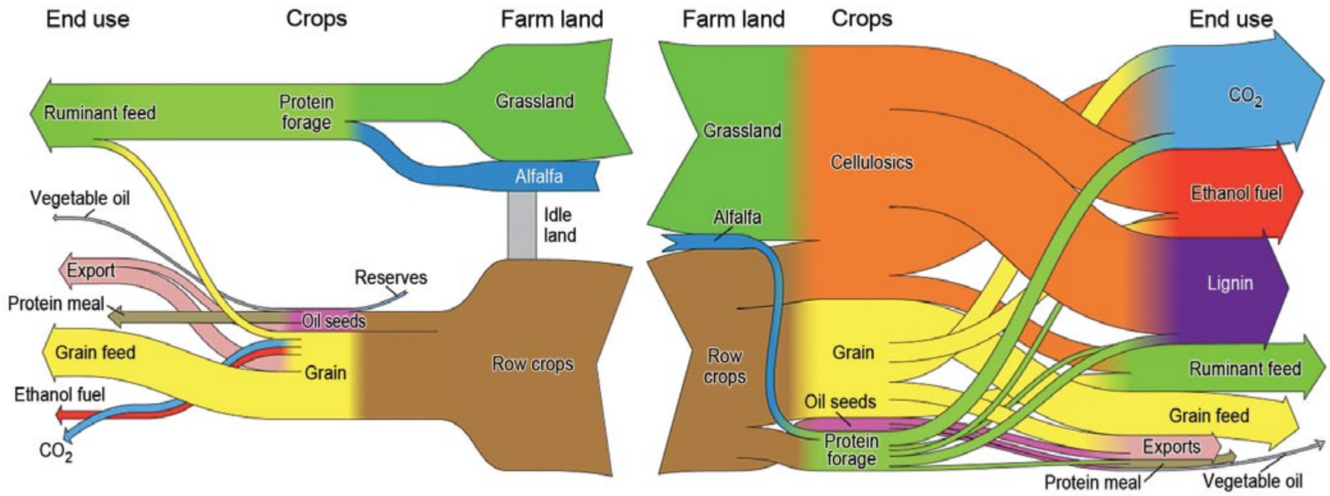


Figure 7. Current allocation of 114 million ha of U.S. agricultural land to produce feed, food, and fuel (left-hand side) versus a land-efficient allocation of those same acres to produce much more biofuel (right-hand side). (Reprinted with permission from Dale et al. [2010]. Copyright 2010 American Chemical Society.)

Figure 7 is a "spaghetti" diagram showing current land use patterns on the left and, on the right, how this same amount of land might be reconfigured to provide all of the food/feed it currently supplies while also providing enough additional biomass to produce a very large amount of biofuel.

Sensitivity analysis indicates that the most important variables are the fraction of land in cover crops, yields of perennial grasses, and animal feed requirements. The results outlined in Figure 7, however, are robust across a wide range of assumptions, as shown in Figure 8. The bottom line is that very large amounts of cellulosic biomass for second-generation biofuel production can be provided on existing land without compromising domestic food production or agricultural commodity exports. Production of more double crops and perennial grasses on a fraction of the existing land would decrease U.S. GHG production by approximately 10%, increase biodiversity, and improve soil fertility, and, if done correctly, could decrease nitrate emissions to groundwater and hence to the Gulf of Mexico, limiting the *anoxic* ("dead") *zone* there.

Looking to the future, if the yield of grasses increases to approximately 27.5 tonnes/ha/year during the next decade (Sokhansanj et al. 2009) while corn grain yields increase to approximately 13.4 Mt grain/ha/yr (250 bushels per acre per year), the amount of cellulosic biomass that could be produced on existing acres would expand further.

A very recent analysis of double crop coproduction in corn and soybean agriculture (Richard et al. 2010) shows that the arbitrary estimate of double cropping on one-third of corn and soybean acres used earlier is probably too conservative. Richard and his colleagues at Pennsylvania State University and the U.S. Department of Agriculture (USDA) conclude that approximately 180 million dry Mt of double crops could be grown on existing corn and soybean acres per year, which is more than double the estimate used earlier of approximately 73 million dry Mt per acre. Searchinger and colleagues (2008) suggest that the expansion of agricultural land due to rising prices associated with biofuel and the indirect land use change (ILUC) affiliated with this extensification is a major drawback of the technology. Recent studies have found these estimates to be overstated, but concerns still remain (Khanna and Crago 2012). Since the current products of the land continue to be generated, this approach of producing additional biomass on existing land avoids the so-called ILUC effect.

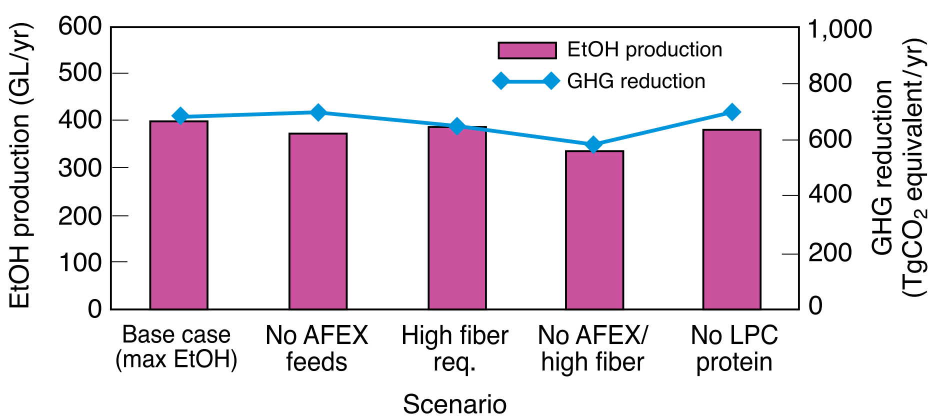


Figure 8. Sensitivity of ethanol production and GHG reduction to various assumptions about animal feed replacements (EtOH = ethanol; AFEX = ammonia fiber explosion). (Reprinted with permission from Dale et al. [2010]. Copyright 2010 American Chemical Society.)

This analysis only addresses the technical potential of these changes. Multiple drivers would be required to actually institute them. Changes in land use patterns are more likely to occur if they are economically attractive to farmers, livestock producers, and the biofuel industry. Chen, Huang, and Khanna (2012) assessed adoption and impact of various second-generation biofuels in the United States using different assumptions and showed that adoption patterns would depend on policies as well as parameters of the technology. For example, the Renewable Fuels Standard 2 and the Low Carbon Fuel Standard are more likely to enhance the adoption of *Miscanthus*, whereas a carbon tax may lead to decreased GHG emissions primarily by enhancing conservation, yet low adoption, of second-generation biofuel because of its cost. The high price of conversion of feedstock to biofuel was a major barrier for the expansion of second-generation biofuel in the Chen, Huang, and Khanna (2012) study, and policy instruments were required for the introduction of these technologies to make economic sense. Thus, much further exploration of the technologies mentioned earlier, as well as the economics of combined food/feed/fuel systems, is required.

Continued policy emphasis and incentives tied to improving the environmental performance of biofuels as well as animal feed production also would be needed to drive the desired changes, at least during the period of adjustment. Combining double crops with increased corn stover harvest is a key driver because of the large amounts of cellulosic biomass made available with concurrent improvements in several environmental parameters. The use of double cropping in biofuel systems can be induced by policies that support these practices as well as policies that minimize N emissions for the maximum environmental benefits. Design of these policies will require further analysis of their environmental and economic impact, as well as their direct cost.

As noted, the technologies that provide most of the benefit to food and biofuel production are extensive double cropping and large-scale production of diverse cellulosic crops appropriate to different regions of the country. These are not exotic, expensive, or high-risk technologies. Considering their large benefits to energy and climate security, extensive double cropping and production of diverse cellulosic crops deserve more study for widespread application in integrated biofuel and animal feeding systems than they have received to date.

The United States is the world's largest petroleum user and also a significant exporter of agricultural commodities. The analysis of this paper shows that the United States can produce very large amounts of biofuels, maintain domestic food supplies, continue the contribution to international food stock, increase soil fertility, and significantly decrease GHG emissions. If so, then integrating biofuel production with animal feed production may also be a pathway available to many other countries. Resolving the apparent "food versus fuel" conflict seems to be more a matter of making the right choices rather than hard resource and technical constraints. With investment in technology and policy commitments, adaptation of the agricultural system to produce food, animal feed, and sustainable biofuels is possible.

Environmental Issues

First-generation biofuels do have some environmental advantages and drawbacks. For example, corn ethanol provides GHG reductions relative to gasoline, and gasoline-ethanol blends tend to burn more cleanly than straight gasoline.[6] Increased corn production for ethanol (particularly on poorer soils), however, will tend to increase soil erosion and could increase N losses to streams, rivers, and eventually the Gulf of Mexico, enlarging the anoxic zone there (Donner and Kucharik 2008).

Second-generation biofuels, particularly those based on perennial grasses, are likely to provide significant environmental improvements, especially if the overall system is designed to supply environmental, as well as economic, benefits. Perennial grasses tend to build soil organic matter over time, thereby increasing soil fertility; they essentially eliminate soil erosion, provide better wildlife habitat, improve water quality, and effectively capture N and other nutrients. Furthermore, ethanol from cellulosics decreases life cycle GHG emissions by approximately 90% compared with gasoline (Farrell et al. 2006). A major advantage of the double-cropping system described earlier is that it provides some features of perenniality (e.g., year-round ground cover) while preserving farmers' flexibility regarding planting decisions.

Plant Nutrient Issues in Biofuel Production

Given the need for fuels and the availability of plant matter at energy equivalent prices well below those of petroleum, it will almost certainly be possible to overcome the technical obstacles that currently limit expansion of biofuels. Efficient use of land to grow plants for biofuel production, however, will require increased nutrient inputs overall and possibly limit the potential of biofuel production (Murrell et al. 2011).

Regarding the environmental issues discussed previously, it is necessary to think of the whole system and work to improve its overall performance rather than focusing exclusively on small pieces of the system. The fundamental fact regarding plant nutrient issues is that the important fuel atoms are carbon and hydrogen. Ideally, there should be no other chemical elements in our fuels. Thus, there will be a strong incentive to recover and recycle plant nutrients (N, P, K, etc.) during the biorefining process in which raw plant matter is converted to biofuel. For example,

[6] Recent studies (Khanna and Crago 2012) suggest that even when taking into account indirect land use, biofuel emits less GHG than gasoline in many cases.

the fermentation residue from biofuel production will likely be burned to recover its energy value and increase the overall energy efficiency of biofuel production. Depending on the system design, the plant mineral nutrients could be concentrated in the resulting ash stream and then might be recycled to the land.

Other contributions to this issue deal with increased production of plant nutrients and greater efficiency in plant nutrient uptake. Biofuel production, however, influences a rapidly growing demand for agricultural and forestry products and potentially a way to reverse the decades-long economic decline in agricultural communities around the world. Therefore, both research and systems analysis are needed to design and implement effective means by which plant nutrients are recovered and recycled in biofuel production processes. This is another prime area for increased attention and research funding.

Land Use and Productivity

Rapid human population growth since 1950 (Table 1) has caused rapidly growing demands for food, water, timber, fiber, and fuel. These demands have impacted ecosystems more extensively than in any comparable time period in human history. Approximately 12% (1.55 billion ha) of total world land area and 32% of agricultural land (4.93 billion ha) is current cropland (FAO 2008). The remaining 3.38 billion ha of agricultural land, primarily (90%) in Latin America and sub-Saharan Africa, are in forests, permanent pasture, and other noncrop uses. Wiebe (2003) estimates these remaining agricultural lands represent only 20% of the yield potential of the most productive cropland, thus cropland expansion in these areas occurs at a large economic cost (poor soil fertility, soil depth, low rainfall, etc.) and great risk to biodiversity, soil erosion, and other factors impacting ecosystem function. The total agricultural land has been relatively constant since 1990, whereas cropland, arable and permanent cropland, has increased slightly (~0.22%/yr), likely into these less productive areas (FAO 2008).

Per capita cropland use decreased nearly 50% from 0.44 ha/person in 1960 to 0.23 in 2007. By 2050, world cropland use will further decrease by approximately 30% to 0.16 ha/person, assuming constant cropland area. If the annual increase in cropland area from 1996 to 2007 continues (~3.38 million ha/yr or 0.22%), then per capita cropland use will be nearly 0.18 ha/person. Per capita cropland assessments are misleading, however, because of the changing distribution of human populations in rural and urban areas. Similar to population growth rate, the rate of urbanization has been decreasing, but the absolute urban population is increasing. For the first time in history, more than 50% of the world population in 2008 lived in urban areas. By 2050, more than 60%, or nearly 6 billion people, will live in urban areas. Therefore, the impact of increasing population on conversion of cropland to urban uses is lessened by the disproportionate expansion of urban areas. Urban population growth, however, commonly occurs on highly productive lands, and urban expansion in developing countries decreases cropland by 0.5 million ha/yr (Rosengrant et al. 2001).

Future food, fiber, and fuel demand obviously will not be met by expanding cropland area. Unfortunately, only an estimated 13% of the global land surface can be considered prime cropland (Class I) or lands with few problems limiting sustainable grain production (Classes II and III) (Table 2). Approximately 76% of the global population resides on the least productive lands (Classes IV–IX). This may seem alarming; however, with equitable food input-export systems and policies, crop production from the most productive lands can meet and has met global food and other resource demands. Although many factors limit grain crop productivity, soil moisture and temperature stresses occur on more than 52% of the land area (Wiebe 2003). A number of soil physical and chemical properties, either natural or *anthropogenic*, also limit cropland productivity.

Expanding cropland into remaining agricultural lands that are substantially less productive than current croplands will limit global crop production growth. For example, Wiebe (2003) suggests that 80% of future increases in crop production in developing countries will come from intensification instead of expansion of cropland. The poorest cropland, unfortunately, occurs in regions with the greatest need to expand production (Wiebe 2003). In developing countries (countries in sub-Saharan Africa, Latin America, etc.), projected croplands will increase only 0.3%/yr or 120 million ha/yr during the next several decades, which is less than in previous decades, whereas little or no increases are expected in developed countries (Bruinsma 2009). Accounting for the decrease in cropland in developed nations, the net gain in cropland is estimated to be only ~70 billion ha.

Because cropland expansion will have minimal impact on total global crop production, increased production on existing cropland areas must occur, which is limited by continued land degradation. Land degradation represents deterioration of one or more land properties decreasing land quality or the ability of the land to sustain a specific function such as crop production (Karlen et al. 1997; Lindert 2000). Because soils are the fundamental component of land, soil degradation leads to land degradation. Soil degradation, both natural and anthropogenic, represents a change in chemical, physical, or biological properties that individually or collectively lowers agricultural productivity or some other ecosystem service. Soil erosion by water or wind, nutrient depletion, compaction, desertification, salinization, and acidification are examples of processes that degrade soils.

Table 2. Distribution of global lands and population[a] in land quality classes[b] (Beinroth, Eswaran, and Reich 2001)

	Land Quality Class[b]	Land Area		Population	
		Million ha	%	Millions	%
Decreasing Land Productivity	I	409	3.13	337	5.87
	II	653	5.00	789	13.75
	III	589	4.51	266	4.63
	IV	511	3.91	654	11.40
	V	2,135	16.35	1,651	28.77
	VI	1,722	13.19	675	11.76
	VII	1,165	8.92	639	11.13
	VIII	3,696	28.30	103	1.79
	IX	2,178	16.68	625	10.89
Total		13,058	100.00	5,739	100.00

[a]Population only between 72°N and 57°S latitudes.

[b]Includes risk for sustainable grain crop production: Class I, <20%; Class II, 20–30%; Class III, 30–40%; Classes IV–VI, 40–60%; Class VII, 60–80%; and Classes VIII–IX, >80%. Class I: Few soil limitations restricting use for crop production. Class II: Moderate soil limitations restricting crop choice or requiring moderate conservation practices. Class III: Severe soil limitations restricting crop choice and/or requiring special conservation practices. Class IV: Very severe soil limitations restricting crop choice and/or requiring very careful management. Class V: Soils subject to little or no erosion but have other limitations, impractical to remove, that restrict use to pasture, rangeland, forestland, or wildlife habitat. Class VI: Severe soil limitations; generally unsuitable for cultivation; use restricted to pasture, rangeland, forestland, or wildlife habitat. Class VII: Very severe soil limitations; unsuitable for cultivation; use restricted to grazing, forestland, or wildlife habitat. Class VIII: Soils and miscellaneous areas have limitations precluding commercial plant production; use restricted to recreational, wildlife habitat, watershed, or esthetic purposes. Class IX: Mainly the deserts where biomass production is very low.

Continued degradation of world soil productivity threatens the ability to meet future global food and fiber demands. The Global Assessment of Soil Degradation (GLASOD) estimated that nearly 2 billion ha (15% of total global land area; 23% of 8.7 billion ha used for crops, pasture, and forests) had been degraded by human activity (Oldeman, Hakkeling, and Sombroek 1991). Although soil degradation varies widely between regions (developed vs. developing), approximately 38% of the world's cropland has degraded (USDA–ERS 2008). By region, 65% of cropland in Africa, 51% in Latin America, 38% in Asia, and 25% in North America, Europe, and Oceania have been degraded. Approximately 2 million ha of rain-fed and irrigated agricultural lands are lost to production every year because of severe land degradation, which increases the productivity demand on the remaining croplands while increasing pressure on converting less-productive land into cropland (Oldeman 1994).

Water erosion represents the most important mechanism for loss in cropland productivity, whereas overgrazing, deforestation, and agricultural activities are the greatest causes of soil degradation worldwide (Oldeman, Hakkeling, and Sombroek 1991).

Using GLASOD data, Crosson (1997, 1998) concluded that from 1945 to 1990 average annual productivity declined 0.4%. Of the 8,700 million ha used by humans, however, cumulative productivity decreased 5% or 0.1%/yr during the 45-year period. Oldeman (1998) also reported cumulative cropland and pasture productivity losses from 5 to 9% or 0.1 to 0.2%/yr, although in some regions cropland losses were considerably higher (25% or 0.5%/yr in Africa and 37% or 0.7%/yr in Central America). In North America cropland productivity losses are much lower, with estimates ranging from 0.0 to 0.1%/yr (0.04%/yr average) depending on crop, slope, and management (Alt, Osborn, and Colacicco 1989; Crosson 1986; Pierce et al. 1983). Averaging over regions, Wiebe (2003) estimated a 0.1 to 0.3% global average annual erosion-induced decline in cropland productivity, depending on level of adoption of conservation and other management practices.

Although it is difficult to quantify and few studies are available, one can use the estimates of Wiebe (2003) to evaluate the potential impact of soil degradation on cropland productivity. Assuming an average annual productivity loss of 0.3%, combined with the 1961–2007 cereal yields (Figure 3), the potential increase in cereal yield can be estimated assuming the 0.3%/yr yield loss had not occurred. Using linear estimates of total cereal production (MMt) and yield (kg/ha), a 0.3%/yr adjustment was made for 1961–2050 (Figure 9).

These data demonstrate that in 2007 an additional 400 kg/ha cereal yield could have been produced. By 2050, approximately 1,000 kg/ha or 19% more cereal yield was possible. Adjusting for world cropland area in cereals, an additional 278 MMt could

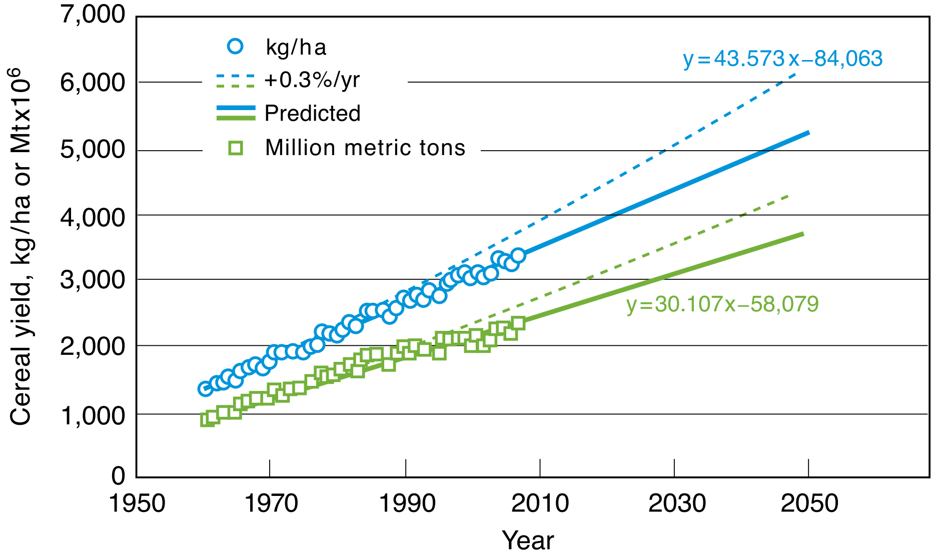


Figure 9. Historical projected trends in cereal production (MMt) and cereal yield (kg/ha) under current levels of soil degradation and those corrected for a 0.3%/yr loss in cereal productivity (FAO 2008; Wiebe 2003).

have been produced in 2007, whereas more than 700 MMt of cereal grains could have been available in 2050. As documented previously, the FAO (2006) projects a global cereal demand of 350 kg/person/yr (Figure 1). Under projected growth in population and cereal production (assuming relatively constant cereal cropland area), nearly 400 kg/person/yr will be needed and likely can be produced (Figure 10). Adjusting these projections for the 0.3%/yr loss in productivity, nearly 470 kg/person/yr was possible without the deleterious effects of soil degradation.

Because future increases in food production will come from increased yield per unit of land area instead of increased arable land area, it is imperative that efforts to sustain and enhance soil productivity be increased, especially in developing countries. Continued trends in soil degradation will jeopardize the capacity to meet future food demand. Removal of a significant proportion of field crop residues for fuel production also may lower soil organic matter and accelerate soil degradation, which lessens soil productivity.

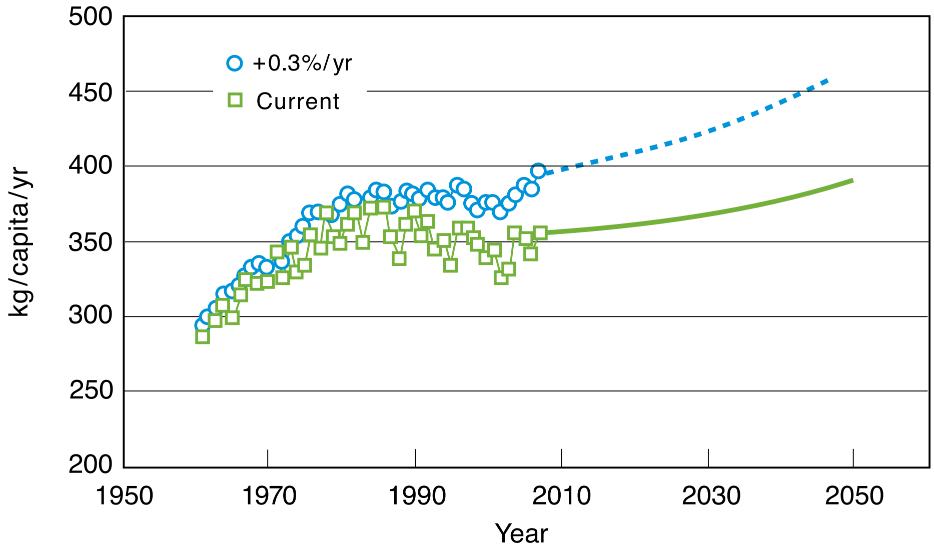


Figure 10. Estimated per capita world cereal consumption. Open squares represent historical and projected cereal production divided by population (UN 2007) to obtain kg/person/yr. The open circles represent kg/person/yr adjusted for the 0.3%/yr loss in productivity.

Applied Nutrients and Nutrient Availability

Plant nutrients are essential inputs for all forms of crop production, and meeting future societal needs will require careful attention to plant nutrition. A recent review of long-term studies showed that estimates of the contribution of commercial fertilizers to food production generally ranged from 40 to 60% in the United States and England and tended to be much higher in the tropics (Stewart et al. 2005). Estimates made at the end of the millennium were that fertilizer-N alone was responsible for supplying the basic food needs of at least 40% of the population and that population growth and increasing prosperity would eventually increase that estimate to at least 60% (Smil 2001). Any meaningful evaluation of the future of food or biofuels must consider the plant nutrients involved in their production.

Historical Nutrient Use and Crop Removal in the United States

Realistic contemplation of future nutrient use is facilitated by an understanding of past and current nutrient use, especially in light of nutrients removed in crop harvest. Fertilizer consumption in the United States increased rapidly from the early 1960s to 1980, then experienced a few turbulent years resulting in a decline in use in the mid-1980s (Figure 11) (Slater and Kirby 2011). Since approximately 1986, N fertilizer consumption has been increasing linearly at a rate of 97,000 Mt per year, reaching nearly 12 MMt in 2007. Consumption of P and K during this same period has been nearly constant except for a sharp decline in 2009 resulting mostly from a spike in fertilizer prices.

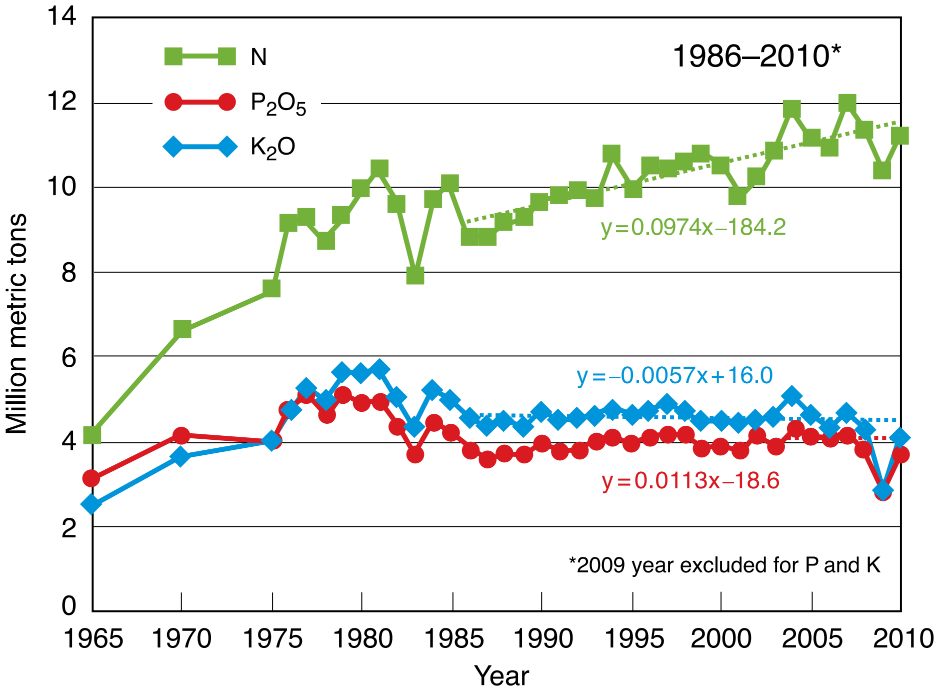


Figure 11. Fertilizer consumption in the United States and trends from 1986 to 2010 (P_2O_5 = phosphate; K_2O = potash).

From 1965 to 2010, crop production increased markedly, driven by increasing crop yields (USDA 2012). Increased yields resulted in increased nutrient uptake by crops and increased removal of nutrients from farm fields. Nutrient removal can be estimated using standard crop removal coefficients (amount of nutrient contained in each tonne of crop removed from the field) (IPNI 2012; Johnston and Usherwood 2002). Figure 12 shows the history of nutrient removal by crops in the United States.[7] Nitrogen removal by alfalfa, soybeans, and peanuts is not included because they are legume crops that fix their own N from the atmosphere and typically receive little N fertilizer. Removal of all three nutrients across the United States has been increasing linearly during this entire period with annual rates of increase of 70, 51, and 67 thousand Mt for N, P_2O_5, and K_2O, respectively.

The primary roles of commercial fertilizer use are to supply plants with the nutrients they cannot obtain from the soil or other sources and, for the soils that are at optimum nutrient levels, replace the nutrients removed by crop harvest. It is instructive to directly compare fertilizer consumption to crop nutrient removal (Figure 13). Since the late 1970s, fertilizer-N consumption has exceeded crop-N removal (excluding alfalfa, soybeans, and peanuts) by approximately 3.5 MMt or 45% of current average removal. In contrast, P removal has exceeded P fertilizer use since approximately 1990, and K removal has always exceeded K fertilizer use due primarily to many soils in the western United States that are indigenously high in plant-available K and generally unresponsive to K fertilization.

Livestock manure is another potentially significant nutrient source for crop production, although it does not represent new nutrients in agricultural systems but rather the recycling of nutrients within systems (Figure 14). Manure nutrients are difficult to account for in nutrient budgets on a national scale because of the partial decoupling of livestock and crop production. The resulting geographic separation of feed production location and consumption location frequently causes accumulation of nutrients in regions of high livestock density, resulting in low nutrient use efficiency.

The USDA–Natural Resources Conservation Service (Kellogg et al. 2000) has estimated that 55 to 65%

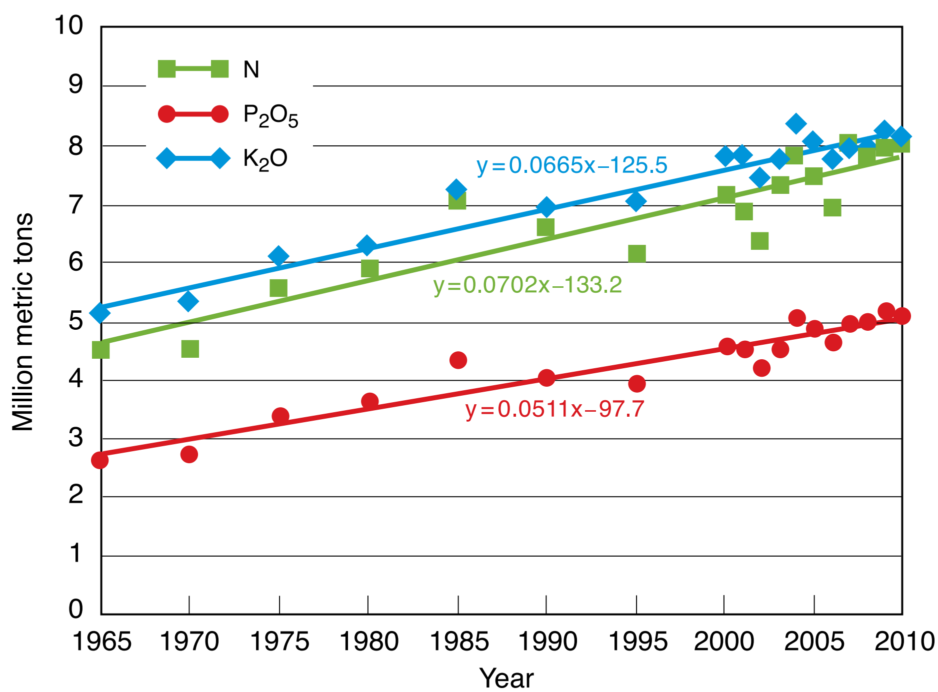


Figure 12. Nutrient removal by crops in the United States (N removal by alfalfa, soybeans, and peanuts excluded).

[7] Removal coefficients used for most major crops are from the IPNI reference. Crops not found in this source are from the older Johnston and Usherwood reference.

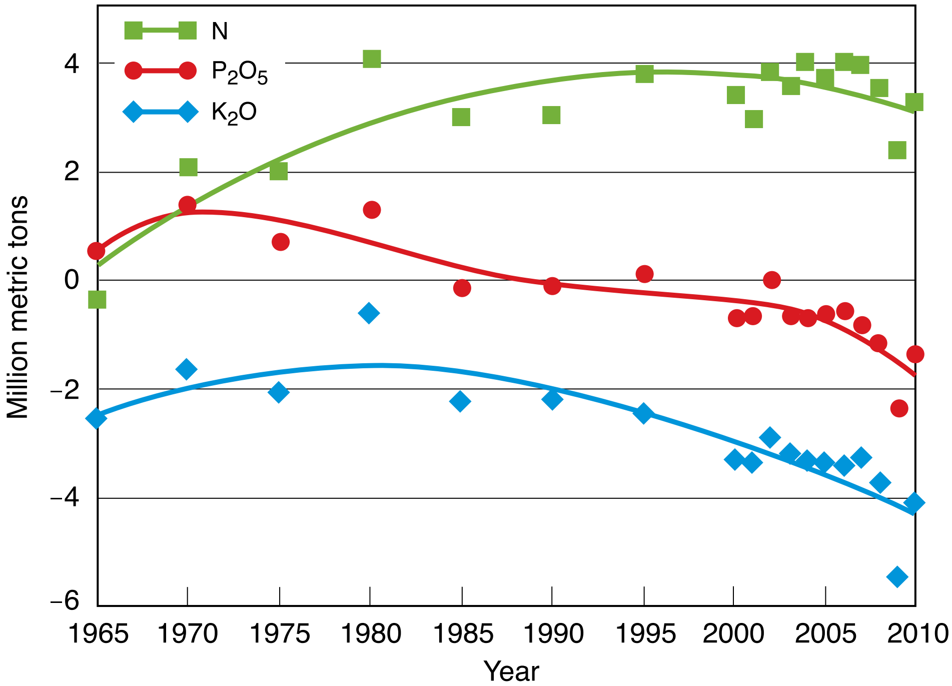
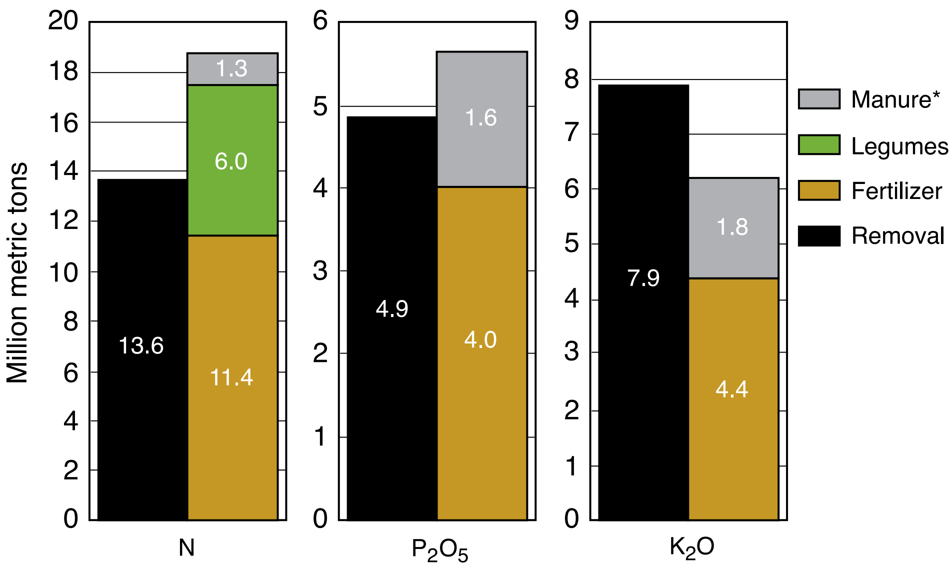


Figure 13. Fertilizer nutrient consumption in excess of crop nutrient removal in the United States (N removal by alfalfa, soybeans, and peanuts excluded).



*Based on 2007 livestock census using Kellogg et al. (2000) procedure.

Figure 14. Comparison of nutrient removal by crops in the United States to nutrient applied as fertilizer, recoverable manure, or fixed by legumes (average of 2006–2008).

of recoverable manure is farm-level excess and may not be usable as a nutrient source because of transportation costs. Recent increases in fertilizer prices have raised the affordability of manure transport, but higher fuel costs have had the opposite effect. Inclusion of recoverable manure-N in the national nutrient budget increases the N in excess of nonlegume removal by 1.3 MMt, for a total excess of approximately 4.8 MMt. Recoverable manure-P more than balances P removal, but the K budget remains substantially negative even with all recoverable manure-K included.

Current Soil Fertility Status and Trends

The implications of the partial nutrient budgets discussed previously regarding fertilizer needs in the near future depend in part on current soil P and K fertility. If more nutrients are removed by crops than are applied, declining soil fertility occurs and at some point in the future when a critical level is reached, nutrient application would need to be increased for yield levels to continue to improve and for the system to remain sustainable. The higher the current level of fertility, the further into the future that point will be encountered.

Soil testing is the primary means by which farmers evaluate soil fertility levels in the United States. Fixen and colleagues (2010) and the International Plant Nutrition Institute (2010) summarized soil test P and K levels in North America from an extensive study of 4.4 million soil samples. These studies revealed that approximately 45% of the soil samples tested below P or K critical levels, meaning that they required annual fertilization to avoid profit loss in most major crops. Similarly, P or K application could be less than crop removal for one or more years for 55% of the samples.

Similar summaries of soil fertility in North America were completed in 2001 and 2005. Comparing soil test levels across the period from 2001 to 2005 at a state or province scale demonstrated that most of North America showed no change in soil-P levels, suggesting that the current practices were roughly maintaining existing soil-P fertility (Fixen et al. 2006). From 2005 to 2010, however, soil-P fertility declined significantly in the Corn Belt where P budgets were negative. Potassium changes across the decade were more complex. Nearly the entire Great Plains showed decreases in soil-K levels, whereas the eastern states or provinces showed no change, a slight increase, or a slight decrease. The highly negative K budgets in the Great Plains will eventually lower soil-K to critical levels, at which point K fertilization will need to increase to sustain improvement in productivity.

A Baseline for Future Nutrient Needs

These historical trends in nutrient use and crop removal combined with current status can be used to establish a baseline for evaluating nutrient use into the future (Table 3). All six parameters included show a decidedly linear trend line from 1986 through 2010, simplifying projections of status quo relationships into the future. These are not projections of expected nutrient needs or nutrient balance, but rather a projected baseline from which such estimates of needs and balance can be made.

- **Baseline fertilizer-N** consumption is increasing at a slightly higher rate than N removal and should increase by 44% in 2050, which would increase N in excess of crop removal from 3.6 MMt currently to 4.8 MMt. However:
  - Higher N prices and environmental concerns are likely to speed both development and adoption of efficiency-enhancing N sources and practices (IPNI 2012) and will likely slow this rate of fertilizer growth.
  - Advances in biotechnology of corn and other crops combined with advances in crop management may accelerate the rate of yield increase over that of the past several decades and increase crop-N demand/removal, resulting in upward pressure on fertilizer use compared with the past. This could be offset if the seed industry succeeds in developing crop varieties exhibiting increased N use efficiency or if management practices are adopted that lead to increased efficiency.
  - Expansion of biofuel production, stimulating additional increases in corn acreage, increased crop biomass removal, or shifting of Conservation Reserve Program land to crops managed for biomass could all increase N use and removal, resulting in additional upward pressure on fertilizer use.
  - The net effect would be that these changes could offset making the original baseline projection of a 44% increase in fertilizer-N application reasonable, or efficiency gains could be large enough to lessen this increase.
- **Baseline fertilizer-P** consumption is increasing at a much slower rate than crop removal and should increase only 12% by 2050, which would further increase the annual fertilizer-P_2O_5 deficit from -0.8 MMt currently to -2.5 MMt.

However:

  - This negative P balance would be greater than all the recoverable manure-P in the United States. Because it is highly doubtful that all manure-P could be transported the distances needed to enable it to be used only where crop needs exist, and because most soil-P levels have either been constant or declining under the current P budget, this additional deficit likely will cause loss of soil-P fertility, resulting in higher fertilizer-P recommendations and higher P use than the baseline projections.
  - Higher P prices should encourage greater use of soil testing, better soil sampling, more sophisticated P placement, and more judicious general P management, which should increase P application accuracy and efficiency. This should lessen the magnitude of P use increases.
  - As with N, advances in crop genetics and technology could increase crop removal and fertilizer-P use.
  - As with N, biofuel developments could increase fertilizer-P use.
  - The net effect indicates that it seems highly probable that fertilizer-P use will need to increase more than the baseline would predict.

Table 3. Baseline projections to 2050 of the balance between U.S. fertilizer consumption and crop nutrient removal using rates of change from 1986 through 2010

	2007 Trend Line	1986–2010 Rate of Change*	2020 Projection	2050 Projection	2050 Balance (applied-removed)
	Million metric tons (MMt)				
Fertilizer-N applied	11.3	0.0974/yr	12.6	15.5	4.8
Crop-N removal	7.7	0.0702/yr	8.6	10.7	
Fertilizer-P_2O_5 applied	4.1	0.0113/yr	4.2	4.6	−2.5
Crop-P_2O_5 removal	4.9	0.0511/yr	5.5	7.1	
Fertilizer-K_2O applied	4.6	−0.0057/yr	4.5	4.3	−6.5
Crop-K_2O removal	8.0	0.0665/yr	8.8	10.8	

*2009 year excluded for P and K.

- **Baseline fertilizer-K** consumption is essentially constant, which by 2050 would increase the annual fertilizer-K_2O deficit to -6.5 MMt compared with the current level of -3.4 MMt. However:
    - This substantial negative K balance with accumulative effects should continue to mine indigenous K from soils of the western Corn Belt and Great Plains. The resulting soil-K depletion will expand the area where K fertilization is common practice and increase fertilizer-K consumption above the baseline projection.
    - As with P, higher K prices should encourage improved K management and should have a positive impact on fertilizer-K effectiveness.
    - Genetics, biotechnology, and biofuel developments—as with N and P—could increase fertilizer-K use.
    - The net effect, as with P, indicates that it seems highly probable that fertilizer-K use will need to increase more than what the baseline would predict.

This baseline evaluation indicates that P and K fertilizer use in the United States will likely need to increase in the future even without adjustments for increases in biofuel feedstock production or exports. Adjustments from the baseline for N have greater uncertainty. The following section will quantify the impacts of biofuels and growth in global food demand on plant nutrient needs in the United States.[8]

Food and Fuel Impacts on Future Plant Nutrient Needs

United States agriculture is challenged by global increases in demand for food resulting from population growth and increases in income in developing countries as well as the emergence of the biofuel industry and the growing role of agriculture in providing both fuel and food. The growing demand for food and fuel, however, is likely to raise the income generation capacity of U.S. farmers, who will become a major contributor in improving the U.S. balance of trade. Continued investment in improved genetic materials and other agricultural technologies is likely to enable U.S. agriculture to keep pace with growing demand for agricultural commodities and continue its leading role in the global food and fuel supply system. The expected growth in agriculture, however, will increase the amount of nutrients consumed in production. The extent to which potential growth of agricultural production will occur depends on the ability to obtain the nutrients required through different means.

Availability of Fertilizer Raw Materials

The raw materials needed for fertilizers are natural resources. Nitrogen fertilizer production uses N from the air and, in most instances, natural gas to create ammonia. The ammonia is then either directly applied or used to manufacture other N fertilizer products. Coal, fuel oil, and naphtha can substitute for natural gas. The cost of natural gas accounts for 70–90% of the production cost of ammonia, so the competitiveness of an ammonia plant in global markets is largely determined by the local cost of natural gas (TFI 2008). The high cost of natural gas in the United States relative to other regions prior to 2010 has caused numerous ammonia plant closures. New discoveries of natural gas reserves, mostly through the development of "*fracking*," and the prospect of further discoveries, however, have decreased the price of natural gas and are likely to decrease the price of N-based fertilizers, reversing a long-lasting trend (*The Economist* 2012).

Commercial P_2O_5 fertilizers are processed from mined P_2O_5 rock concentrated in geologic deposits in various parts of the world. At approximately 26 MMt/yr (7.5 MMt P_2O_5 equivalent), the United States currently is second only to China in P_2O_5 rock production and contributes more than 15% of the world's P_2O_5 rock. Based on rock value, cost of extraction, and 2009/2010 mine production, the U.S. Geological Survey has estimated U.S. P_2O_5 reserve life at 53 years (USGS 2011a). Life estimates increase markedly if higher value is attributed to the P_2O_5 rock as more of the U.S. P resources become economically minable. The U.S. Geological Survey has estimated world rock reserve life at 380 years at 2009/2010 production levels. A study of world P_2O_5 rock reserves and resources by the International Fertilizer Development Center provided similar estimates for U.S. and world reserves of 69 years and 351 years, respectively, based on 2009/2010 production levels (Van Kauwenbergh 2010).

Potash is also mined from extensive geological deposits, with the largest known economically minable deposit located in Canada. More than one-fourth of the world's K_2O production comes from Canada, and nearly half the world's known K_2O reserves are located within its borders (USGS 2011b). United States K_2O production is currently 0.8 MMt/yr, equivalent to about one-fifth of domestic consumption. World K_2O reserve life is estimated at 353 years at 2009/2010 production levels. As for P_2O_5, however, the reserve life estimates increase significantly if higher value is attributed to the K_2O ore.

The world supply of raw materials needed for fertilizers should be sufficient to meet anticipated growth in demand. Future P and K needs in the United States will be met to an increasing extent by imported raw materials or final products, whereas future N needs could be met primarily by North American production

[8] Predictions are consistent with the Association of American Plant Food Control Officials and The Fertilizer Institute concerning N and somewhat higher concerning P and K fertilizers.

if current natural gas prices remain globally competitive.

Conclusions and Recommendations

Escalating population is the primary driver in increasing crop production and nutrient use. In addition to population gains, per capita caloric intake in developing regions will increase much more than in developed regions, further enlarging food and nutrient demand.

Societal food and fuel needs are growing, and in order to increase current scale of production under decreasing amounts of land, a reliable supply of plant nutrients to replace those removed by cropping is essential. Commercial fertilizers are responsible for 40 to 60% of current U.S. food production. For more than 40 years, removal of the three primary plant nutrients by crops in the United States has been increasing linearly at rates of 70,000, 51,000, and 67,000 Mt of N, P_2O_5, and K_2O per year, respectively. If crop yields increase at a faster rate in the future, these rates of removal will likely increase further.

For more than 20 years, P and K fertilizer use in the United States has been increasing at considerably lower rates than crop removal, with increases of 11,000 Mt of P_2O_5 per year and essentially no change in K_2O use. The combination of soil nutrient reserves indigenously present or developed from past fertilization and the use of recoverable manure nutrients has supplemented the negative nutrient budgets of the past 20 years to sustain the productivity increases during this period. Evaluation of existing soil fertility levels and the supply of recoverable manure nutrients suggest that the nutrient budget deficits must be lessened in the future to sustain current productivity increases. Any additional nutrients removed from cropping systems as a result of bioenergy production will intensify the need for more balanced P and K budgets. The net effect would be that future P and K fertilizer use will need to increase or more nutrients will need to be recovered and recycled from farm and nonfarm waste streams.

If fertilizer-N use follows the trend of the last 20 years, it will increase 44% by 2050. Improved N use efficiency could lessen this increase but likely will not eliminate it. Therefore, U.S. agriculture will conceivably be more dependent on commercial fertilizer N in 2050 than it is today. Higher prices of natural gas in the near past decreased the domestic capacity of N, yet it has to be expanded to meet the challenge of the future. Application of future N may need to be more precise to address environmental concerns. Phosphate reserves in the United States are estimated to be equivalent to a 50- to 70-year supply at current production rates but increase substantially at higher rock prices. Domestic K_2O production is equivalent to only approximately 20% of consumption with world reserves equivalent to 350 years or more at current production rates.

The increased demand for biofuels has a direct impact on the use of nutrients. There is an urgent need to support research and development to decrease total land requirements for biofuel production by integrating animal feed production with cellulosic biofuel production and to recover and recycle key plant nutrients during biofuel production.

Glossary

Anoxic zone. An area deficient in oxygen.

Anthropogenic. Relating to the influence of human beings on nature.

Biofuel. A fuel composed of or produced from biological raw materials.

Biomass. Plant materials and animal waste used especially as a source of fuel.

Biorefinery. The processing facility that converts crops to fuels.

Cellulosic. Of, relating to, or made from cellulose, a polysaccharide of glucose units that constitutes the main part of the cell walls of plants.

Double crops. Planting a second crop after the first has been harvested.

Evapotranspiration. The process that takes water from the soil, passes it through the plant, and releases water vapors into the atmosphere.

Fracking. High-volume hydraulic fracturing or horizontal industrial-scale gas drilling to access deep shale formations.

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