# *Scientific Challenges Underpinning the Food-Versus-Fuel Debate*

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Humanity has enjoyed a unique period of food surplus since the green revolution began in the mid-1960s. Since then, population doubled, food prices steadily decreased, and the proportion of malnourished has been reduced substantially. These conditions laid the foundation for sustained economic development in a large number of countries, including those with the largest populations. In the past two years, however, there has been an abrupt reversal of trends in food cost and availability as prices for the major cereals have tripled. This paper briefly reviews the factors responsible for this reversal and explores the implications for research and technology development in the basic and applied plant and crop-production sciences.

## Megatrends Affecting Food Supply and Demand

Human population is projected to stabilize at something over 9 billion by mid-century (United Nations Population Division, 2008). From 2008 to 2020, however, population growth will average about 77 million people per year—equivalent to an annual growth rate of 1.2% of the current population (6.7 billion). Rapid economic development in the world's poorest and most populous countries is the primary factor contributing to the expected reduction in population growth because female fertility has a strong negative correlation with income, which, in turn, is highly correlated with education—especially for women.

Both per-capita food consumption and energy use increase markedly as incomes rise (Naylor *et al.*, 2007). As incomes rise from low levels, people consume more livestock products, which increases total grain requirements because 1 kg of meat or dairy product requires 2 to 3 kg of grain as feed (Delgado *et al.*, 2002). Per-capita energy use increases with rising incomes because people can afford improvements in comfort and quality of life through climate control (heating, fans, air conditioning), household lighting, cooking energy, and transportation. Thus, both cereal and energy production must increase more rapidly than population to meet demands of a wealthier human race on the road to zero population growth.

But current transportation technology requires enormous amounts of liquid motor fuels at a time when petroleum use exceeds petroleum discovery. Hence, the price of petroleum has increased more than five-fold in the past 10 years. Most of the world's known petroleum reserves are located in politically unstable countries, which further add to prices due to supply uncertainty. The high costs and uncertainty of supply provide strong motivation for investment in biofuels made from crops, and a number of countries have enacted favorable policies and incentives to foster a rapid expansion of biofuel production. In the United States, ethanol production from corn has doubled to 30 billion liters per year since 2005; biorefineries to produce another 20 billion liters per year are currently under construction. Brazil is rapidly expanding its production of sugar-cane ethanol, Europe and Canada are expanding biodiesel production from canola oil, and Indonesia and Malaysia expect to greatly increase biodiesel production from palm oil.

At current petroleum prices, the highest value use of corn is as feedstock for biofuel rather than for human food or livestock feed (CAST, 2006). As a result, the amount of corn used for ethanol is rising rapidly; about 25% of US corn production will be used for ethanol in 2008, which represents about 10% of global corn supply.

Because the amount of arable land suitable for intensive crop production is limited, the use of food/feed crops for biofuels is placing tremendous pressures on global food supply and on land and water resources. Although irrigated agriculture produces about 40% of global food supply on 18% of total cultivated area (Cassman and Wood, 2006), water resources available for irrigation are decreasing due to competition from other economic sectors (Postel, 1998; Rosegrant *et al.*, 2002) and climate change (Vörösmarty *et al.*, 2000). Moreover, the net effects of climate change on crop productivity appear to be negative in many cases because adverse impacts of higher temperatures offset benefits of increased atmospheric $CO_2$ (Peng *et al.*, 2004; Lobell and Field, 2007).

In the face of these megatrends, and given limited funding, research prioritization is crucial to ensure global food security and protection of environmental quality for future generations. Clear understanding of the most critical scientific issues to meet these challenges is central to effective prioritization.

## Scientific Challenges to Ensure Food Security

Cereal crops account for nearly 60% of all calories in human diets. The area devoted to cereal crops has decreased by 1.8 million ha per year since 1980, while global expansion of urban areas is expected to require 100 million ha of additional land by 2030 (FAO, 2002). Most of this urban expansion will occur on prime agricultural land because cities were located near their food supplies before modern transportation systems and global food trade. Moreover, the relative rate of gain in crop yields has been declining steadily since release of the semi-dwarf crop varieties that initiated the green revolution in 1966 (Table 1), and these rates of yield gain are not sufficient to meet projected demand on existing arable land (Cassman, 2001). Therefore, ensuring an adequate supply of crop commodities for food, livestock feed, biofuels and biobased products without a large expansion of crop area into rainforests, wetlands and grassland savannahs will require massive increases in crop yields on existing farm land. Given these trends, there is an urgent need to accelerate crop yields to rates well above the historical trajectories of the past 40 years, while at the same time protecting soil and water quality and reducing greenhouse-gas emissions.

*TABLE 1. GLOBAL RATES OF INCREASE IN YIELDS OF MAIZE, RICE, AND WHEAT FROM 1966 TO 2006 BASED ON DATA FROM FAOSTAT (HTTP://FAOSTAT.FAO.ORG/SITE/497/DEFAULT.ASPX).*

| Crop | Mean yield 1966 | Mean yield 2006 | Linear yield growth rate[a] | Proportional rate of gain 1966 | Proportional rate of gain 2006 |
|---|---|---|---|---|---|
| | ($kg\ ha^{-1}$) | | ($kg\ ha^{-1}\ yr^{-1}$) | (%) | |
| **Maize** | **2,260** | **4,759** | **62.5** | **2.8** | **1.3** |
| **Rice** | **2,097** | **4,235** | **53.5** | **2.6** | **1.3** |
| **Wheat** | **1,373** | **2,976** | **40.1** | **2.9** | **1.4** |

[a] Linear growth rates in yield are based on regression of global average yield for each cereal on year over 4 decades, from 1966 to 2006. $R^2$ values for linear regression are: maize = 0.94, rice = 0.98, wheat = 0.97.

Accelerating yield growth while reducing the environmental footprint of agriculture is a process called "ecological intensification" (Cassman, 1999). It is one of the most difficult scientific challenges facing humankind and requires an integrated, interdisciplinary systems approach. For example, yield growth during the past 40 years has relied equally on crop genetic improvement and improved management of crops and soils (Fig. 1). But even with development of powerful new technologies that supported growth of US corn yields since 1966, the negative environmental effects from intensive agriculture were not avoided.

Another major challenge is to increase crop-yield potential, which is the maximum yield an adapted crop cultivar or hybrid can achieve when grown without limitations from water, nutrients, or pests (Evans, 1993). Because it is not possible for all farmers to achieve the perfect management required to reach yield potential, national crop yields stagnate when average farm yields reach 80–85% of the yield potential ceiling—as has occurred for rice in China, Japan, and Korea (Cassman *et al.*, 2003). It is, therefore, crucial to maintain an exploitable gap between average farm yields and yield potential. Unfortunately, yield potential of inbred rice has not increased since the International Rice Research Institute released the first modern variety, IR8, in 1966 (Peng *et al.*, 1999), and there is no evidence of an increase in corn-yield potential since 1975 (Duvick and Cassman, 1999; Cassman *et al.*, 2003). Eventually, yield growth will stagnate in a number of other key grain-producing countries unless yield potentials can be increased.

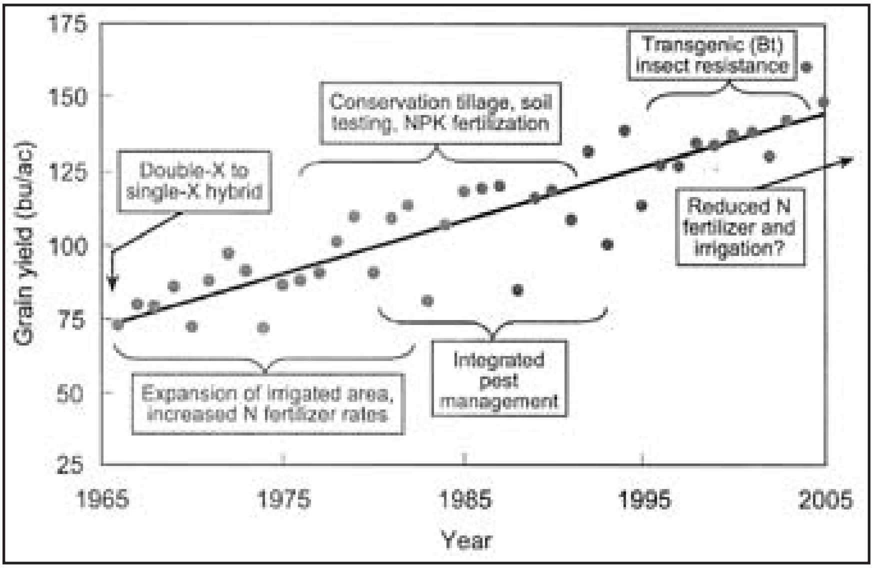

Figure 1. US maize-yield trends from 1966 to 2005, and the technological innovations that contributed to this yield advance. The rate of gain is 112 kg $ha^{-1}$ $yr^{-1}$ ($R^2$ = 0.80). Modified from CAST (2006).

Given these trends, the most critical scientific challenges are:

- closing the existing exploitable yield gap while protecting environmental quality,
- achieving large improvements in water and nitrogen use efficiency, and
- increasing the yield potential ceiling of the major food crops.

## Opportunities for Biotechnology and Plant Molecular Sciences

Commercial success of transgenic crops and excitement about future contributions of genomics and metabolic engineering have motivated an enormous increase in funding for biotechnology research since the mid-1990s, in both the public and private sectors. To date, however, *Bt* insect resistance and Roundup-Ready® herbicide tolerance have had the major impacts from biotechnology, although both breakthroughs were made in the 1980s and incorporated into transformed plants in the early 1990s. Since the release of *Bt* and Roundup-Ready® crop varieties there has been relatively little commercial impact from biotechnology despite huge investments. At issue, therefore, is whether a framework can be developed to improve identification of plant traits that are amenable to transgenic solutions.

Denison and colleagues (2003) proposed a global hypothesis to address this issue. They hypothesized that traits conferring general advantages for individual plant fitness in competing against other plants of the same or different species would likely have been optimized by the evolutionary process over millions of years and would, therefore, not easily be improved by conventional breeding or biotechnology. Such traits include photosynthesis, respiration efficiency, drought tolerance, and nitrogen-use efficiency. They argue that selection pressure would have either accepted or rejected genetic modifications based on up- or down-regulation of gene expression, or changes in protein conformation and enzyme activity. Moreover, evolution is relatively efficient at fine-tuning a biochemical pathway to optimize performance under a given set of environmental conditions. For example, there are nineteen independent cases of parallel evolution that developed C4 photosynthesis from a C3 progenitor—a process that requires modifications to numerous genes. In contrast, evolution would not have had the time to optimize traits that confer collective advantages to a community of similar plants of the same species, as found in a farmer's field, because agriculture originated only 10,000 years ago. Hence, traits amenable to rapid genetic improvement, via both conventional means and biotechnology, include short plant stature (semi-dwarf rice and wheat), non-shattering grain, and resistance to diseases and insect pests that are more common in monoculture environments.

Looking to the future, and given the need for average farm yields to approach the genetic yield potential ceiling, transgenic solutions are likely to help develop resistance to diseases that thrive in crop stands of high plant density, large leaf area, and high nutrient concentration—especially of nitrogen. A large, nitrogen-rich leaf canopy is essential for high yields, yet nitrogen-rich plants are more susceptible to a number of important diseases. Moreover, disease progression is more rapid and yield loss more severe in nitrogen-rich leaf canopies. Examples include blast and sheath blight in rice, grey leaf spot and several stem diseases in corn, and powdery mildew and rusts in wheat. Other promising traits for genetic manipulation include those that confer advantages to changes in climate or soil fertility that did not occur in pre-agricultural times, and thus variants adapted to these changes may have been rejected by past selection pressure (Denison, 2006). New objectives, such as improvements in grain quality for specific end uses or for biofuels and biobased products also are highly amenable to genetic manipulation, especially through biotechnology.

## Validation of Transgenic Progress

The large investment in biotechnology research is yielding an increasing number of publications that declare improvements in yield, drought tolerance, or nitrogen-use efficiency. A common oversight in these reports is that transformed plants are compared only against the parent, which in most cases is not the best performing commercial cultivar or hybrid. Comparisons must, therefore, include the best-performing commercial varieties. Claims based on greenhouse or growth-chamber experiments are another concern. Sometimes plants are grown in a nutrient solution for comparisons of nutrient efficiency. While such studies provide controlled conditions for evaluating gene expression and physiological processes, they do not predict yield or efficiencies under production-scale field conditions. Even studies conducted in small field plots are not adequate, because harvest areas are too small to avoid border effects. Instead, valid documentation of putative transgenic crop improvements for traits such as yield, drought tolerance, and nitrogen-use efficiency must be made in large, replicated field plots with appropriate agronomic management. Such tests must also be conducted in the target environment, which adds the additional burden of regulatory approvals, field sanitation, and biosafety standards. In summary, all reports to date of increased yield or yield potential, drought resistance, or nitrogen-use efficiency—that I am aware of—are premature because they do not document improvement compared to the best commercial cultivars or hybrids under appropriate ranges of relevant field conditions.

## Biofuels Derived from Non-Food Crops

Some suggest that a transition to second-generation biofuels made from non-food crops will reduce food-versus-fuel concerns because cellulosic biomass crops will be grown on marginal land and will not compete with food crops for prime agricultural land. In reality, there may be no such decrease in pressure on food crops. If petroleum prices remain high, biofuels will be made both from food crops and cellulosic crops, such as switchgrass and poplar. In addition, large-scale deployment of cellulosic crops to produce billions of gallons of annual biofuel production is at least 10 years away. In that time, biofuel production capacity from food crops like corn and sugar cane will build out rapidly.

## Final Comment

Humanity is in a race against time to ensure global food security on a planet with limited supplies of arable land, water, and low-cost energy resources, and a rapidly growing human population. Biotechnology and plant molecular sciences provide critical tools for meeting the challenge of food security, but they are not silver bullets. Achieving food security and protecting natural resources will require scientific breakthroughs and technology developments from a large number of basic and applied disciplines. Too often, however, plant molecular geneticists and biotechnologists claim breakthroughs that lack theoretical justification or appropriate validation. This situation highlights the need for greater involvement of agronomists and ecophysiologists in the prioritization, review and implementation of biotechnology—especially for projects that seek to improve complex traits such as yield potential, drought tolerance, and nitrogen-use efficiency. Ecological intensification is possible, but it will take a substantial increase in research funding with appropriate focus and collaborations.

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