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The Role of Biotechnology in a Sustainable Biofuel Future

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Biofuel production has increased dramatically since 2000, impacting markets for food and fuel. This article uses a partial equilibrium model to simulate biofuel impacts. We find that US biofuel production imposes costs on food consumers but benefits gasoline consumers by reducing gas prices. Current biofuels, therefore, create a trade-off between food and fuel. The demand for agriculture to provide food and fuel to a growing world population creates an imperative for improved agricultural productivity. Biotechnology and transgenic crops can be powerful drivers of productivity growth, but it demands increased investment and reduced regulation. We argue that biotechnology is essential to reduce land-use changes associated with rising biofuel demand that not only reduce biodiversity, but also release greenhouse gases into the atmosphere.

Key words: biotechnology, climate change, ethanol, biofuel, greenhouse gas emissions, agricultural productivity, transgenic crops.

Introduction

US fuel ethanol production quadrupled between 2001 and 2007 to reach 6.1 billion gallons. Global ethanol production also exhibited tremendous growth, reaching 13.1 billion gallons in 2007. Much of this growth was in response to high energy prices since 2004 and was made possible by policies in the United States and elsewhere that subsidized ethanol production and imposed minimum-use requirements.

Biofuels have been promoted by governments around the world because they are perceived to reduce greenhouse gas emissions relative to fossil fuels, improve energy independence, and spur rural development. While existing biofuel technologies have been shown to increase farm income in theory and in practice (see, for instance, Hochman, Sexton, & Zilberman, 2008; US Department of Agriculture, Foreign Agriculture Service [USDA FAS], 2008), the extent to which they achieve other policy objectives has been questioned in the literature. Carbon emissions savings from corn ethanol relative to fossil fuels are marginal at best (Farrell et al., 2006). Corn ethanol and other first-generation biofuels (sugarcane ethanol and biodiesel from soy, canola, and palm oil) may, in fact, increase emissions over the next century if they induce land-use changes that are not properly managed (Fargione, Hill, Tilman, Polasky, Hawthorne, 2008; Searchinger et al., 2008). And while biofuel production has grown markedly in recent years, it represents only 3% of world oil consumption. Offsetting just 10% of oil imports would require the dedication of between 30% and 70% of total cropland for the United States and the EU (Rajagopal & Zilberman, 2007).

Not only is there mounting evidence that current biofuels do not provide the substantial benefits they were first perceived to offer, but there is also a growing understanding that biofuel production imposes significant costs on environmental preservation and food security. As the world entered its first food crisis in more than 30 years, governments revised their biofuel policies in 2007 and 2008 to target next-generation technologies that reduce the competition between food and fuel for staple crops and land. The United States has reduced growth of conventional ethanol mandates, while accelerating mandated growth in the production of advanced biofuels and cellulosic ethanol, which make use of dedicated energy crops and agricultural residues to reduce land intensity and greenhouse gas emissions (Energy Independence and Security Act [EISA], 2007).

This article provides a conceptual overview of the economics of first-generation fuel ethanol and estimates the impacts of US corn-ethanol and soy-biodiesel production on food and oil markets. We present a dynamic perspective on the causes of growing food insecurity and highlight the role of recent slowing in agricultural productivity growth. We argue that declining rates of productivity growth stem from a depletion of potential gains from the Green Revolution, regulation of traditional farm inputs, declining research and development expenditure, and overregulation and underuse of agricultural biotechnology. With demand for food expected to grow by more than half (and perhaps double) in the first half of the 21st Century, and with increasing

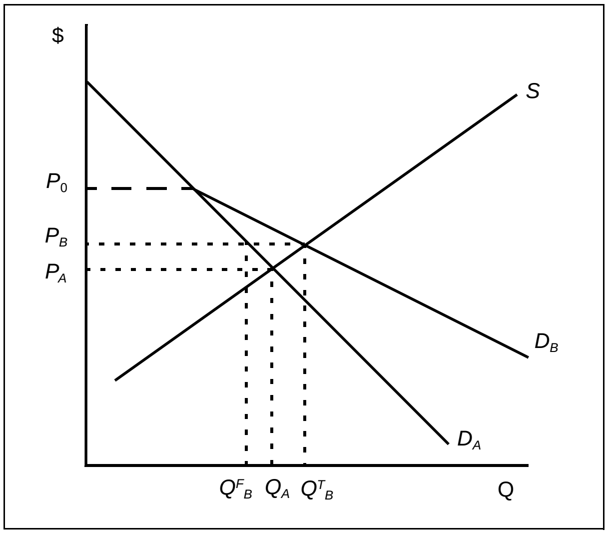

Figure 1. US market for corn.

demand for agriculture to provide transportation fuel, a renewed commitment to biotechnology is needed to produce higher yields and improved biofuel technologies. In short, we need to embrace a Gene Revolution.

The Economics of Biofuel Impacts on Fuel and Food

First-generation biofuels have a direct impact on food and fuel markets by increasing demand for the former, and increasing supply of the latter. Current technologies convert corn and sugarcane to ethanol and soy and oil seeds to biodiesel. Their production, therefore, demands a share of the harvest of staple crops, which has traditionally been used solely for the production of food and feed. Figure 1 depicts the international market for staple crops, where D_A denotes demand for US staple crops when there is no biofuel production. It encompasses demand for food and feed, as well as export demand. We will refer to it as demand for traditional uses. When there is no demand for biofuels, it constitutes total demand for staple crops. Equilibrium is given by the intersection of D_A and supply, S. The equilibrium price is P_0 and equilibrium quantity Q_0, where total output is allocated for food and feed production.

With demand for biofuels, there is another source of demand for staple crops, which can be horizontally added to demand for traditional uses. Above a given price for staple crops, $\overline{P}$, it is unprofitable to produce biofuel given fixed costs of other inputs. Therefore, above $\overline{P}$, there is no demand for staple crops for biofuel. The total demand for staple crops is given by D_B when there is demand for biofuels. There is only demand for staple crops for "traditional uses" above a price of $\overline{P}$. When there is biofuel demand for staple crops, equilibrium is given by the intersection of S and D_B. The equilibrium price is P_1 and equilibrium quantity is Q_1^T. Biofuel production raises the price of staple crops ($P_1 > P_0$) and increases production of staple crops ($Q_1 > Q_0$). The quantity of staple crops available for "traditional uses" including food and feed, however, is given by Q_1^F, where $Q_1^F < Q_0$. The quantity Q_1^T - Q_1^F is used to produce biofuels.

This partial equilibrium model demonstrates the direct effect of biofuel production on demand for staple crops. Biofuels raise the price of staple crops and reduce the availability of staple crops for food, feed, and export. Biofuels also have indirect effects on food markets, which this model ignores. In particular, biofuel production increases demand for agricultural production, which increases demand for farm inputs, including land, water, machinery, and chemicals. As demand for these inputs rises, so too will their prices, ceteris paribus, which increase the marginal cost of agricultural production. In the present model, this effect could be reflected by an upward shift of the supply curve. It would yield higher prices and reduced output, all else equal.

Responsibility for the current food crisis has been principally directed at biofuel policies, and chiefly those of the United States, which have made the United States the single-largest producer of ethanol. Much less noted in the literature, popular press, and policy debate, is the role of biofuels in reducing gasoline prices relative to prices that would have prevailed absent biofuels. Reducing gas prices has, nevertheless, been a policy objective in the United States in spite of stated concerns about greenhouse gases and failed efforts to introduce carbon taxes. The impact of biofuels on the global market for transportation fuel can be modeled by an outward shift in the supply curve, which increases output and lowers prices.

Using the foregoing model, and with assumptions on demand and supply elasticities, we simulate the effect of biofuels in a multimarket partial equilibrium setting in order to characterize the effect of US biofuels on consumers, producers, and total welfare. Importantly, and consistent with intuition, we find considerable benefits accrue to consumers of gasoline who face lower prices with biofuel production than they do without. However, consumers of staple crops suffer, while farmers unambiguously benefit. We refer to the effect modeled in this analysis interchangeably as that of the US conventional biofuel mandate and US biofuel production. This is per-

Table 1. Elasticity assumptions for three scenarios of simulation analysis.

	Scenarios		
	High	**Mid**	**Low**
Own price supply elasticities			
Corn	0.5	0.4	0.3
Soy	0.5	0.4	0.3
Gas	0.3	0.4	0.5
Own price demand elasticities			
Corn	-0.5	-0.4	-0.3
Soy	-0.5	-0.4	-0.3
Gas	-0.3	-0.4	-0.5

mitted given an assumption of no demand for US biofuel excepting mandates. We consider two regions, the United States and the Rest of the World (ROW), and assume that the responsiveness of quantity supplied and demanded to prices—the elasticities—do not vary by region.

As before, we assume demand for corn in the United States is composed of domestic ethanol demand, domestic demand for other uses (such as food and feed), and world excess demand. As in Figure 1, we assume linear supply and demand functions for simplicity. We assume the US market for staple crops clears, and, because the United States supplies 70% of traded corn, we assume the US market determines the global price for traded corn. The soy, ethanol, and gasoline markets are modeled as described in Rajagopal, Sexton, Roland-Holst, and Zilberman (2007).

We provide simulation results for three scenarios, which we call high, mid, and low, depending on the change in net consumer surplus due to biofuels. The high scenario is characterized by an elastic food market and inelastic gasoline market. It is in this scenario that biofuel supply has the largest positive impact on gasoline consumers and smallest negative impact on food consumers. In the opposite scenario, characterized by a highly inelastic food market and a highly elastic gasoline market, food consumers suffer the most and gasoline consumers benefit the least. The mid scenario lies in between. The elasticities we use in the three scenarios are reported in Table 1.[1]

Using data from 2007, in which 18.3% of US corn production was used for ethanol, we find that ethanol raised corn prices at least 18% and perhaps as much as 39%, depending on elasticity assumptions. These results are summarized in Table 2, along with dollar savings per bushel, based on an average price of corn in the United States of $4.72/bushel in 2007. Under reasonable estimates, we find that US ethanol production in 2007 (4.4 billion gallons on an energy equivalent basis) reduced world gasoline prices at least 1.4% and as much as 2.4%. The average cost savings to gasoline consumers from US biofuels was $0.04 to $0.07 per gallon. These results are also reported in Table 2.

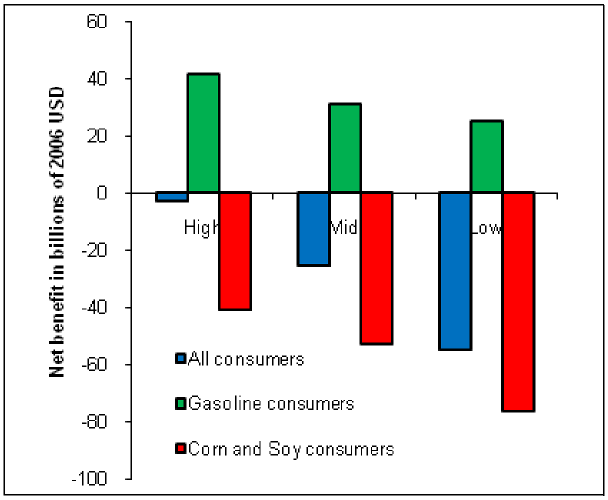

Figure 2. Net benefits to gasoline and food consumers from ethanol supply in 2006.

This analysis finds that under the most optimistic assumptions on biofuel impacts, gasoline consumers around the world benefited from lower gasoline prices by $41.7 billion. Consumers of soybean and corn, however, lost $40.6 billion from higher food prices. On net, consumer welfare declined by $2.6 billion from US ethanol production in the best-case scenario (after deducting the taxpayer cost of ethanol subsidies from net consumer benefits). In the worst-case scenario, world consumers lost $54.8 billion in surplus. These results are summarized in Figure 2. Total US welfare (net US consumer benefit + net US producer benefit) improves by $0.9 billion with biofuel production under the most optimistic ("high") assumptions on elasticities. It declines under the other scenarios considered here. Total global welfare is improved under the "high" and "mid" scenarios by $1.7-18.2 billion, but falls under the "low"

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[1] *Research suggests our "high" scenario may not be too optimistic and may, in fact, be conservative; elasticities for gasoline, soy, and corn tend to be less than 0.25 in the short run. We hold cross-price elasticities between corn and soy constant in all scenarios for simplicity. Although we include the impact of biodiesel on the soy market, we do not estimate the impact of biodiesel production on diesel prices, which also serves to make our estimate of the fuel market impact of biofuels a conservative one.*

Table 2. Price changes from US biofuel production.

	Corn price changes		Soybean price changes			
	% change	Change in dollars per bushel	% change	Change in dollars per bushel	% change	Change in dollars per gallon
High	-15%	-0.72	-10%	-1.00	2.4%	0.07
Mid	-20%	-0.92	-13%	-1.34	1.8%	0.05
Low	-28%	-1.31	-20%	-2.02	1.4%	0.04

Table 3. Welfare impacts of US biofuel production (in billions of dollars).

	High	Mid	Low
Global consumers	-2.5713	-25.2875	-54.8611
US consumers	-3.8153	-10.2098	-19.1565
US consumers net of tax	-7.5303	-13.9248	-22.8715
ROW consumers	4.959	-11.3627	-31.9896
Global gas consumers	41.695	31.2709	25.0166
US gas consumers	9.6271	7.2203	5.7762
ROW gas consumers	32.0678	24.0506	19.2404
Global food consumers	-40.5513	-52.8434	-76.1627
US food consumers	-13.4424	-17.4301	-24.9326
ROW food consumers	-27.1089	-35.4133	-51.23
Global corn and soybean producers	20.7519	27.016	38.8874
US corn and soy producers	8.4425	10.9703	15.7465
ROW corn and soybean producers	12.3095	16.0457	23.1408
Total US welfare	0.9122	-2.9545	-7.125
Total global welfare	18.1806	1.7285	-15.9737

scenario by $16 billion. Table 3 summarizes welfare gains to US, foreign, and all producers and consumers under the three sets of elasticity assumptions.

Our analysis demonstrates that biofuels reduce the price of gasoline to the benefit of gasoline consumers and confirms other reports that biofuels hurt food consumers. Ours is the only analysis to consider distributional concerns, which suggest a tradeoff between fuel for the rich and food for the poor. De Gorter and Just (Forthcoming), however, develop a framework that considers the interaction of biofuel policy with farm policy and find that biofuel support exacerbates inefficiencies associated with farm subsidies.

Our simulations suggests biofuels are responsible for between 25% and 60% of recent corn price increases, which is consistent with reports from the President's Council of Economic Advisors (CEA), the USDA, and the Farm Foundation. These other studies generate a range in the share of food price increases attributable to biofuels of 23% to 61%. A report by the World Bank identified much larger impacts from biofuels on food markets. It found that biofuels were responsible for three-fourths of a 140% increase in food prices from 2002 to 2008, or roughly a 50% increase in the past year (Mitchell, 2008). This estimate is considerably higher than an estimate by the CEA that biofuels raised food prices 1.5% from 2007 to 2008. The World Bank analysis included indirect effects and long-term trends, such as the dynamics of food inventories, while other analyses did not. This may account for the magnitude of the World Bank estimate. The World Bank study, however, included no formal modeling and is based on only a superficial assessment of long-term trends. Further research in this area is needed.

A Dynamic Perspective on Food Price Inflation from 2007-2008

The food price boom that began in 2006 resulted from a number of demand and supply-side forces as well as macroeconomic conditions. While biofuels increased demand for corn and soybeans, they should have had only an indirect effect on prices for wheat and rice. Yet, wheat and rice prices have increased more than prices for corn and soybean. The price spikes in rice and wheat can be blamed on negative supply shocks from bad weather in Russia, Australia, and India over the past several years. Global consumption has exceeded production on several occasions, causing a drawdown in grain inventories. Inventories are at lows not seen since World War II. Because they serve to moderate price fluctuations when negative supply shocks occur, low inventories make food prices vulnerable to even small deviations in supply from long-term trends.

Food market uncertainty led many countries to begin reducing—or even banning—rice exports in 2007 and 2008 in order to moderate domestic prices and ensure supply. Such hoarding by exporting countries further reduced supply to international markets, driving prices higher still and thus inducing more export controls. Export controls particularly hurt poor countries that rely on imports. Had supply not exceeded expectations in 2007 and 2008, international markets for rice could have collapsed entirely (Carter, Rausser, & Smith, 2008).

Low interest rates also contribute to short supply because it becomes cheaper to hold grains in inventory and wait for higher prices to sell. Low interest rates also depreciate the American dollar, which induces greater export demand and raises the prices of food commodities that are denominated in American dollars (Carter et al., 2008).

Short-term trends like low inventories, supply shocks, and monetary policy go a long way in explaining food price inflation that began in 2006. However, the tightness in the market and low inventories would not exist but for long-term supply and demand trends. As the world population rises by half by 2050 and as per-capita income increases, a growing number of people are demanding a growing quantity of food per capita. This demand-side pressure is matched on the supply-side by declining agricultural productivity growth and limited potential for agricultural land expansion. For the first time in nearly a century, agricultural productivity is growing slower than population. These forces provide sustained upward pressure on prices even if they do not explain recent price spikes. Were production increasing faster than demand, there would be hope for a return to low and stable prices.

The Need for Improved Productivity in Food and Biofuel

Until recently, and for more than 30 years, food prices had been stable and supplies sufficient to produce incremental reductions in the number of starving people throughout the world. In fact, food prices fell 75% in real terms from 1974-2005 (*The Economist*, 2007), allowing an entire generation to grow up in an era of cheap food and yielding a sense of complacency about agricultural production and plant science. Human hunger, it seemed, had been defeated by the Green Revolution. But increased demand for agricultural production, combined with negative supply shocks and stagnating productivity growth, produced in 2008 the second-most rapid one-year increase in food prices in history. From March 2007 to March 2008, the world food price index of the Food and Agriculture Organization of the United Nations (FAO) climbed 55%, a rate exceeded only by the doubling of food prices from 1973-1974. These exceptional increases in food prices have resulted in deadly food riots around the world and hunger among the world's poor.

Farmers responded in 2007 to record-high food prices by planting their largest-ever corn crop and their largest cereal and grain crops in a decade. Farmers harvested 157.8 million hectares (ha) of corn in 2007, 10 million ha more than in 2006. They produced the largest harvests in history—784.7 million tons of corn, 2.3 billion tons of cereals, and 1.1 billion tons of coarse grain (FAO STAT, 2008). Consumption growth has kept pace with increases in production, however, and actually exceeded it over the past 10 and 20 years. In fact, consumption has grown more rapidly than production for every staple from 1997 through 2008 (USDA Economic Research Service [ERS], 2008). And since 2000, world annual consumption of corn has exceeded production seven times, indicating a drawdown in corn inventories.

With demand for agriculture to provide food, feed, and fuel to a growing world population and in light of record-high food prices, it is evident that agricultural production must grow. This means either that more land must be recruited into production or that more food must be produced on existing land. While some lands that have been idled amid low prices and relatively abundant food can be brought back into production, it will not be without environmental costs and it will not be sufficient to meet demand. The FAO expects only 20% of production growth to come from land expansion (FAO, 2002). Most of the 51 million ha that will be added to production by 2020 will be concentrated in low-yielding sub-Saharan Africa (von Braun, 2007).

The overwhelming majority of production growth will need to come from improved yields. FAO and IFPRI rely on yield gains to provide 60% of production growth over the next few decades in order for supply of staple crops to meet demand. Yet yield gains have been slowing, not just in developed countries that saw large yield gains from the Green Revolution, but also in developing countries. Yield growth in cereals, for instance, averaged 3% per year during the 1960s, but fell to only 1.3% in the 1990s. It is expected to fall further still over the next decade. Even sustaining current yields will be difficult as yield increases from incremental fertilizer applications are falling and pesticide resistance is growing (FAO, 2008; Ruttan, 2002; von Braun, 2007).

Some suggest agricultural production will need to double in the first half of the 21st Century strictly to feed the world (Johnson, 2000; United Nations, 2001). Given this pressure facing agriculture and the pressure for agriculture to produce clean transportation energy, the world

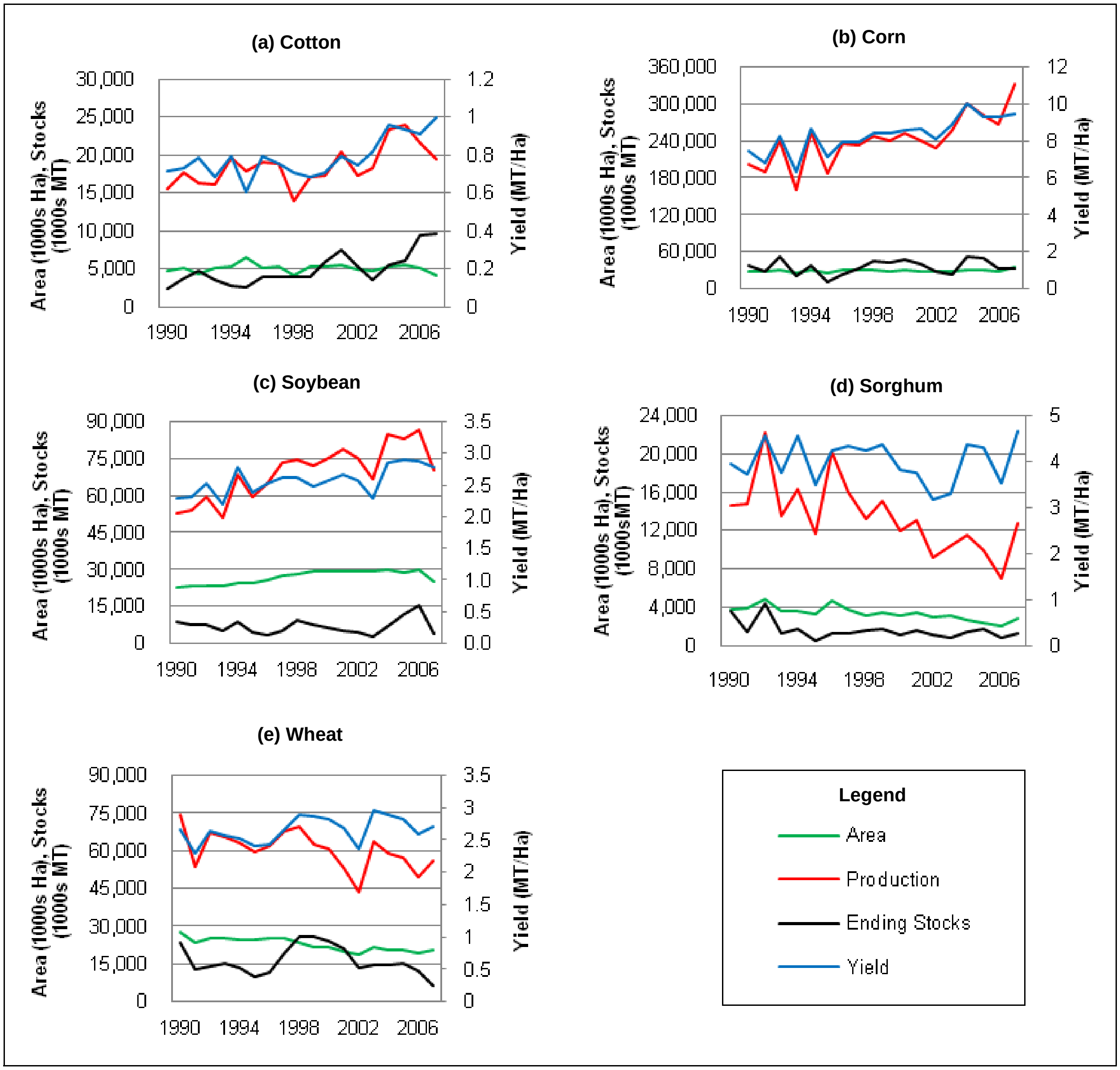


Figure 3. Production, stocks, area harvested, and yields for corn, cotton, sorghum, soybean, and wheat.

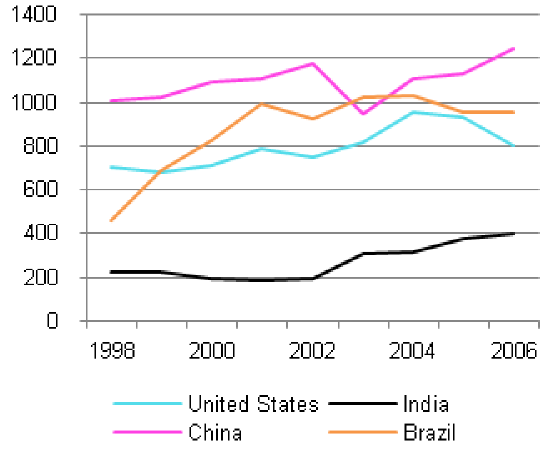
community will need to redouble its commitment to plant science. Genetic engineering of traditional agricultural crops and of new energy crops offers opportunities to increase agricultural production without land expansion and without more intensive use of inputs. Biotechnology can also produce more efficient processes for converting plant material to liquid fuel, meaning more fuel can be produced per unit of farm output. While productivity growth from traditional sources may be uncertain, modern genetic engineering has been shown to be a consistent source of yield gains over more than a decade.

The tools of biotechnology—molecular and marker-assisted selection—have produced a first generation of genetically modified (GM) staple crops that are engineered to either produce Bacillus thuringiensis (Bt), a naturally occurring chemical deadly to common agricultural pests, or offer protection to crops against the common herbicide Round-Up, or both. These traits have been introduced to corn, cotton, and soybean and are intended to reduce pest damage and chemical applications. Since transgenic crops were commercialized in the mid-1990s, a number of studies have shown reduced chemical use on transgenic crops for corn, cotton, and soybean. Yield gains are observed nearly everywhere transgenic cotton is planted, from the United States to South Africa, and from Argentina to China and India (Ismael, Beyers, Lin, & Thirtle, 2001; Qaim & Zilberman, 2003; Thirtle, Beyers, Ismael, & Piesse, 2003; Traxler, Godoy-Avila, Falck-Zepeda, & Espinoza-Arellano, 2001). Transgenic corn has consistently produced higher yields than conventional corn throughout the United States, but yield effects outside the United States remain uncertain because engineered varieties have not been widely adopted. Transgenic soybean in the United States has produced lower yields than conventional soybean, but provided sufficient cost savings from chemical applications to make adoption a profit-maximizing decision (Marra, Pardey, & Alston, 2002).

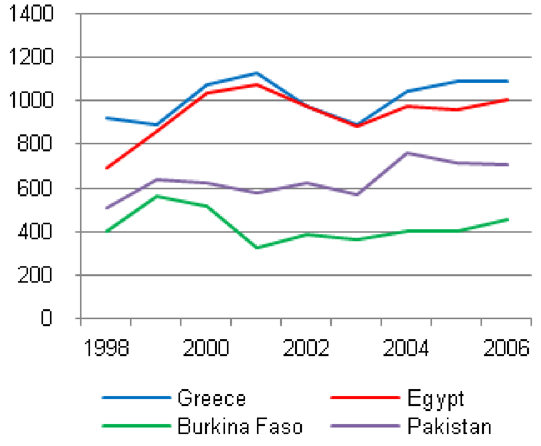
The benefits of transgenic varieties are expected to vary by region and country. In developed countries, where chemical applications effectively controlled pests before adoption of GM crops, adoption will produce small gains in yield but large reductions in chemical use. In developing counties, where pest pressure is high and chemical use is low, adoption of biotechnology is expected to have minimal effects on chemical applications but significant effects on yields. Observed yield effects of transgenic cotton, for instance, vary from 20% to 80% in India (Qaim, Subramanian, Naik, & Zilberman, 2006; Qaim & Zilberman, 2003). Reductions in chemical pesticide use in the United States are as great as 60% in cotton. Given the heterogeneity of biotechnology effects and the “case study” nature of formal analyses, it is difficult to characterize global impacts, except for cotton, which has been widely adopted around the world and consistently produced gains in yields and reductions in chemical use.

Still, a comparison of yield growth between commodities that have transgenic varieties and those that do not suggests biotechnology has been an important driver of yield growth in the past decade. Figure 3 shows yield, production, area, and ending stocks for five staple crops: cotton, corn, soybean, wheat, and sorghum. Panels (a), (b), and (c) depict cotton, corn, and soybean, respectively. All three crops include transgenic varieties that have been adopted to varying degrees. For a simple experiment, they constitute a treatment group. Panels (d) and (e), on the other hand, show crops that have not been genetically engineered, namely sorghum and wheat. They constitute a control group.

Based on observation alone, one concludes that yield growth has been more persistent among crops that include transgenic varieties. Growth seems to accelerate in the mid-1990s, when GM crops were first commercially planted. Sorghum and wheat, on the other hand, show no persistent gains in yield. From 1990 to 2007, corn and cotton yields averaged 2% growth per year. Soybean, a crop for which transgenic varieties were more recently introduced, had yields grow by 1% per year. Wheat grew at only 0.5% per year and sorghum yields actually declined one-tenth of 1% per year. Figure 3 also shows that stocks have declined for all crops except cotton, which has seen the greatest share of acreage planted to transgenic seed. Wheat stockpiles declined from 2000 to 2007 as production stagnated, closely tracking yields. While the foregoing “experiment” does not control for variation in farming practices apart from adoption of GMOs, it does suggest agricultural biotechnology could substantially increase the rate of productivity growth (perhaps doubling the rate of



(a) Countries with GMO varieties



(b) Countries without GMO varieties

Figure 4. Cotton yields, 1998-2006.

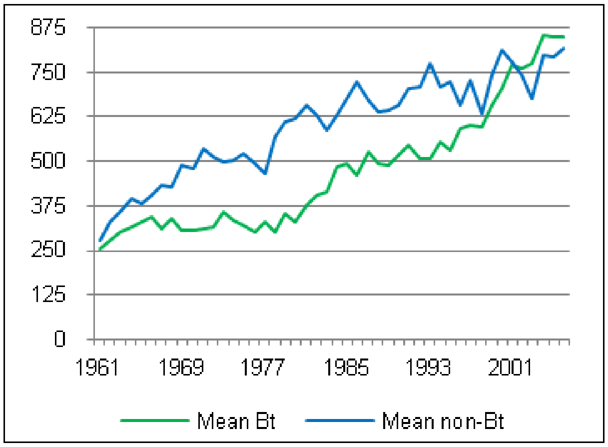


Figure 5. Mean yields by GMO countries and non-GMO countries.

growth) and permit yields to grow at least as fast as population over the next half-century. More detailed analysis of this potential is a topic for further research.

Comparing cotton yields in those countries that have adopted GM varieties and those that have not further demonstrates the importance of GM technologies in providing yield growth in recent years. Figure 4 shows in panel (a) the yields for the four top-producing countries that have adopted GM cotton—the United States, India, China, and Brazil. Panel (b) shows yields for Greece, Egypt, Burkina Faso, and Pakistan, the four top-producing countries that have not adopted GMOs. The average annual yield growth of the former is more than twice the yield growth of the latter from 1998 to 2006. Figure 5 plots mean yields for the four countries that planted GM cotton against the mean yields for the four countries that did not plant GM cotton. It shows countries that planted GM cotton enjoyed persistent yield gains since the mid- to late-1990s, while those that did not plant GM cotton have not seen any stable gain in yields.

Increased productivity in food and feed is important in order to avert future food crises. But so too is improved productivity of biofuels. The first generation of biofuels has made clear the obstacles that must be overcome in order for biofuels to provide a real solution to global food, energy and environmental challenges. First, they will need to compete less intensely for staple food crops to avert future food crises. Second, biofuels will need to offer greater greenhouse gas emissions reductions. And third, biofuels will need to be less land intensive to avoid negative impacts on food and global warming, and to prevent the loss of biodiversity, which some have estimated to be more costly today than global warming (Mooney & Hobbs, 2000).

Table 4. Productivity matters in biofuels.

Crop	Harvestable biomass (tons/ acre)	Ethanol (gal/acre)	Million acres needed for 35 billion gallons of ethanol	% 2006 harvested US cropland
Corn grain	4	500	70	25.3
Corn stover	3	300	105	38.5
Corn total	7	800	40	15.3
Prairie	2	200	210	75.1
Switchgrass	6	600	60	20.7
Miscanthus	17	1700	18	5.8

Source: Heaton, Dohleman, and Long (2008).

Additional innovation in plant science can provide the tools to overcome these obstacles. The path forward is clear, but global progress down that path is uncertain. Emerging plant science can convert cellulosic plants like switchgrass and Miscanthus into liquid fuel, make use of agricultural residues, and turn marginal land into productive land. It cannot yet scale up these processes in a commercially viable way. As described by Chris Sommerville, a leading plant biologist, the challenge is not to invent new processes, but rather to replicate in a commercial setting the processes that occur every day in nature (Sommerville, 2007).

The search for enzymes that break down lignocellulosic biomass and can be mass-produced is perhaps the most critical task undertaken by biotechnologists. They are looking to the digestive ecosystems of ruminants and termites, both of which contain enzymes that efficiently break down plant cell walls. Once efficient enzymes are available in large quantities, potential ethanol feedstocks expand beyond starch-based crops like corn and sugar to the entire class of cellulosic plants, including grasses, trees, and shrubs.

Cellulosic ethanol promises to resolve the most significant problems associated with existing biofuels. Table 4 shows that cellulosic crops, particularly Miscanthus, can greatly reduce the land intensity of biofuel production. Whereas only 4.5 tons of harvestable corn grain are extracted from each acre of corn grain, 13 tons of harvestable biomass is produced on each acre of Miscanthus. Thirteen-hundred gallons of cellulosic ethanol can be produced from each acre of Miscanthus. Only 450 gallons of corn-ethanol are yielded per acre of corn. Under a hypothetical scenario of 35 billion gallons of ethanol production, corn ethanol would demand one-quarter of all harvested cropland in the United States. Miscanthus would need less than one-tenth (Heaton, Dohleman, & Long, 2008). Corn-ethanol is among the most inefficient first-generation biofuel. Sugarcane-ethanol, for instance, yields more fuel per unit of land and less emissions per unit of fuel. Nevertheless, the second generation of biofuels performs better in terms of land and carbon intensity. With dedicated energy crops that can be grown on marginal lands and that are, in fact, more productive on lands where traditional crops are less productive, the next generation of biofuels would permit the entire harvest of staple crops to be used for food and feed (Khanna, 2008).

Cellulosic ethanol can also overcome the challenge of biofuels to offer significant greenhouse gas emissions reductions relative to fossil fuels. By utilizing a greater share of harvested plants, by utilizing crops that produce more biomass per acre, by reducing input intensity of feedstock production, and by increasing efficiency of depolymerization and fermentation, the next generation of biofuels can greatly reduce the carbon-intensity of biofuel production. Table 1 also reports the greenhouse gas emissions of various biofuel technologies as a percentage of gasoline emissions. Corn ethanol emissions are at best 25% below gasoline emissions. But Miscanthus emits 89% less emissions. Corn stover, which uses the residue of corn food and feed production, causes only 18% as much pollution as gasoline (Khanna, 2008).

A Renewed Commitment to Biotechnology

Given the potential for biotechnology to not only produce more productive food and energy crops, but also develop more efficient biofuel conversion processes, it seems there is cause for optimism that the global challenges of the new century can be met. With continued yield improvements like those of the Green Revolution, agriculture has the capacity to provide a daily diet of 3,000 calories to a population of 10 billion while using 200 million fewer hectares of cropland (Waggoner, 1995). Yield improvements are not continuing apace, however. And perhaps as a result of decades of stable food prices and supplies, complacency has set in with regard to plant science.

Federal spending for research and development has declined as a percent of GDP since 1975. It fell from 1.27% of GDP in 1975 to a low of 0.88% in 2001, before recovering marginally through 2005. It has since fallen again to 1% of GDP in the 2009 federal budget (American Association for the Advancement of Science [AAAS], 2008). Public funding for agricultural research has fallen in recent years—in some cases in nominal as well as real terms. Alston, Pardey, and Roseboom (1998) attribute the decline in federal funding to a diminished farm constituency and worry that productivity gains in an era of crop surpluses increase government outlays for farm subsidies. As Alston, Pardey, and Roseboom cautioned in 1998, the consequences of reduced commitments to agricultural productivity are not immediately evident and can be persistent.

Because of spillover effects, economic theory predicts underinvestment in research and development by the private sector relative to social optimality; private firms cannot appropriate all the benefits of their R&D efforts (Grilliches, 1991). Given the modern tools of plant science, the returns to agricultural research can be as large as they were during the Green Revolution. Government support is needed for biotechnology generally, but also specifically for the development of transgenic crops in poor countries that do not provide sufficient profit incentives for investment from the private sector.

Public investment in research by itself is not sufficient to enhance productivity. There exist complementarities between the public sector and the private sector with respect to developing new technologies, particularly in biotechnology. The public sector is adept at basic research, whereas the private sector is better able to develop new technologies.

The capacity to introduce new varieties also depends on regulation. Europe's de facto ban on GMOs since 1998 precluded imports of crops containing GMOs and heavily restricted the transgenic varieties that can be planted on European soil. As Paarlberg (2008) argues, the European attitude toward biotechnology influenced their former colonies in Africa, where regulation blocked the introduction of GMOs despite the significant potential for improved yields and reduced costs (Evenson, 2006). Burkina Faso, for instance, could reduce the costs of agricultural production by 10% with the adoption of GMOs for 80% of its crops.

Graff and Zilberman (2007) show the fall in patent applications, investment dollars, and firm start-ups that occurred during the European ban. Without markets for their crops, farmers faced a strong disincentive to adopt GMOs. And seed companies, without markets for transgenic varieties, faced a strong disincentive to invest in new research. As a consequence, the second generation of agricultural biotechnology has stalled in laboratories, despite the promise it holds to produce drought- and saline-tolerant varieties and infuse staple crops with added nutrients that might end malnutrition in poor regions of the world.

If agriculture is to be relied upon to solve the resource challenges of the 21st Century, then a renewed commitment to biotechnology is urgently needed. A precautionary approach that places uncertain impacts in the future ahead of certain hunger in the present should be reconsidered. With a safe track record and considerable potential to prevent future food crises, agricultural biotechnology should be freed from heavy regulation. Biotechnology innovations should be evaluated in a risk assessment that is based on scientific knowledge and includes a balancing of costs and benefits. Regulation not only slows the adoption of technology ex post, but reduces innovation ex ante. New varieties of transgenic seed that contain already-approved GM traits should not face the full battery of ex ante testing that the first seeds had to undergo. New technologies can be introduced into the field and monitored over the course of their lives, with greater monitoring intensity early on. In this way, society can manage risks without unnecessarily impeding innovation.

A sustainable biofuel future hinges critically on the capacity of agriculture to meet demand for energy crops without bringing natural lands into production. Natural lands act as carbon sinks, absorbing greenhouse gases and storing them in the ground and in biomass. If these lands are converted to productive uses (food or energy crop production), much of the stored carbon is released when the ground is tilled and the biomass destroyed. In addition, these lands no longer store as much carbon; productive lands sequester less carbon than natural lands, and their sequestration capacity is highly dependent on farming practices. It is these effects of land-use changes that drive the remarkable result by Searchinger et al. (2008) that a 15 billion gallon increase in US corn-ethanol production causes the greenhouse gas emissions from transportation over 30 years. This carbon debt is slowly paid off as the marginal savings of corn-ethanol relative to gasoline accumulate over 167 years. It is this effect that so closely binds the fate of biofuels to growth in agricultural productivity.

Conclusions

Biofuels raise prices of agricultural commodities and reduce food availability by increasing demand for crops and diverting food crops away from their traditional uses. Amid a food crisis that has induced suffering and starvation not seen in more than a generation, government support for biofuels has been questioned. With a renewed commitment to plant science and agricultural research, the farming community may well meet demand for food and biofuel.

Agricultural biotechnology is demonstrated to improve crop yields and reduce pesticide applications. A second generation of biofuels, already produced in laboratory settings, promises to use productive, dedicated energy crops to produce greater quantities of ethanol or superior fuels with fewer carbon emissions. These two fields of plant science alone offer the capacity for biotechnology to make strides as significant as those of the Green Revolution. But the success of the Gene Revolution will depend on a reduced regulatory burden and a dedication of public funds to drive innovation. If yield gains from 1950-2000 can be matched in the next 50 years, and if cellulosic ethanol can move from the laboratory to the retail station, then the world can likely produce its way out of a food and energy crisis. The capacity to take advantage of biofuels to enhance fuel supply with less contribution to climate change depends on the effective utilization of the potential of agricultural biotechnology.

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Authors' Notes

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