Agricultural Biotechnology: The Promise and Prospects of Genetically Modified Crops[†]

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For millennia, humans have modified plant genes in order to develop crops best suited for food, fiber, feed, and energy production. The earliest efforts, far predating Gregor Mendel's 19th-century discoveries on trait inheritance, involved the selective breeding of plants with desirable characteristics, but the recombination of DNA in offspring was random. Consequently, plant breeding often took decades and frequently yielded crop varieties with unforeseen and undesirable properties. Today, conventional plant breeding remains inherently random and slow, constrained by the availability of desirable traits in closely related plant species. In contrast, agricultural biotechnology employs the modern tools of genetic engineering to reduce uncertainty and breeding time and to transfer traits from more distantly related plants.

Arguments in support of and in opposition to the use of genetically engineered seeds have changed little since the technology emerged in the 1980s. On one side, critics express concerns that the technology imposes negative environmental effects and jeopardizes the health of those who consume the "frankenfoods." On the other side, supporters emphasize potential gains from boosting output and lowering food prices for consumers. They argue that such gains are achieved contemporaneous with the adoption of farming practices that lower agrochemical use and lessen soil

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erosion. Although the arguments have changed little since the 1980s when the first generation of genetically engineered crops were created to reduce pest damage, genetic plant engineering became the most rapidly adopted agricultural innovation in history, planted to a cumulative 1.25 billion acres from commercialization in 1996 to today. Roughly 10 percent of all cropland employs the technology in spite of lingering public concerns (James 2011).

The extensive experience with agricultural biotechnology since 1996 provides ample evidence with which to test the claims of supporters and opponents and to evaluate the prospects of genetic crop engineering. In this paper, we begin with an overview of the adoption of the first generation of agricultural biotechnology crops. We then look at the evidence on the effects of these crops: on output and prices, on the environment, and on consumer health. We then consider intellectual property issues surrounding this new technology; a common complaint from critics is that much of the basic research supporting genetic plant engineering was conducted by the public sector, yet the technologies that followed were developed and commercialized by private firms that enjoy intellectual property protections, upending a decades-long tradition of public sector seed development.

We argue that while a number of the environmental issues with genetically engineered seeds warrant scrutiny, the accumulated experience with the first wave of agricultural biotechnology has generated considerable benefits to consumers and the environment. While the next wave of genetic engineering has potential to improve crop response to climate change and boost the nutrient density of staple crops, attention must be paid to the unique risks each new trait may pose. Policy must also seek to ensure that innovation is not unnecessarily burdened and that those who stand to benefit most from the technology—the poor in developing countries—are not neglected. Agriculture is challenged at the outset of the 21st century to feed, clothe, and fuel a world population growing in size and wealth. The history of modern farming lends optimism that the challenge can be overcome, but with the sources of historic growth—mechanization, conventional plant breeding, agrochemicals, and irrigation—reaching diminishing returns, a commitment to new technologies like agricultural biotechnology is needed.

Adoption of Insect-Resistant and Herbicide-Tolerant Seed

The first generation of agricultural biotechnology introduced insect-resistant and herbicide-tolerant traits into four principle row crops. The insect-resistant trait, introduced into corn, cotton, and soybeans, caused crop plants to produce the naturally occurring chemical *Bacillus thuringiensis* (Bt), which is toxic to common agricultural pests, such as the European corn borer, but harmless to humans and relatively environmentally benign. In producing the toxin, which has been applied to plants for nearly a century and is employed in modern organic farming, insect-resistant crop plants rebuff pests without farmers' application of chemicals. The herbicide-tolerant crops express tolerance to glyphosates, a class of broad-spectrum, low-toxicity herbicides

that include Roundup®, a Monsanto product employed also in residential settings. Such tolerance, introduced into corn, soybeans, and canola, allows farmers to control weeds more easily. In the absence of herbicide-tolerant varieties, farmers must rely more heavily on either controlling weeds before crop emergence: for example, by repeatedly tilling the soil in a process that causes erosion, or applying relatively more toxic "narrow spectrum" chemicals that can target weeds without affecting post-emergent crops.[1]

Genetically engineered crops were quickly adopted following commercialization in 1996. By 2010, genetically engineered crops were annually planted across 140 million hectares in 29 countries. The technology was adopted on 42 percent of land planted to the four principal genetically engineered crops: corn, soybean, cotton, and rapeseed. Twenty percent of all cropland was planted to genetically engineered seed. Genetically engineered seed was planted to 70 percent of total soybean area, 25 percent of total corn area, 60 percent of total cotton area, and 20 percent of total rapeseed area. The majority of genetically engineered crop area was concentrated among a few countries that aggressively adopted the technologies: the United States and Brazil planted 85 percent of genetically engineered corn, and, with Argentina, 92 percent of genetically engineered soybean. Ninety percent of genetically engineered cotton was planted in India, China, and the United States, while Canada alone planted 85 percent of genetically engineered rapeseed. The area planted to each of these genetically engineered crops is reported in Table 1 for the top adopting countries.

Agricultural biotechnology adoption occurs along an intensive margin as conventional seed is replaced by genetically engineered seed of the same crop. Adoption also occurs along an extensive margin, when natural land and land previously planted to other crops is recruited into production of a genetically engineered crop. Analysis of supply and price effects of genetically engineered crop adoption, as well as environmental impacts, depends critically on rates of adoption across the two margins. Supply effects, for instance, will be greater where the introduction of genetically engineered crops induces farming on marginal lands that were previously unfarmed. But such recruitment of unfarmed lands into agricultural production may come at a cost of environmental damage associated with land-use change.

Figure 1 plots world aggregate acreage over time of four crops with genetically engineered varieties, decomposing total crop area into area planted to traditional seed technology, area planted to genetically engineered seed along the intensive margin, and area planted to genetically engineered seed along the extensive margin. In the absence of records documenting the prior use of land planted to agricultural biotechnology, the decomposition of crop area into these component parts follows an algorithm we develop in Barrows, Sexton, and Zilberman (2013). The algorithm employs aggregate, country-level changes in total and genetically

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[1] Glyphosate has a US Environmental Protection Agency (EPA) Toxicity Class of III (on a I to IV scale, where IV is least dangerous) for oral and inhalation exposure. EPA requires that products containing glyphosate carry a label that warns against oral intake, mandates the use of protective clothing, and instructs users not to re-enter treated fields for at least four hours.

Table 1
Genetically Engineered Area Harvested in 2010
(millions of hectares)

Cotton		Soybean	
India	9.4	United States	29.4
United States	4.1	Brazil	18.4
China	3.5	Argentina	18.0
Argentina	0.6	Paraguay	2.7
Rest of world	1.3	Rest of world	3.1
Corn		Rapeseed	
United States	28.2	Canada	6.1
Brazil	7.5	United States	0.5
Argentina	2.8	Australia	0.1
South Africa	1.9	Rest of world	0.0
Rest of world	1.9		

*Source:* Author's own calculations using data from Graham Brookes.

engineered crop area and a fundamental assumption that if the area planted to a genetically engineered crop is observed to increase from one year to the next, then there were no land transitions out of production of that genetically engineered crop over the same period.

Adoption of genetically engineered cotton, corn, and rapeseed has occurred mostly along the intensive margin, with new seed technology substituting for conventional seed. By contrast, adoption of genetically engineered soybeans has occurred roughly evenly along intensive and extensive margins. Soybean acreage has grown more than 50 percent since the introduction of genetically engineered seed, with most of the gains in Brazil and Argentina.

Agricultural biotechnology adoption along the extensive margin is of considerable interest because of important implications for supply of crops and for environmental quality. Regrettably, there is little information documenting the degree to which production of genetically engineered crops has recruited land from production of other crops or from nonagricultural uses like forest. However, some evidence suggests that growth on the extensive margin also occurs by "double cropping," the practice of planting two crops per growing season instead of just one crop (Trigo and Cap 2003). When double-cropping, farmers produce one early and one late season crop per year, growing in the "shoulder seasons" when pest damage is typically too high for profitable production with conventional seed technology. Seeds engineered with herbicide tolerance are expected to increase double cropping. They permit control of weeds after the crop plant has emerged from the ground, lessening demand for pre-emergence weed control, which typically delays planting long enough to preclude maturation of a follow-on crop. Double-cropping reflects increased annual productivity for a given plot of land, enabling increased

Figure 1
World Area of Four Crops with Genetically Engineered Varieties
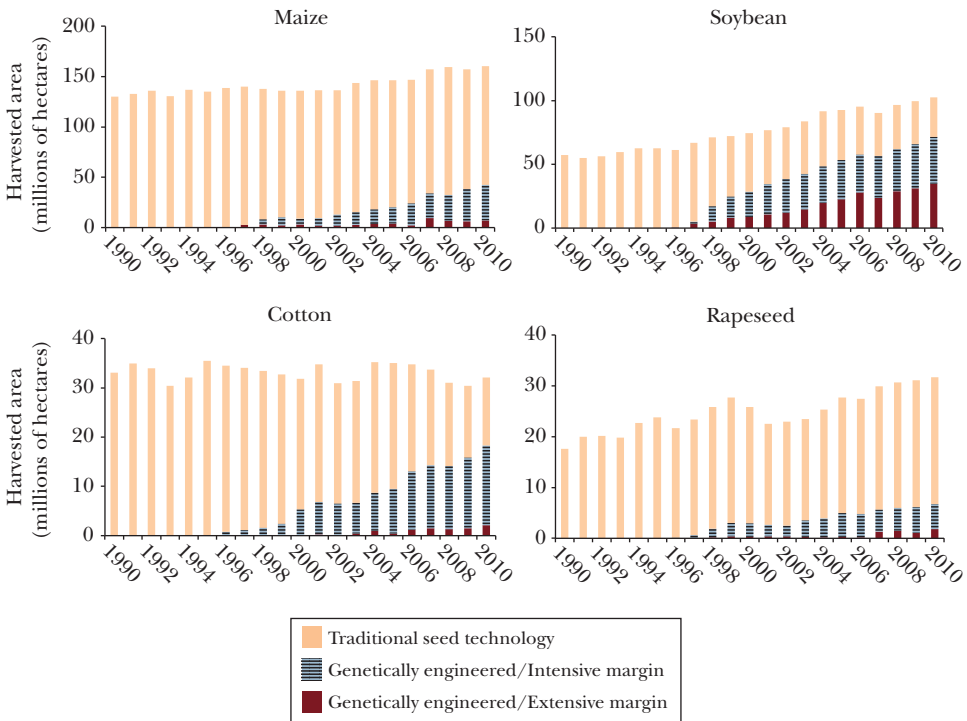

Source: Barrows, Sexton, and Zilberman (2013).
Notes: Figure 1 plots world aggregate acreage over time of four crops with genetically engineered varieties, decomposing total crop area into area planted to traditional seed technology, area planted to genetically engineered seed along the intensive margin, and area planted to genetically engineered seed along the extensive margin.

agricultural output without increasing the footprint of agriculture. There is evidence that adoption of double cropping is correlated with agricultural biotechnology adoption, and that double cropping increased the area planted to soybean in Argentina by 4 million hectares (Trigo and Cap 2003).

To understand agricultural biotechnology adoption patterns and subsequent input and output effects, we model the decision of farmers to use insect-resistant or herbicide-tolerant technology within the damage control framework of Lichtenberg and Zilberman (1986). This framework defines output as the product of potential output and the share of crop not damaged by pests. Pest damage is mitigated by pest control efforts, which may include pesticides applications, agricultural biotechnology adoption, or other agricultural practices. The benefits of adoption are increasing in pest pressure, so, *ceteris paribus*, adoption is more likely in areas characterized by substantial pest problems. When genetically engineered seed replaces chemical applications, the main effect of the adoption is to lower the cost

Figure 2
Adoption of Genetically Engineered Technology
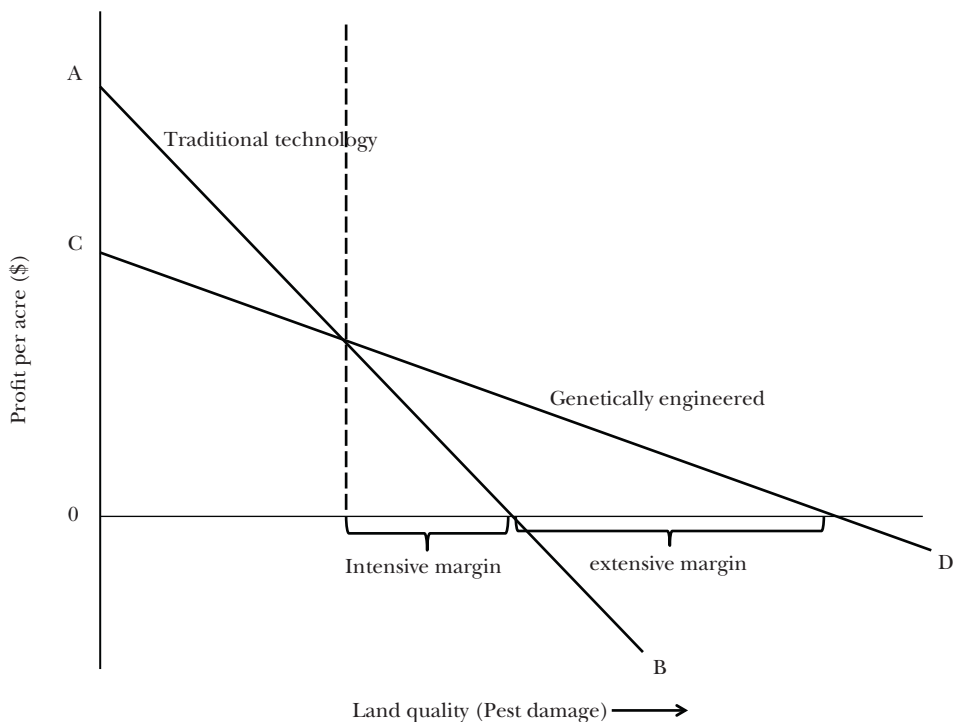
Source: Authors.
Notes: Figure 2 illustrates the damage control model. Land quality is decreasing along the horizontal axis, with low-pest-pressure, high-quality land located on the left and low-quality, high-pest-pressure land on the right. Profit per acre is measured along the vertical axis.

of damage control. When genetically engineered seed are adopted on farms with uncontrolled pest problems, the main effect of adoption is to increase yield (Qaim and Zilberman 2003). In both cases, adoption is more likely in locations with more significant pest problems.

Figure 2 illustrates the damage control model. Land quality is decreasing along the horizontal axis, with low-pest-pressure, high-quality land located on the left and low-quality, high-pest-pressure land on the right. Profit per acre is measured along the vertical axis. Line segment AB depicts profit per acre as a function of land quality (or pest pressure) under the traditional technology, and line segment CD shows profit per acre for genetically engineered technology. In areas characterized by sufficiently low pest pressure, the conventional technology yields higher profits because crop losses avoided by genetically engineered seed are too small to compensate for its higher costs. As the level of pest pressure rises, the gains from adoption of genetically engineered seed increase. For sufficiently high pest pressure, it is only profitable to farm using genetically engineered seed because crop

losses from conventional technology are too great. Genetically engineered seed is expected to boost crop production by generating incremental yield gains along the intensive margin and by inducing production along the extensive margin on land that otherwise generated no output.

 While profitability has been identified as the major reason for farmer adoption of agricultural biotechnology, the literature has identified other benefits to adoption as well, including reduced exposure to pesticides and reduced effort for pest monitoring that is necessary for optimality of pesticide applications. The magnitude of these benefits is also correlated with pest pressure (Piggott and Marra 2008; National Research Council 2010).

Estimating Effects of Genetically Engineered Seeds on Production and Prices

A number of studies using farm-level data in various countries have found that genetically engineered seeds increase crop yields. The model above suggests that the greatest potential for yield gains from genetically engineered seeds exist in places with high pest pressure and little access to alternative damage control—that is, mainly in low-income developing countries. A corollary implication, discussed in the next section, is that the greatest reductions in insecticide use and toxic herbicide use are expected to occur in developed countries where chemicals were aggressively deployed to reduce damage before the introduction of genetically engineered seed (Qaim and Zilberman 2003). Qaim (2009) summarizes impact studies, finding yield gains of 37, 33, and 24 percent for the insect-resistant genetically engineered Bt cotton in India, Argentina, and China, respectively. Estimated yield gains in the developed world are smaller, with the US yield gains at only 10 percent. A similar pattern holds for insect-resistant Bt corn, with an estimated yield increase of 34 percent in the Philippines, 11 percent in South Africa, 9 percent in Argentina, and only 5 and 6 percent in the United States and Spain, respectively.

Much of the literature has explored the yield benefits of genetically engineered crops in randomized controlled trials settings, where farmer behavior is held constant. The foregoing estimates, therefore, can be considered a pure "gene effect" on yields, reflecting only the damage control benefits afforded by the transgenic trait of the seed. Theory suggests, however, that the observed yield gains should exceed those attributed to the gene effect because diminished crop damage increases the marginal value product of other yield-increasing inputs, like fertilizer, water, labor, and capital. Farmers who adopt genetically engineered crops, are, therefore, likely to also increase use of other inputs that further boost yields.

Of course, the additional crop production due to genetically engineered seed adoption is comprised of yield gains on existing cropland as well as total production on new lands recruited into production by the damage-control savings afforded by the technology. Using the decomposition from Barrows, Sexton, and Zilberman (2013) mentioned in the previous section, aggregate supply and crop price effects

are estimated for the four principal crops. Lacking estimates of the causal impact of genetically engineered technology on extensive growth in output, we compute effects under two assumptions providing upper and lower bounds. In the upper bound, we assume all production on the extensive margin is attributed to genetically engineered seed, while in the lower bound, we assume production occurring on the extensive margin would have occurred even without genetically engineered seed. The true effects likely fall somewhere in between, and the range indicates the potential importance of the extensive margin. Across the eight yield estimates for corn appearing in Qaim (2009) and Barrows, Sexton, and Zilberman (2013), the supply effect is estimated to vary from a 2–14 percent increase in total corn supply at the lower bound and a 9–19 percent increase in total corn supply at the upper bound. The smallest estimates are based on estimated yield gains in the United States, Spain, and South Africa. For cotton, lower bound estimates range from 0–25 percent while upper bound estimates range from 5–29 percent. The larger range for cotton reflects the greater variance in estimated yield gains. While there aren't many estimates of yield gains from genetically engineered soybeans, the gains estimated in Sexton and Zilberman (2011) imply a supply effect ranging between 2 and 39 percent, depending on the assumptions about the extensive margin. In Barrows, Sexton, and Zilberman (2013), we offer details on these calculations of extensive growth in output (which should be considered in addition to the intensive estimates above).

Following a standard approach in the literature (for example, de Gorter and Zilberman 1990), the effects of genetically engineered seed on production can be translated into price effects given assumptions about price elasticities of supply and demand. Assuming an own-price demand elasticity of −0.5 and an own-price supply elasticity of 0.3, and attributing equal weight to each of the eight studies reviewed in Barrows, Sexton, and Zilberman (2013), we find that adoption of genetically engineered corn in 2010 lowered prices 13 percent. The expected price decline for cotton was 18 percent. For soybeans, the estimated price decline implied by calculations in Barrows, Sexton, and Zilberman (2013) ranges from 2 to 65 percent.

Crop consumers benefit from lower prices. But all else equal, lower prices hurt farmers. The impact of agricultural biotechnology adoption on farm income has been a subject of considerable concern. A substantial literature has assessed the distribution of benefits and costs from adoption of genetically engineered varieties, mostly using partial equilibrium models (Lapan and Moschini 2004). For example, a National Research Council (2010) survey showed that the relative distribution of benefits among groups varies across products and locations. The share of overall gains accruing to farmers is estimated to be between 5–40 percent. Seed developers capture between 10 to 70 percent of the benefits, and the share of benefits flowing to US consumers is estimated to be between 6 and 60 percent. Consumers in the rest of the world capture 6–30 percent of total benefit. In most cases, seed developers capture less than half of the benefits, with the majority of surplus accruing to farmers and consumers. The differences in estimated outcomes reflect variations in

the impacts of different traits at different locations, market structure, and demand and supply parameters.

Genetically engineered seed is relatively easy to adopt as it only requires the substitution of one seed for another. While richer farmers may have been early adopters of the technology (Crost, Shankar, Bennett, and Morse 2007), near 100 percent adoption of Bt cotton in many regions of India and high rates of adoption in Burkina Faso and South Africa yielded gains to smallholders. The contributions of genetic modification technology to food security in a global context are presented in Godfray et al. (2010). A case study by Kathage and Qaim (2012) in India showed that adoption of insect-resistant Bt cotton resulted in a 50 percent increase in profit per hectare and an 18 percent increase in expenditures. Gouse, Pray, and Schimmelpfennig (2004) document gains to smallholders in South Africa from Bt cotton. The total benefits from genetically engineered varieties have been substantial in absolute terms. The global net benefit to producers over the period 1996–2009 was estimated by Brookes and Barfoot (2012) to be $65 billion, of which $30 billion accrued to US producers. Estimation of the overall benefits of genetically engineered technology and the distribution of those benefits is an ongoing area of research.

Environmental Benefits and Risks

Since its inception, genetic plant modification has engendered concerns about adverse impacts on ecosystems and environmental quality. These concerns persist, and include the risks of gene flow to noncrop plants and natural lands, agricultural biodiversity loss, and pesticide resistance build-up for common pesticides. We consider each of these in turn.

Genetic engineering introduces plants with novel phenotypes into existing ecological networks. If these traits escape the farm and spread elsewhere, the effects on surrounding ecosystems could be novel and complex (Wolfenbarger and Phifer 2000). For example, a gene that makes a certain crop heartier might spread to a related weed species and make that weed more invasive. Organic farmers particularly worry about the spread of genetically engineered material from adjacent farms to their fields. Such accidental transfer of transgenic material jeopardizes access to organic markets, which is often premised on sufficient purity. The coexistence of transgenic crops and organic farming typically relies upon the imposition of buffers between crops, the optimal size of which depends upon the risks of material transfer and the costs of impurity (Beckmann, Soregaroli, and Wesseler 2006).

While natural hybridization is common among plants that have close genetic relationships, the ecological effects of gene flows are not well understood. Existing genetically engineered crops are not typically planted in proximity to native relatives, which reduces the risk of traits jumping into wild species. Few crops produced in the United States originated there and have proximal wild relatives. There are no weedy relatives of corn and soybean, the dominant genetically engineered crops

in the United States. In areas where wild cotton populations exist in the United States, production of genetically engineered cotton is forbidden to avoid risk from gene flow (Warwick, Beckie, and Hall 2009). Rapeseed has been designated a moderate-risk crop because herbicide-tolerant traits are reported to have spread to wild relatives (Stewart, Halfhill, and Warwick 2003).

Opposition to genetically engineered seed also centers on the technology's propensity to increase monoculture agriculture by reducing its agronomic costs (Pollan 2001). Though monocropping can deplete soil quality and increase pest problems, it affords efficiencies and productivity gains that explain why it is favored by many farmers. The phenomenon began well before the commercialization of genetically engineered seed.

Concerns about resistance build-up are not unfounded. Like other pest control methods, transgenic seed are not immune to evolutionary forces that can induce resistance absent proper management. The National Research Council (2010) reported that resistance to toxins in insect-resistant crops had evolved among only three pest species in the first 14 years of commercial insect-resistant cropping. Bennett, Phipps, Strange, and Grey (2013) report on newer cases of resistance development and their implications. Growing pest resistance to insect-resistant corn in Puerto Rico resulted in the voluntary withdrawal of the genetically engineered seed in 2006 (Tabashnik, Van Rensburg, and Carrière 2009).

At least 10 species of weeds have evolved resistance to glyphosate in herbicide-tolerant fields in the United States due to the nearly exclusive reliance on glyphosate for weed control (Duke and Powles 2009). A growing number of weeds are evolving resistance to glyphosates, but the number of locations in which resistance build-up is problematic is growing faster because of the widespread adoption of herbicide-tolerant crops. Because farmers typically respond to the diminished efficacy of resistant glyphosates by increasing dosage and application frequency and by supplementing with other chemical applications, resistance build-up can adversely impact the natural ecosystem to the extent that farm chemicals drift (National Research Council 2010; Mueller, Mitchell, Young, and Culpepper 2005). Amid resistance build-up, farmers are expected to rely more heavily on tilling operations in lieu of glyphosate applications, potentially worsening soil erosion and water quality and impeding soil carbon sequestration (Mueller et al. 2005).

While the risk of resistance build-up is not unique to genetically engineered seed, the risk is likely greater in transgenic crops than conventional crops. The selection pressure is omnipresent in insect-resistant traits, whereas on traditional crops, the selection pressure can be managed by controlling insecticide applications and varying damage control agents. The efficacy of glyphosates for weed control also suggests that resistance build-up will be greater among herbicide-tolerant crops to which glyphosates can be applied post-emergence.

Pest susceptibility is a common pool resource likely to be underprovided relative to social optimality; no individual farmer faces the full cost of his use of damage-control agents nor accrues the full benefit from his effort to minimize selection pressure. Consequently, regulators mandate that farmers who plant

insect-resistant seed also plant refuges of non-insect-resistant crops. Susceptible pests can survive and interbreed with resistant pests in the refuges, and thus maintain the stock of susceptibility. In the United States, such refuges are mandated to be equal in size to at least 20 percent of the area devoted to insect-resistant crop production (Bourguet, Desquilbet, and Lemarié 2005). In some cases, the non-insect-resistant seed are intermingled with the transgenic seed to produce "refuge in a bag."

Given their monopoly status afforded by intellectual property rights, seed companies have incentive to manage resistance in order to preserve the efficacy of their seed technologies. Such an incentive would not exist among competitive suppliers. Seed companies responded to resistance concerns by "stacking" multiple traits in insect-resistant seed. Each trait is designed to target pests differently, lessening the selection pressure. The advent of stacked traits has slowed resistance build-up among insect-resistant traits, but a similar solution is lacking for herbicide-tolerant traits. Seed companies are developing traits that express tolerance to other herbicides, though the other herbicides are less benign than glyphosates.

In spite of environmental risks posed by agricultural biotechnology, theory and empirical evidence suggest genetically engineered crops deliver environmental benefits by saving land and agrochemicals and by maintaining rather than diminishing agricultural biodiversity. While critics assert that agricultural biotechnology has increased pressure to monoculture, genetic engineering can reduce that pressure and maintain crop diversity. It inserts traits into existing crop varieties, modifying them slightly. If the costs of inserting transgenic traits into seed, inclusive of regulatory costs, are low, then the adoption of genetically engineered traits does not necessarily reduce agricultural biodiversity. In fact, much of soybean biodiversity has been sustained (Zilberman, Ameden, and Qaim 2007). Moreover, genetic engineering allows the reintroduction of seed varieties that had been abandoned because of pest damage. Genetic engineering also permits production of differentiated varieties with unique properties, enhancing biodiversity. For example, a new soybean variety with reduced artery-clogging transfats was announced in 2013 (Pollack 2013), and in Bennett, Chi-Ham, Barrows, Sexton, and Zilberman (2013), we enumerate new varieties with desirable health or agronomic properties.

Because insect-resistant seeds substitute for insecticide applications, they are expected to reduce agrochemical applications and limit environmental damage from chemical runoff and drift. Many of the randomized trials surveyed in Qaim (2009) estimated changes in pesticide use in addition to changes in yields. Bt cotton adoption is estimated to reduce pesticide use by 65 percent in China, 47 percent in Argentina, 36 percent in the United States, and 33 percent in South Africa. Cotton is the most pesticide-intensive crop worldwide, and an estimated 128 million kilograms of pesticide applications were avoided worldwide from 1996 to 2007 because of insect-resistant Bt cotton adoption. This is estimated to have reduced the environmental impact of cotton pesticides by 25 percent (Brookes and Barfoot 2006). The reduction in pesticide on genetically engineered corn crops tends to be smaller. While insecticide use in Spain declined 65 percent on insect-resistant Bt corn fields,

the United States, South Africa, and the Philippines experienced reductions of only 8, 10, and 5 percent, respectively (Qaim 2009).

In contrast to insect-resistant seeds, which act as substitutes for insecticides, herbicide-tolerant seeds are complimentary with herbicides. However, herbicide-tolerant seed varieties permit the substitution of relatively environmentally benign alternatives for the toxic, narrow-spectrum chemicals used on conventional crops. Thus, while overall quantity of pesticide use may increase with the adoption of herbicide-tolerant crops, the total toxicity of applied chemicals does not (National Research Council 2010). Glyphosates, such as Roundup®, for instance, are less prone than alternative herbicides to leaching, more biodegradable, and less toxic to a variety of animals, including mammals, birds, and fish (Fernandez-Cornejo and McBride 2002; Cerdeira and Duke 2006; Malik, Barry, and Kishore 1989).[2] From 1996 to 2008, the per-acre quantity of glyphosate use in the United States increased roughly proportional to the nearly fivefold increase in herbicide-tolerant soybean acreage (National Research Council 2010). Applications of substitute herbicides, which tended to be more toxic, decreased nearly commensurately. Overall, the quantity of active ingredients applied to cotton and soybean crops increased slightly in the United States since the introduction of genetically engineered seed technology.

While chemical use is shown to increase with adoption of herbicide-tolerant seed, such adoption is also associated with adoption of reduced tillage operations. Tilling is a mechanical form of weed control that causes soil erosion, releases carbon from the soil (which contributes to climate change concerns), and increases farm runoff, which is responsible for nitrification and "dead zones" in the Gulf of Mexico (National Research Council 2010; Brookes and Barfoot 2010). With the adoption of herbicide-tolerant crops, post-emergence glyphosate applications substitute for pre-emergence tilling operations, so that no-till and reduced-till practices increase. In fact, the no-tillage soybean area in the United States doubled from 1996 to 2008 and increased fivefold in Argentina. The no-tillage canola area in Canada tripled from 1996 to 2005, while the no-tillage cotton area increased fivefold in the United States.

Diminished reliance on chemical applications and tillage operations also lowers demand for fuel for farm machinery, which generates cost savings to the farmer and lowers air pollution and greenhouse-gas emissions. By lowering the optimal level of insecticide applications, insect-resistant crops reduce the number of passes farm equipment must make through fields. Though there is no direct evidence of the magnitude of fuel savings associated with adoption of insect-resistant crops, a reasonable approximation is that insecticide use accounts for half of total fuel use on a field (Mitchell, Munk, Prys, Klonsky, Wroble, and De Moura 2006). Assuming a monotonic correspondence between insecticide savings and savings on fuel for insecticide applications, the adoption of insect-resistant seeds generated an estimated 32 percent overall fuel savings on cotton fields in China or corn fields in Spain, and 18 and 4 percent savings on insect-resistant cotton and corn fields in the United

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[2] Shaner (2000) compares the active ingredients of glyphosates to other groups of herbicides and documents the relative advantage of glyphosate use.

States, respectively. The yield gains on the intensive margin also avert fuel consumption that would accompany cropland expansion. The use of no-tillage operations on herbicide-tolerant fields lowers fuel use 30–73 percent according to various estimates (Mitchell et al. 2006; Sanders 2000; USDA-NRCS 2008; Jasa 2000).

At the most basic level, the yield gains from genetically engineered seeds reduce the size of the agricultural footprint necessary to produce a given quantity of food, fiber, feed, and fuel. The simulation framework of Sexton and Zilberman (2011) estimates that 20 million additional hectares of land would have been necessary to produce the 2008 harvest of soybeans and corn absent the yield gains from genetically engineered seeds. Because land-use changes account for a leading share of anthropogenic greenhouse gas emissions, this reduction in agricultural land demand represents a meaningful contribution to the abatement of greenhouse gas emissions and also averts biodiversity loss associated with recruitment of native lands into agricultural production.

Human Health Impacts of Genetically Engineered Crops

Consumers have exhibited a willingness to pay to avoid perceived health risks associated with genetically engineered foods (for a survey, see Lusk, Jamal, Kurlander, Roucan, and Taulman 2005) in spite of being generally uninformed about the risks and the benefits of agricultural biotechnology (European Commission Eurobarometer 2000; Pew Charitable Trusts 2001). Moreover, there exists a gap between public perception and scientific knowledge (for example, McHughen 2007; Hoban 1998; Marchant 2001; Marris 2001). Consumer willingness to pay, however, changes in response to new information (Kiesel, McCluskey, and Villas-Boas 2011), and products containing genetically engineered material that delivers health benefits may fetch a premium at market (Colson, Huffman, and Rousu 2011).

One health concern surrounding consumption of genetically engineered food is the possibility that genes inserted into the DNA of plants will be toxic to humans—for example, it may induce allergic reactions. Regulators have sought to prevent the intentional or accidental transfer of genes encoding major allergens into food crops in which they were previously absent (Goodman et al. 2008). There is no evidence that a transgenic gene has introduced allergenicity into a crop or caused the endogenous allergenicity of the crop to increase (Taylor 2006).

A related worry concerns genetic modification techniques that also (inadvertently) select for antibiotic-resistant genes. In particular, there is concern that the efficacy of therapeutic antibiotics may be diminished by consumption of genetically engineered foods derived from crops that contain antibiotic-resistant genes. Some also fear that antibiotic resistance may spread from the crop plant to intestinal or soil microorganisms. Bennett, Phipps, Strange, and Grey (2004) and the European Food Safety Authority (2004), among others, have determined that the risk of horizontal gene transfer from the plant to microorganisms is extremely low and that consequences would be minimal even if the transfers were to occur. European

regulators concluded that the antibiotic selectable markers in commercial use present no inherent risk to human health. And new techniques are now available that avoid the problem (Hare and Chua 2002).

The safety paradigm governing regulation of genetically engineered crops is one of "substantial equivalence" that compares novel plants to already existing plants, such as conventionally bred plants for which there is a substantial record of safety. Any characteristic of a new plant that deviates substantially from that of the conventional counterpart is investigated for allergenicity, toxicity, or other unintended effects. The substantial equivalence paradigm is endorsed by the Codex Alimentarius Commission (2003a, 2003b)—a joint Food and Agriculture Organization/World Health Organization food standards program. It is also consistent with a consensus in the scientific community that the recombinant DNA process is not inherently less safe than conventional forms of plant breeding and that the content of crop plants and foods should drive their regulatory scrutiny, not the process by which they were bred (National Research Council 1989, 1994, 1996, 2000, and 2010; European Commission Eurobarometer 2010).

Paarlberg (2010) surveys evidence from the British Medical Association, French Academies of Science, Organisation for Economic Co-operation and Development, and the UN Food and Agriculture Organization in asserting that "GMO [genetically modified organism] foods and crops currently on the market have brought no documented new risks either to human health or to the environment." Yet future traits may pose more risk, so that continued scrutiny of new transgenic crop introductions is warranted. Whereas food safety organizations find nothing inherently unsafe in the process of genetic engineering, they note that new plant characteristics developed in the next wave of agricultural biotechnology could present new risks. At the same time, future generations of biotechnology may well provide food products with higher vitamin or protein content and lower allergenicity, yielding benefits to food consumers.

Even first-generation agricultural biotechnology likely delivers some health benefits that weigh against health risks. Food consumers benefit from reduced exposure to mycotoxins, the toxic and carcinogenic chemicals produced by fungi that colonize crops. By reducing insect pest pressure, insect-resistant crops can reduce fungal contamination. Insect-resistant Bt corn, in particular, has significantly lowered levels of mycotoxins in field trials. The risk from mycotoxin accumulation in food is more severe in developing countries because of ineffective pest control and poor food-storage conditions. Wu (2006) estimated that the economic benefits of reduced contamination due to Bt corn could reach $100 million annually.

Farm workers stand to benefit from reduced exposure to chemicals. Huang, Hu, Rozelle, and Pray (2005) found that fields in China planted with insect-resistant rice reduced pesticide use by 80 percent, which in turn eliminated pesticide-induced illness that afflicted from 3 to 8.3 percent of farmers of conventional rice. Similar health benefits were observed among insect-resistant cotton farmers in China (Huang, Pray, and Rozelle 2002). Though the benefit of reduced pesticide exposure has not been widely investigated, the reduced chemical use associated

particularly with insect-resistant seed has been documented widely (see survey by Qaim 2009). The health gains from avoided pesticide applications are likely larger among adopters in developing countries who are less likely to have access to protective equipment.

Finally, the reduction in pesticide use on genetically engineered crops lowers pollution emissions from the production and transportation of agrochemicals and field operations. Lower emissions, in turn, reduce smog formation, toxic particulate matter concentrations, ecotoxicity of water, and water and soil acidification and nitrification (Bennett et al. 2004). Overall, genetically engineered crops are about one-tenth as toxic to the environment as the conventional crop (Bennett et al. 2004).

Intellectual Property Rights and Regulation

Next-generation traits in the biotechnology research pipeline include those that would enhance drought tolerance, nutritional content, shelf life of produce, nitrogen fixation, and adaptability to climate change (Graff, Zilberman, and Bennett 2009; Ronald 2011). The success of future genetically engineered plant technologies, however, depends on innovators' incentives, which are affected by intellectual property rights regimes and safety regulations.

For much of the 20th century, seeds in the United States were often provided by the public sector and distributed to farmers at low cost. In contrast, genetically engineered seed technologies are usually protected by intellectual property law and sold to farmers at monopolistic prices. As some of the relevant patents were developed by university research and subsequently licensed to the private sector, many oppose genetically engineered seeds on the grounds that seed companies are profiting from publicly funded research. Indeed, seed companies (like medical companies) pay to use the rights of patents that were developed by the public sector, but they then spend much larger amounts on development and registration activities (Bennett et al. 2013). Furthermore, the private seed industry was remade, decades before the advent of genetic plant engineering, when hybrid seed varieties were introduced by crossing two parent varieties exhibiting strong phenotypes. Hybrid corn varieties consistently outperformed conventional seed in the 1930s and provided inherent protection of private investment in research and development as the hybrid seed does not express parent traits and, therefore, cannot be saved by farmers (Duvick, Smith, and Cooper 2004).

Growing private sector investment in seed technology, motivated by the potential royalties from innovation, has occurred alongside a prolonged decline in public sector agricultural research and development (Alston, Beddow, and Pardey 2009). Basic research has largely been carried out at universities, which license technologies to seed companies, which conduct comprehensive testing and undertake development and marketing efforts—a division of labor that mirrors what occurs in biomedical research and development. Without investments by major agrochemical

companies, such as Monsanto, many genetically engineered crop technologies would not have been developed (Graff, Cullen, Bradford, Zilberman, and Bennett 2003).[3]

Reliance upon private sector intellectual property incentives for agricultural innovations creates some problems. Importantly, huge social welfare gains could be obtained by employing genetic plant engineering to address some of the agronomic problems in developing countries. But seed companies have little incentive to develop traits for these applications because of limited purchasing power. While intellectual property rights have induced private sector research, they have limited the application of these technologies in poor parts of the world. Policies to make patented technologies more widely available in poor countries would enhance both the social benefits of the technology and its perception among the public. Likewise, specialty crop applications are often neglected because the markets are small.

The introduction of intellectual property rights for genomic information has fragmented ownership of traits and enabling technologies across many parties, creating an "anti-commons." Introducing a single new genetically engineered crop can require innovations protected by 40 or more individual patents and license agreements. Public efforts have sought to improve access to intellectual property rights and, in particular, to ensure that developers of philanthropic applications have "freedom to operate" (Atkinson et al. 2003; Koo, Nottenburg, and Pardey 2004). The development of a clearinghouse for agricultural biotechnology property rights serves to improve coordination and access for developing countries and specialty crops (Graff and Zilberman 2001; Graff et al. 2003).

While the patenting of "genes" per se is restricted, there is a strong case for patenting knowledge about functions of genes as it provides a base for useful product innovations that can be developed by the private sector. However, development of such technologies requires access to process innovations. A crucial process innovation in agricultural biotechnology is the use of agrobacterium to "ferry" genes. The rights to this patent are exclusively held by Monsanto. This is in contrast to the rights to use the gene transfer technology in medical biotechnology (the Cohen–Boyer patent), which were nonexcludable and, consequently, utilized by many startups. The limited access to the agrobacterium patent has limited development and commercialization of agricultural biotechnology innovations.

Whereas property rights for genomic information create incentives for private agricultural productivity research, safety regulations create disincentives for new trait introductions by imposing costly testing (Potrykus 2010). In the United States, the cost of regulatory approval for a single variety of genetically engineered seed can reach $15 million. It typically takes ten times more money and ten more years

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[3] Global public research in agricultural research and development is $33.7 billion as of 2009, and private agricultural research and development is about 60 percent the amount of public agricultural research and development. However, only a small amount of public research in the United States is allocated to plant genetics. Federal expenditures on this category of research are below half a billion dollars, and the total US (federal and state) spending on plant genetics is below $1 billion, and the United States is the biggest spender on this research (Current Research Information System 2012). On the other hand, Monsanto alone spends about $1.5 billion on research and development annually.

to bring a genetically engineered crop to market than a nongenetically engineered crop (Just, Alston, and Zilberman 2006; Potrykus 2010).

In most of Europe and in many other countries, the production of genetically engineered crops is essentially banned. The perception of many Europeans is that agricultural biotechnology does not benefit them directly but instead only poses health and environmental risks (Paarlberg 2008; Graff, Hochman, and Zilberman 2009). European biotechnology regulations frequently rely on the precautionary principle, which neglects benefit–cost analysis and instead holds that potential risks should be avoided even absent scientific evidence of harm (Foster, Vecchia, and Repacholi 2000). Onerous regulation and de facto bans on genetically engineered crops diminish the market for the technology, lowering the expected return to seed company research and development. For instance, Graff, Zilberman, and Bennett (2009) show that Europe's introduction of a de facto ban on genetically engineered crops in 1999 was associated with a significant contraction in agricultural biotechnology research and development. Investment slowed and the number of field trials fell. As a consequence, hundreds of new traits were stranded in the research and development pipeline, including those that proposed to boost nutrient content of staple crops; extend the shelf lives of food products; enhance the efficiency of animal feed; and protect crops from drought, flood, and saline soils.

The regulatory treatment of agricultural biotechnology deserves careful scrutiny. While existing practices and safety regulations have avoided any major human or environmental health impacts, genetic engineering technologies remain confined to only a handful of commercial crops expressing only a few traits. In the future, the regulatory balance should more evenly balance pre-market testing and post-market review, depending on the novelty of the crop and the nature of the safety risk. For instance, the introduction of an already commercialized trait into a new crop should probably require a less-strenuous review than the introduction of an entirely new trait.

Conclusion

More than a decade and a half since the commercialization of first-generation agricultural biotechnology, concerns about transgenic crop impacts on human and environmental health remain, even though the experience across a cumulative 1.25 billion hectares suggests the relative safety of first-generation genetically engineered seed. The risks posed by agricultural biotechnology warrant continued attention, and new transgenic crops may pose different and bigger risks. Weighing against uncertain risks are benefits from increased food production, reduced insecticide use, and avoided health risks to food consumers and farm workers. At the same time, adoption is shown to increase herbicide use while reducing herbicide toxicity, save land by boosting yields while also making previously unfarmed lands profitable. Adoption benefits food consumers and farmers but also enriches seed companies that enjoy property right protections over new seed varieties. The

balance of scientific knowledge weighs in favor of continued adoption of genetically engineered seed, which may explain why some longtime critics have reversed course. For example, Lord Melchett, who was the head of Greenpeace, has been advising biotechnology companies on overcoming constraints to the technology (St. Clair and Frank forthcoming). Mark Lynas, a journalist and organizer of the anti–GM (genetic modification) movement, publicly apologized for helping start the movement in his "Lecture to Oxford Farming Conference" (2013).

Agricultural biotechnology remains regulated by regimes developed at the introduction of the technology. Whereas precaution may have been appropriate before the relative magnitudes of risks and benefits could be empirically observed, accumulated knowledge suggests overregulation is inhibiting the introduction of new transgenic varieties. Regulation also discourages developing-country applications, where benefits are likely greatest. In the future, new genetic traits may promise greater benefits while also posing novel risks of greater magnitudes than existing traits. Efficient innovation and technology adoption will require different and, perhaps, more stringent regulation in the future, as well as continued insights from researchers, including economists, in order to assess evolving costs and benefits.

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