The Economics of Agricultural Biotechnology Adoption: Implications for Biofuel Sustainability

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1 Introduction

Since the commercial introduction of genetically modified seed in 1996, farmers around the world have rapidly adopted the technology because of its potential to reduce pest damage and lower production costs. By 2008, 13.3 million farmers in 25 countries were annually planting 8% of global cropland to transgenic crops. In 2009, U.S. farmers planted more than 80% of the sugar beet crop to transgenic varieties that had only been introduced one year earlier. Despite the seeming popularity of agricultural biotechnology on the farm, its introduction in the marketplace has met strong resistance from critics who advocate a precautionary approach to the technology due to potential risks to humans and the environment. Consequently, genetically modified (GM) seeds and crops are banned in some countries and highly regulated in others, including those that lead in its adoption. The European Union, for instance, only lifted a de facto ban on GM crop imports in 2008, amid pressure from the United States and the World Trade Organization, which concluded European resistance lacked scientific merit. Consumer sentiment against GM foods has also constrained the market for GM seed. Products derived from GM seed are relegated to feed and fiber uses only, and producers must segregate GM crop output throughout the supply chain.

The empirical record of GM crop impacts on farm yield is mixed. Australia, for instance, experienced no measurable yield improvements from adoption of Bt cotton (Fitt 2003), but India experienced yield gains of 37% (Gurian-Sherman 2009). Estimates vary by crop and region, prompting some researchers to conclude that conventional plant breeding offers greater potential for yield improvements than genetic engineering (Gurian-Sherman 2009). The accumulating evidence, however, suggests at least modest yield improvements from GM seed adoption on average. To the extent agricultural biotechnology does improve yields, it constitutes an important source for farm productivity growth at a time when other sources are increasingly exhausted and productivity growth is lagging. From the 1940s to the 1990s, the Green Revolution generated sufficient agricultural productivity growth to increase per capita calorie production even as the world population doubled from 3 billion. Today, the agricultural community is similarly challenged to feed a growing world population. By 2050, the population will grow again by half on its way to an expected peak of 10 billion. Because of rising incomes, particularly in developing countries, demand for food is also growing on a per capita basis.

Agriculture has been challenged in the 21st century not just to fill the stomachs of 10 billion people, but also to help fill their fuel tanks. Governments around the world have begun to support production of biofuels as an alternative to oil because of growing concern about the climate impact of carbon emissions, oil scarcity, and national security considerations, including balance of payment constraints. In 2008, total support for biofuels in OECD countries was more than $11 billion, even though the sustainability of widespread biofuel production is in doubt (Steenblik 2007, VON LAMPE 2008). The environmental merits of biofuels have been questioned, particularly where production depends on converting natural land to farmland. Biofuels have also been blamed for rising food prices and for inducing a food crisis in 2008.

Since 2008, government support for biofuels has waned, or at least become more targeted. Britain, for instance, halted its plan for an ambitious biofuel program pending the completion of a thorough review of the program's likely impacts on the environment and the food supply. In the U.S., aggressive targets for biofuel production have been more narrowly targeted to advanced biofuels, an acknowledgement that biofuels are not all equally sustainable. The first generation of biofuels has yielded ethanol produced from maize and sugarcane and biodiesel made largely from soybean and rapeseed. Biofuels made from these crops are land and energy intensive and compete directly with food markets for farm output. Consequently, scientists have focused on commercializing a second generation of biofuels that produces ethanol from cellulosic feedstocks that generate more liquid fuel per unit of land and can be planted to land not already used to produce food. While the technologies work in laboratory settings, the process of scaling up the technology in a competitive way is still underway. Even if cellulosic ethanol can be competitive with fossil fuels in the future, doubt remains as to whether biofuels can ever displace considerable portions of oil demand. And if they do displace a large share of oil consumption, what will be the toll on the other principal competing uses of land? If land in food production will be kept off limits to biofuels in order to protect the food supply, then expansion of biofuel production will necessarily bring new land into production at the expense of environmental uses.

Agricultural biotechnology presents at least a partial response to the growing concerns about biofuel production. First, if today's agriculture can obtain the same rates of yield growth that were achieved in the second half of the last century, then per capita food production can grow as the population grows and still free land for production of biofuels. Adoption of GM seeds is one of the most promising sources of yield growth today. The advance of this technology can alleviate upward pressure on food prices by relaxing the constraint on the stock of land. Furthermore, the environmental record of biofuels is criticized because of the energy intensity of feedstock production and the conversion of natural land to cropland that is induced by feedstock demand. By reducing demand for cropland expansion and boosting feedstock yields, agricultural biotechnology can improve the carbon accounting of biofuels and minimize the loss of biodiversity.

This paper considers the extent to which agricultural biotechnology can lower the downside risk of biofuel adoption by reducing land scarcity and improving the productivity of biofuel feedstock production. It proceeds as follows. The next section describes the state of biotechnology and biofuels. Then, in section three, we present a prototype model of GM crop adoption that not only explains the heterogeneity of impacts demonstrated in the antecedent literature, but also projects how impacts will evolve over time. The model also yields prescriptions for policy to maximize the benefits of GM technology. The fourth section provides the first global assessment of agricultural biotechnology impacts on farm yield employing panel data methods. The results of this analysis inform numerical analysis in Section 5 of the extent to which agricultural biotechnology adoption in 2008 mitigated food price increases. This section also considers how wider adoption of agricultural biotechnology could have averted the food crisis in 2008. Section six concludes.

2 Biotechnology and Biofuels

2.1 Biotechnology

Advances in molecular and cellular biology have revolutionized crop science–permitting scientists to introduce traits from other species into crop plants. Conventional plant breeding was constrained to introducing traits from similar types of plants and yet it yielded the Green Revolution of the mid-to-late 1900s and produced dramatic gains in agricultural productivity. Agricultural biotechnology has largely generated crops that produce insecticides in order to reduce pest damage or that express resistance to common herbicides that effectively control a broad-spectrum of weeds. The applications of the technology, however, are manifold, and the potential for a "Gene Revolution" that surpasses the yield gains of the last century is high. Genetic plant engineering is expected to also yield drought-tolerant crops within the next few years and to fortify staple crops with additional nutrients that can help avert malnutrition, especially in poor parts of the world.

Genetically engineered traits have been introduced to four principal crops: cotton, maize, rapeseed, and soybean. Rapeseed and soybean seeds have been engineered to tolerate broad-spectrum herbicides like glyphosates and gluphosinates, chemicals that effectively target a host of weed species. Adoption of such herbicide-tolerant (HT) varieties permits farmers to more effectively control weeds. Absent the HT trait, farmers are forced to apply targeted chemicals in order to kill weeds and not the crop. Because glyphosates have historically sold at prices below the targeted chemicals, adoption of HT varieties is likely to reduce damage control expenditures. Some cotton and maize varieties have also been engineered with the HT trait, while others are engineered to produce *Bacillus thuringiensis* (Bt), a naturally occurring toxin that is lethal if ingested by a number of common insect pests. These are referred to as Bt crops or insect-resistant (IR) crops. Some maize and cotton varieties are engineered to express both traits and are commonly referred to as "stacked" varieties. HT traits have also been introduced into sugar beets and alfalfa, though both are planted on a relatively small scale. Crops with HT traits have always been the dominant GM crop, occupying 63% of total GM crop area in 2008, followed by "stacked" traits (22%) and IR traits (15%). HT soybeans occupied the majority of total GM-crop land (53%) and constituted 70% of the world soybean crop in 2008 (James 2008). GM maize constituted 30% of all GM crop area in 2008 and 24% of the world maize crop.

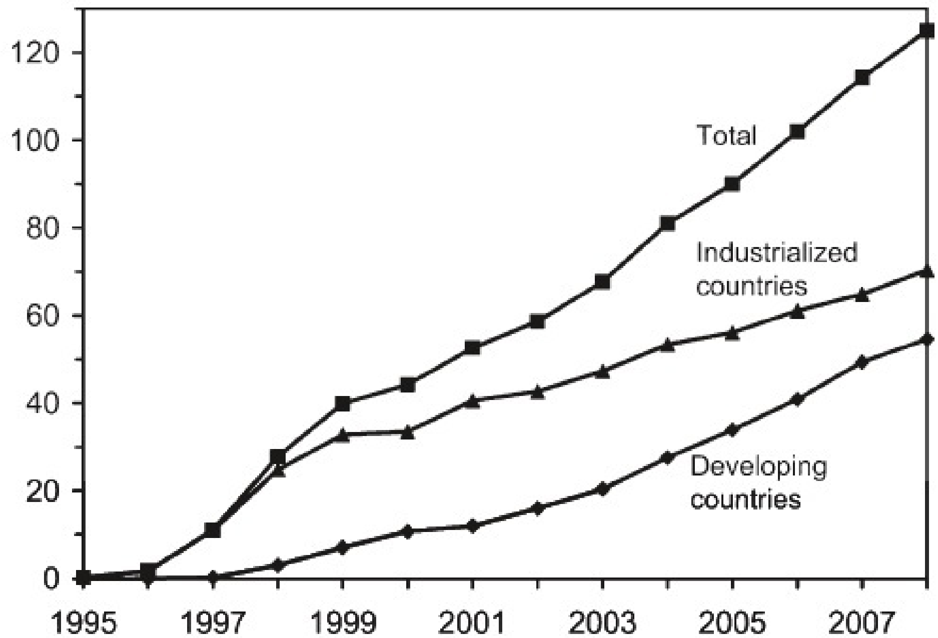
Adoption of GM crops has been rapid. The technology was first commercialized in 1996, but by 2009, half of all U.S. cropland was planted to GM seed and approximately 80% of the cotton, maize and soybean crops were each produced from transgenic varieties. The U.S. has been a leader in adoption, planting more than half (62.5 million hectares) of all GM area in 2008. But other countries have been similarly aggressive in their adoption. South Africa, Australia and Argentina all planted more than 90% of their 2008 cotton crops to GM varieties, up from 1-2% a decade earlier. Canada planted virtually its entire maize crop to GM seed in 2008. Of the 25 countries that planted GM crops in 2008, 15 were developed countries and 10 were industrialized (James 2008). Table 1 reports the total area planted to GM seed in 2008 for the 25 adopting countries and lists the GM crops planted in each country. Figure 1 shows the annual area planted to GM crops from 1996-2008 by country-type.

That 13.3 million farmers employed GM seed in 2008 and that as many as 70 million

Table 1: Adoption of GM Crops (in hectares)

Soybean													
	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
World	522,633	5,054,086	17,125,614	24,484,713	28,856,508	35,105,426	39,452,191	43,357,717	48,476,052	54,226,017	58,227,187	57,734,059	62,080,160
USA	485,633	3,197,086	11,776,609	16,390,125	18,211,251	22,177,256	24,281,667	25,738,567	27,195,467	26,871,712	27,201,368	23,433,513	27,789,960
Argentina	37,000	1,756,000	4,800,000	6,640,000	9,000,000	10,925,000	12,446,000	13,230,000	14,058,000	15,048,000	15,840,000	16,419,526	16,630,000
Brazil		100,000	500,000	1,180,000	1,300,000	1,311,000	1,742,440	3,000,000	5,000,000	9,000,000	11,400,000	13,562,500	13,320,000
Canada		1,000	49,005	200,800	212,140	320,670	435,115	522,150	662,585	705,600	764,820	688,000	880,000
Paraguay				58,288	94,117	337,500	476,969	737,000	1,200,000	1,742,500	1,928,571	2,600,000	2,327,500
Romania				15,500	36,000	18,000	33,000	40,000	70,000	87,500	130,000	0	0
Uruguay					3,000	10,000	20,000	60,000	240,000	300,000	370,000	443,520	485,100
S Africa						6,000	17,000	30,000	50,000	156,000	160,500	144,000	184,000
Mexico									14,203	10,565	6,928	5,000	10,000
Bolivia										304,140	425,000	438,000	453,600
Maize													
World	301,000	2,628,000	8,106,569	10,177,496	9,177,761	9,528,778	12,897,944	15,325,094	17,922,549	20,316,945	23,994,697	34,000,971	30,848,098
USA	300,000	2,565,000	7,859,102	9,581,325	8,048,500	7,965,360	10,855,520	12,724,000	14,610,600	17,209,920	19,336,087	27,651,963	25,459,856
Canada	1,000	63,000	212,000	379,100	446,200	582,820	731,420	715,750	706,730	845,000	891,000	1,174,000	1,190,000
Argentina			13,000	192,000	580,000	840,000	1,120,000	1,600,000	2,022,500	1,695,000	2,263,000	2,960,000	1,955,000
Philippines								20,000	54,000	70,000	132,365	385,190	350,000
S Africa					77,000	129,000	170,000	232,000	450,000	410,000	1,258,000	1,607,000	1,667,693
Spain			22,467	25,071	26,061	11,598	21,004	32,344	58,219	53,225	53,667	75,148	79,269
Uruguay								1,000	20,000	30,000	50,000	105,000	110,000
France										500	5,028	22,135	0
Portugal										780	1,250	4,263	4,851
Czech REP										270	1,290	5,000	8,380
Germany										250	950	2,685	3,173
Slovakia											30	900	1,930
Poland											30	327	3,000
Romania												360	7,146
Honduras								500	500	2,000	2,000	7,000	7,000
Egypt													800
Cotton													
World	770,740	1,158,912	1,571,270	2,399,279	5,287,560	6,809,096	6,472,951	6,690,132	8,722,825	9,480,731	13,099,203	14,281,385	14,158,407
USA	730,000	1,050,000	1,170,000	1,580,000	3,830,800	4,402,890	4,142,140	3,546,340	4,015,840	4,286,540	5,130,482	3,812,015	2,634,163
China		34,000	261,000	654,000	1,216,000	2,174,000	2,100,000	2,800,000	3,700,000	3,300,000	3,498,000	3,800,000	3,828,000
S Africa			80	752	16,000	15,000	27,000	39,000	28,000	28,800	10,038	10,250	12,000
Australia	39,843	58,235	99,560	133,850	173,000	181,996	121,516	106,500	235,055	276,598	138,750	60,800	137,859
India							44,500	100,000	500,000	1,300,000	3,800,000	5,868,000	6,972,885
Mexico	897	16,677	35,630	18,677	26,760	25,210	15,195	26,058	65,230	79,793	54,550	64,350	85,000
Columbia							2,000	7,234	18,700	21,500	13,383	21,670	28,000
Argentina			5,000	12,000	25,000	10,000	20,600	65,000	160,000	187,500	320,000	286,300	282,000
Brazil											134,000	358,000	170,000
Burkina Faso													8,500
Rapeseed													
World	148,040	604,400	1,930,080	3,035,684	2,929,541	2,677,244	2,455,760	3,483,274	3,940,996	4,931,620	4,785,429	5,597,354	5,816,912
Canada	138,040	584,400	1,900,080	2,949,079	2,672,560	2,308,972	2,087,488	3,188,656	3,704,250	4,502,620	4,400,159	5,142,541	5,429,378
USA	10,000	20,000	30,000	86,605	256,981	368,272	368,272	294,618	236,746	429,000	385,270	454,813	387,534
Australia													10,100

Figure 1: GM Crop Adoption Overtime



individual adoption decisions have been made cumulatively in the past 13-years, suggests farmers perceive benefits from adoption of GM seed that exceed the cost of technology use fees charged by seed companies. The farm-level effects of various GM seed have been studied in a number of countries. Qaim [2009] surveyed many of the studies and called attention to the empirical limitations of some studies. In general, the literature has found that HT crops provide no significant yield gain relative to conventional crops. They, do, however, provide environmental benefits (NRC 2010). They permit a substitution away from toxic, targeted chemicals that have high residual activity toward broad-spectrum chemicals like Round-Up. Application of broad-spectrum chemicals also substitutes for tillage operations, which deteriorate soil and water quality and release carbon into the atmosphere. HT crops and subsequent substitution to broad-spectrum chemicals reduced expenditures for chemicals, labor, machinery and fuel, but technology fees for HT seed reduced gross margin benefits (Qaim 2009). HT adoption is also correlated with adoption of multi-cropping. IR crops have been shown to reduce insecticide use and increase farm yields. The magnitudes of these impacts vary by country. Bt Maize in Argentina was found to provide no insecticide reductions, but adoption of Bt cotton in Mexico reduced pesticide-use 77%. Bt cotton in Australia didn't generate any yield gains, but India saw yields rise 37%. The model developed in the following section helps to explain this variation and further discussion of such wide-ranging impact estimates is reserved until then. Though gross margin effects also vary by country, the empirical studies reviewed by Qaim [2009] all showed gross margin benefits that exceed the costs of the technology. On average, farmers adopting any GM crop reported reduced crop management effort.

Despite evidence of environmental and economic benefits from GM crop adoption, the commercialization of agricultural biotechnology has met considerable resistance. The technology has been opposed by environmental groups because of the potential for GM traits to "jump" to conventional crop plants and wild plant species. If GM traits were to spread beyond dedicated fields, conventional and organic fields could be jeopardized, as could natural ecosystems. Consumers have also expressed skepticism about the technology. While commercialized crops undergo the same testing and regulatory scrutiny of other food products, fears persist that human consumption of GM foods could lead to bad health outcomes in the long-run. As a consequence, GM crop output is presently relegated to feed and fuel purposes and is not sold for human consumption. Gene flow to other plant species has not been a concern in the U.S., though some instances of gene flow to conventional crops have been documented in other countries, including Canada (NRC 2010). Risks of gene flow are likely to grow as GM crops expand to new locales and as applications of genetic engineering include more and more crops and traits.

Those who worry that GM crops threaten environmental and human health advocate a precautionary approach to the technology. Several studies have consistently shown consumers are willing to pay a premium for foods that are free of GM crops (Qaim 2009). Concern about environmental and human health impacts are a driving force behind an extensive regulatory regime (Miller and Conko 2004, Paarlberg 2008). Because GM crops are viewed as novel, regulatory regimes have been established to ensure biosafety and food safety. Most regimes emphasize ex ante trials of new trait-crop combinations, followed by ex post monitoring for adverse effects. The extensive testing process was estimated to cost \$6-15 million for approval in a single country (Just et al. 2006) and a two-year regulatory delay in deployment of GM technologies caused losses to farmers in India from foregone GM benefits on the order of \$100 million (Pray et al. 2005). In Europe, a de facto ban on GM crops was in effect from 1996 until 2008, when the WTO issued a finding against the E.U., concluding that the ban on GM crops was not supported by science. The E.U. has slowly begun to approve the planting and sale of GM crops. Heavy regulation and bans on the technology not only slow the introduction of new trait-crop combinations, but also reduce incentives for innovation in agricultural biotechnology by constraining the market and reducing the likelihood of commercialization. Miller and Conko 2004 attributed the regulatory burden facing GM technologies to a politicized debate that is not always based on sound science but rather the successful rent-seeking of anti-biotech interests.

2.2 Biofuels

Since 1973, when the energy crisis disrupted a half-century of cheap oil, government policy has promoted biofuels as an alternative to fossil fuels. Since the turn of the century, government support for biofuels has grown because of the perception that they can mitigate climate change, reduce demand for energy imports, and support rural development. In 2006, countries around the world spent an estimated \$11 billion to support biofuel production through subsidies and quotas (Steenblik 2007). By 2014, annual support is expected to grow to \$27 billion (VON LAMPE 2008), even though recent research suggests the benefits of biofuel production are not as large as was first believed in any of these dimensions. For instance, commercialized biofuel technologies were believed to offer a 25% reduction in greenhouse gas emissions relative to fossil fuels (Farrell et al. 2006). Life-cycle analysis (LCA) has become the standard by which the relative carbon intensities of different fuel technologies are compared. But even studies as recently as 2007 ignored the consequences of scaling up biofuel technologies, which include the conversion of natural land to farmland in order to produce biofuel feedstock. The carbon emissions implications of land-use change are significant and considerably reduce the carbon advantage of biofuels (Fargione et al. 2008, Searchinger et al. 2008). Searchinger et al., for instance, determined that annual production of 30-billion gallons of corn-based ethanol would not payoff the carbon debt from induced land-use change for 140 years.

Similarly, as biofuel production has grown in the past decade, it has also become clear that farmers, rural communities, and poor populations, do not universally benefit from biofuels. Growers of corn, sugarcane, soybean and rapeseed enjoy increased demand for their output, but the gains from higher output prices can be capitalized into land values, so that the farmers, themselves, do not benefit. Because biofuels increase demand for cropland generally, farmers of other commodities who do not enjoy increased demand may similarly see land rental rates climb(Taheripour and Tyner 2007). And for farmers who purchase coarse grains as inputs, such as livestock farmers, biofuels raise costs of production(Tokgoz et al. 2007). In developing countries, the landholding poor can benefit by growing biofuel feedstocks, which generally can be produced on marginal lands, but they and the landless poor also suffer from higher food prices, as was evident during the food crisis of 2008(Ewing and Msangi 2009, Msangi et al.). Finally, it is unclear existing biofuel technologies can ever yield sufficient quantities of fuel to displace a significant share of fossil fuel demand. By some estimates, the annual displacement of just 10 percent of U.S. fossil fuel demand by biofuels would require 43% of the total U.S. corn harvest (Rajagopal and Zilberman 2007).

The food crisis of 2008, which ended three decades of declining food prices, brought stark attention to the food market impacts of biofuels. The extent to which biofuel production contributed to near record-high prices for staple crops is unclear. A number of other factors also likely drove food prices up, including record-high oil prices, poor harvests in some regions of the world, low grain stockpiles, speculation, and devaluation of the American dollar, which denominates food prices (Abbott et al. 2008, Trostle 2008). Estimates of the biofuel-induced increase in food prices range from less than 10% to nearly 50%. Nevertheless, the head of the FAO blamed biofuels for the food crisis and politicians around the world responded to reports of food shortages by demanding a re-examination of biofuel promotion policies.

Because of growing recognition about the risks from escalating biofuel production, attention has turned away from the first generation of technologies and toward a second-generation that proposes to convert a broader class of plant material to liquid fuel. Cellulosic ethanol has not yet been commercially scaled-up in a way that can compete with existing oil prices. However, in the laboratory, the technology exists to convert grasses, shrubs and trees to ethanol, making use of more plant material and even agricultural waste material. Cellulusic ethanol technologies permit use of feedstocks that yield more ethanol per unit of land than corn or sugar and that do not compete so directly for land with food production. The technology also exists to create biodiesel from oils extracted from algae, though this technology, too, is in its infancy relative to corn and sugar-based ethanol. Government policies have begun to differentiate among biofuels according to general measures of sustainability. Second-generation technologies that offer the greatest greenhouse gas reductions and the least impact on food markets benefited in 2009 from larger subsidies and from production quotas that are scheduled to grow over time. Support for first-generation biofuel, increasingly viewed as a transition technology and not a panacea, is being phased out in a number of countries, including the U.S. and the U.K.

The viability of biofuel technologies as long-run alternatives to fossil fuels hinges on their performance according sustainability criteria that account for impacts on climate change, biodiversity, and food security. Agricultural biotechnology can improve the sustainability of biofuels along each of these dimensions regardless of which technology dominates. Agricultural biotechnology can directly improve the performance of biofuels if genetic engineering is applied to improving the agronomic characteristics of biofuel feedstocks. Much as existing GM traits have improved yields of food crops, feedstocks, whether grasses, trees, or algae, can also be genetically engineered to produce high yield varieties. Feedstock yield improvements lessen the land constraint, reducing demand for land conversion and upward pressure on food prices. Life-cycle greenhouse gas emissions are reduced as land-use changes decline and as emissions associated with energy inputs in feedstock production are spread over greater biofuel output. Genetic engineering may also produce feedstocks that don't just reduce crop damage but also increase the useable plant material produced by the feedstock. Agricultural biotechnology applied to food crops can also improve the performance of biofuel technologies according to both environmental and food market impacts. To the extent GM crops improve yields for food crops, they reduce demand for land for food production, effectively freeing land for biofuels. By making room for biofuels, such yield gains not only reduce greenhouse gas emissions associated with land conversion, but also lessen upward pressure on food prices that can induce food crises.

3 Theoretical Model

In this section, we develop a prototype model of agricultural biotechnology adoption that explains country-level heterogeneity in mean farm effects and offers predictions for the evolution of those impacts over time. Drawing on the threshold model of diffusion introduced by David [1969], we first develop a firm level model of technology adoption by profit maximizing firms and, then, recognize that heterogeneity of biophysical factors (e.g. land quality and pest pressure) and socioeconomic factors lead to variation in adoption decisions accros units. Our model extends the framework presented by Qaim and Zilberman [2003], which utilizes the the damage control framework of Lichtenberg and Zilberman [1986]. This framework distinguishes between inputs that directly affect production, like capital and fertilizer, and inputs that indirectly affect production by reducing crop damage, such as pesticides and biological control. Finally, we account for the tradeoff some farmers face between using a local seed variety and a GM seed variety by modeling seed attributes as embodied in four distinct technology choices. This framework is general and provides a theoretical foundation for analyzing micro-level impacts of GM crop adoption and impacts from aggregate adoption (i.e. diffusion). The micro-level model is developed here. The macro-level model will be introduced as this research moves forward.

First, to characterize the technology in a tractable way that nevertheless captures the important elements of seed technology choices, assume seed varieties differ in two principal dimensions–suitability to localities and the method of trait selection. We will assume farmers have two distinct choices along each dimension. In theory, they may choose a seed variety that has local or generic germplasm and conventional or GM breeding. The choice set of some farmers, however, may be constrained by the market. Define an indicator function i such that $i = 1$ if a seed technology is GM and $i = 0$ if the seed technology is conventional. Similarly, define the indicator function j such that $j = 0$ if a seed technology is generic and $j = 1$ if a seed technology is local. Therefore, there exist four distinct seed technology packages: generic-conventional ($i = 0, j = 0$), local-conventional ($i = 0, j = 1$), generic-GM ($i = 1, j = 0$), and local-GM ($i = 1, j = 1$). Without loss of generality, assume there are L

identical, profit-maximizing farmers who each farm one unit of land. Land varies in quality as defined by the parameter η, though each farmer operates on a homogeneous parcel and, therefore, makes a discrete adoption decision.

Following Lichtenberg and Zilberman (1986), *effective yield, y_{ij},* is defined as the realized output per acre in any period under technology package ij. It is the product of *potential yield,* $f_j(\cdot)$, and *damage abatement,* $g(\cdot)$, where *potential yield* is the maximum yield per acre that would obtain with given inputs under ideal conditions (e.g. no crop damage) and *damage abatement* is the share of potential output not lost to damage. Potential yield is a function of "directly productive" inputs, $\mathbf{z}$, like fertilizer and capital. It is higher with local seed ($j = 1$) than with generic seed ($j = 0$), i.e. $f_1(\cdot) > f_0(\cdot)$. Damage abatement is a function of "damage control" inputs, $\mathbf{x}$, and "effective" pest pressure, n. Let n be determined by the "initial" or "untreated" pest pressure, η, and a "seed technology" effect, δ_i, according to $n_i = \delta_i\eta$, where δ_i is defined on the interval $[0, 1]$.[1] It is assumed $1 = \delta_0 > \delta_1 > 0$ so that for given $\mathbf{x}$ and η, effective pest pressure is equal to initial pest pressure with conventional seed but less than initial pest pressure with GM seed. Effective yield per acre under technology ij, then is given by:

$$y_{ij} = g(\mathbf{x_{ij}}, n_i)f_j(\mathbf{z_{ij}}), \tag{1}$$

where $g_{\mathbf{x}} > 0$, $g_{\mathbf{xx}} < 0$, $g_n < 0$, $g_{nn} > 0$, $f_{\mathbf{z}} > 0$, and $f_{\mathbf{zz}} < 0$. Profit per acre under technology ij is:

$$\pi_{ij} = pg(\mathbf{x_{ij}}, n_i)f_j(\mathbf{z_{ij}}) - \mathbf{w}\mathbf{z_{ij}} - \mathbf{v}\mathbf{x_{ij}} - T_{ij}, \tag{2}$$

where p,$\mathbf{w}$, and $\mathbf{v}$ are exogenously determined prices for output, "directly productive" inputs, and "damage control" inputs, respectively, and where T_{ij} is a technology fee associated with technology ij. It is assumed $T_{00} < T_{01} < T_{10} < T_{11}$. In what follows, we assume for simplicity that production depends on application of one directly productive input and damage abatement depends on application of one damage control agent so that $\mathbf{z} = z$ and $\mathbf{x} = x$.

Farmers adopt the technology that yields the highest expected profits. We solve the farmer's problem recursively. First, conditional on seed technology choice and land quality endowments, producers choose inputs to maximize profits. The profit maximizing quantity of inputs given technology ij are functions of prices and land quality, such that:

$$\begin{aligned} x^*_{ij} &= x^*_{ij}(w, v, p, n) \\ z^*_{ij} &= z^*_{ij}(w, v, p, n). \end{aligned}$$

Maximum profits under each technology are obtained by substituting the optimal input demands into the profit function. Farmers select the technology that yields highest expected profits. Because we assume each farmer produces on one unit of land of uniform quality, the farmer adoption decision is discrete. The decision to adopt, however, will vary by farmers according to land quality.

Let k_{lm}denote the profit maximizing quantity of k for $k \in \{y, x, z\}$, $l \in \{i, 0, 1\}$, and $m \in \{j, 0, 1\}$, where l and m refer to technologies along dimensions i and j, respectively. For $l, m \in \{0, 1\}$, technology is assumed fixed as defined for $i, j \in \{0, 1\}$ and for $l = i$ and $m = j$, technology is not fixed in the respective dimension. In addition, let $\Delta_i k$ denote the change in k resulting from a change in adoption of technology along dimension i with technology dimension j unchanged, and let $\Delta_j k$ be similarly defined. Let $\Delta_{ij} k$ denote the

[1] While η is given a specific interpretation in this context, it can be defined more generally as a land quality parameter, as in Caswell and Zilberman (1986).

change in k resulting from adoption of technology along dimensions i and j. For instance, the change in damage control input resulting from the transition from a conventional-generic seed to a GM-generic seed is $\Delta_i x$ and the change in damage control input resulting from the transition from conventional-generic to GM-local is $\Delta_{ij} x$.

Given this general framework, we derive a number of propositions that define the farm-level impacts of seed technology adoption, including input-use effects, yield effects, profit effects, and agricultural extensification effects.

3.1 Input-use Effects

3.1.1 Input-use Intensity Effects

Define input-use intensity as the quantity of inputs demanded per unit of output. Then let $\tilde{x}$ denote damage control input-use intensity and $\tilde{z}$ denote "directly productive" input-use intensity such that:

$$\begin{aligned} \tilde{x}_{ij} &= \frac{x_{ij}}{y_{ij}} \\ \tilde{z}_{ij} &= \frac{z_{ij}}{y_{ij}}. \end{aligned}$$

Proposition 1. *Damage control input-use intensity may decline with adoption of IR seed.*

Proof. See Appendix A.1. □

Though GM seed is often considered a threat to environmental preservation, it does, in fact, provide environmental benefits under general conditions by reducing the application of chemicals. The above result holds for IR seed, such as Bt cotton and Bt maize, which reduce the density of pests and therefore reduce the demand for chemicals. The IR trait and chemicals are substitutes. The chemical reduction effect of IR crops has been observed in a number of countries, as will be detailed in the empirical section of this paper. However, to the extent crops are afflicted by pests not controlled by the Bt toxin, reduction of damage due to Bt-susceptible pests may increase the marginal product of chemicals used to control non-susceptible pests, which may induce greater application of those chemicals. As long as the damage reduction effect on the value of marginal product of these other chemicals is smaller than the effect on the value of marginal product of Bt substitutes, then chemical-use will still decline.

HR seed do not directly reduce crop damage, but they do permit substitution toward certain chemicals that kill conventional crop plants. This substitution reduces labor inputs and the use of mechanical control. The broad-spectrum chemicals that can be used on HT crops are less toxic that the targeted chemicals used on conventional crops, so the HT seed-induced substitution does afford environmental benefits in the form of reduced toxicity. Total use of chemicals on HT crops, however, may increase. The chemical reduction effect of IR crops has been observed in a number of countries, as will be detailed in the empirical section of this paper. However, to the extent crops are afflicted by pests not controlled by the Bt toxin, reduction of damage due to Bt-susceptible pests may increase the marginal product of chemicals used to control non-susceptible pests, which may induce greater application of those chemicals. As long as the effect on the value of marginal product of these other chemicals is smaller than the effect on the value of marginal product of Bt substitutes, then chemical-use will still decline.

Proposition 2. *If $|g_{xx}g_n| > |g_x g_{xn}|$ holds, then holding all else constant, adoption of GM seed increases use of directly productive inputs.*

Proof. See Appendix A.1. □

So long as GM seed adoption does not so dramatically reduce chemical applications that damage abatement does not increase, then the damage reduction effect of the seed, particularly IR seed, increases the value of marginal product of directly productive inputs. This effect suggests, for instance, that fertilizer and water use increases with GM seed adoption, which mitigates the environmental benefits of diminished use of damage control inputs. From an environmental perspective, this effect is detrimental to the sustainability argument for biotechnology. However, from a food security perspective, the "directly productive" input intensity effect bolsters the case for GM crop adoption. It suggests that, in addition to boosting yields by minimizing damage, which we will call the "trait effect," GM crop adoption raises yields by increasing the use of inputs that directly enhance productivity. We will call this secondary effect a "farm practices" effect.

3.2 Yield Effects, Yield Lag, and Yield Drag

3.2.1 Yield Lag and Yield Drag

Although GM seed is intended to increase yield by reducing crop damage, farmers sometimes experience a decline in yields after adopting GM seeds (Raymer and Grey [2003]). Yield suppression in GM crops has been documented by a number of empirical studies, particularly those of HT soybeans (Oplinger and Bundy [1998], Nielsen, Elmore et al. [2001b,a]). Yield suppression is caused by two distinct but related effects that reduce potential yield. The first, *yield drag*, is defined as a decline in potential yield that is a consequence of the genetic engineering process. It may be a consequence of the inserted genes or the gene insertion process. In the case of HT crops, yield lag can also be caused by glyphostate applications. The second effect, *yield lag*, is a decline in potential yield attributable to deficiencies in the seed cultivars used for GM seeds.[2] Yield lag is a direct consequence of the profit-maximizing behavior of seed companies who may not undertake effort to insert GM traits into the latest iterations of superior cultivar lines, which are often bred to tolerate region-specific agronomic characteristics. Farmers, therefore, may face a tradeoff between the greater damage reduction of GM seeds and the greater potential yield of conventional seeds that use the latest region-specific cultivars. Generally, such tradeoffs exist where farmers do not have access to GM seeds with local cultivars. Whereas yield drag may be unavoidable given the constraints imposed by existing genetic engineering technology, yield lag can be avoided if seed companies are provided the appropriate incentives.

The tradeoff posed by yield lag is incorporated into the current model, where genetically engineered traits are embodied in four seed technology "packages," by considering that the adoption of GM seed may require a change in seed technology along dimension j, i.e. a switch from either local germplasm to generic germplasm or vice versa. Given constraints on access to GM varieties that match farmers' conventional seed choice along technology

[2]Theoretically, it is possible for GM seed adoption to cause yield push–an increase in potential yield associated with GM seed adoption that forces adoption of superior seed cultivars. Given profit maximizing behavior by farmers and seed companies, the theoretical possibility for yield push is unlikely to be observed in real world conditions.

dimension j, the yield effect of GM adoption is decomposed into two parts:

$$\Delta_i y = \Delta d + \Delta v,$$

where

$$\Delta d = [g(x_{1j}, n_1) - g(x_{0j}, n_0)] \cdot f_0(z_{0j})$$

is called the *gene effect* and captures the change in damage abatement from GM adoption, and

$$\Delta v = [g(x_{1j}, n_1) - g(x_{0j}, n_0)] \cdot [f_{j_1}(z_{1j_1}) - f_{j_0}(z_{0j_0})]$$

is called the *germplasm effect* and accounts for changes in potential yield, including yield drag, yield lag, and yield push. It is assumed $\Delta d \geq 0$, i.e. GM adoption does not reduce damage abatement. The sign of Δv depends on the sign of $f_{j_1}(z_{1j_1}) - f_{j_0}(z_{0j_0})$, which can be positive, negative or zero. The germplasm effect (Δv) is positive if (a) yield push occurs (i.e. if $0j \to 1j \Rightarrow 00 \to 11$), (b) seed variety does not change along dimension j, but use of directly productive inputs increases (i.e. $00 \to 10$ or $01 \to 11$ and $z_{1j} > z_{0j}$), or (c) if yield drag or yield lag occurs, but the ratio of damage abatement with GM seed to damage abatement with conventional seed exceeds the ratio of potential yield with local seed to potential yield with generic seed (i.e. $0j \to 1j \Rightarrow 01 \to 10$ and $\frac{g(x_{1j},n_1)}{g(x_{0j},n_0)} > \frac{f_1(z_{01})}{f_0(z_{10})}$). The germplasm effect is negative if yield drag or yield lag occurs and the ratio of damage abatement with GM seed to damage abatement with conventional seed is less than the ratio of potential yield with local seed to potential yield with generic seed (i.e. $0j \to 1j \Rightarrow 01 \to 10$ and $\frac{g(x_{1j},n_1)}{g(x_{0j},n_0)} < \frac{f_1(z_{01})}{f_0(z_{10})}$). Finally, the germplasm effect is zero if adoption of GM seed does not change potential output. The more negative is the germplasm effect, i.e. the stronger are the yield drag and yield lag effects, the smaller is the increase in yield from GM adoption. If the yield drag effect is sufficiently large, it may cause the germplasm effect to overwhelm the gene effect and generate a loss in yields when GM seed is adopted. We will see that the magnitude of benefits associated with GM seed adoption depends on the strength of the yield drag effect. The magnitude of yield losses resulting from yield drag will be bounded by profit maximizing behavior, i.e. farmers may adopt GM seed even if it lowers yields if it also reduces input costs by enough to offset the loss in output. For given input prices, the magnitude of the acceptable yield loss will be limited.

Yield lag is likely to occur in developing countries, where limited purchasing power constrains seed companies' returns from investment in local cultivars, but the problem exists also in the U.S. because of capacity constraints and orphan crops. Most studies have found yield lag to be responsible where yields declined following GM seed adoption. At least one study, however, has found yield drag associated with glyphosate applications on HT soybeans (Elmore et al. 2001a). Empirical estimates of the GM yield effect that ignore yield lag will be biased estimators of the true gene effect because they will confound the yield lag effect with the gene effect. The implications of this analysis are several. First, econometric estimates of the yield effects of GM traits may understate the true gene effect and, therefore, understate the benefits of genetic engineering of crops. Second, the benefits to GM adoption can be increased with better GM seed choices, e.g. more local-GM seed. If the private sector cannot be incentivized to develop these seed varieties, then there may exist a role for public investment to better match GM seeds to local agronomic conditions.

3.2.2 Total yield effects

The change in crop yield resulting from GM seed adoption is:

$$\Delta_i y = g(x_{1j}, n_1) f_j(z_{1j}) - g(x_{0j}, n_0) f_j(z_{0j}). \tag{3}$$

It is easy to show that, for a given δ_1, the yield effect of GM seed is increasing in:

- initial potential output, $f_j(z_{0j})$
- the change in potential output, $\Delta_i f$
- initial pest pressure, η
- the effectivness of GM seeds, i.e. decreasing in δ_1

and decreasing in:

- initial damage control input use, x_{0j}.[3]

In the context of the threshold model of technology adoption, and for fixed prices, Propositions 6 though 10 explain why some farmers adopt GM seed while others do not. In the context of the antecedent empirical literature on GM yield effects, these propositions not only predict heterogeneous effects of GM seed adoption, but also explain why effects should be larger in some regions than in others. In particular, relatively small yield effects have been attributed to Bt crop adoption in the United States, where agriculture has effectively employed chemical control against pests for decades. Theory predicts small yield effects in this case. Large yield effects have been observed in India and Argentina, where pest pressure is high and chemicals are not effectively employed. In general, this model, consistent with the intuition of Qaim and Zilberman [2003], predicts larger yield effects in developing countries, which are characterized by low access to damage control capital and high pest pressure.

A corollary to Proposition 10 is that while yield effects may be low where damage control input use is high, the reduction in damage control input x will be greater than in areas that do not use conventional damage control input intensively. This follows from the concavity of damage abatement, i.e. $g_{xx} < 0$ (See Proposition 11 in Appendix A.2). Hence, relatively large reductions in chemical applications and relatively small yield gains are observed in regions that intensively use chemicals. GM Maize adoption in Spain, for instance, is reported to have boosted yields only 6% but reduced chemical use by 63% (Gomez-Barbero et al. 2008). Australia witnessed a 48% reduction in chemical use following adoption of GM cotton, but no yield gains materialized. On the other hand, countries with low levels of chemical use, like Argentina and the Philippines, benefit from relatively large yield gains but relatively small changes in chemical demand (See for instance Brookes and Barfoot 2008). The substitution from chemical applications to GM seed is largely overlooked even though it advances one goal of sustainable agriculture: to reduce chemical runoff and percolation. In reducing chemical applications, GM seed also affords the potential for carbon mitigation. Less demand for chemicals reduces the emissions in fuel intensive chemical production. It also reduces direct fuel consumption in agriculture, e.g. for tractor passes over the crop.

[3] See Appendix A.2 for proofs.

3.3 Expanding Agricultural Land

3.3.1 Extensive Margin Effects

Yield losses from pest damage raise the average cost of farm production and reduce farmer profits, which are decreasing in pest pressure. In some regions, pest pressure is so great and losses so substantial that farming is not profitable. Such land is not brought into production. By reducing effective pest pressure, GM seed adoption can turn marginal land into productive land. In doing so, GM seed adoption causes an expansion of the agricultural land base by lowering the threshold land quality (i.e. η) at which farmers are willing to produce. This effect is formalized in the following proposition:

Proposition 3. *For given prices, let $\bar{\eta}_{0j}$ denote the minimum land quality (e.g. maximum pest pressure) at which profit maximizing agricultural production with conventional seeds yields non-negative profits, so that for $n < \bar{\eta}_{0j}$, profits are negative. Then, $\bar{\eta}_{1j}$ is minimum land quality at which profit maximizing agricultural production with GM seed yields non-negative profits, where $\bar{\eta}_{1j} < \bar{\eta}_{0j}$.*

Proof. See Appendix A.3. □

The magnitude of the GM seed-induced change in threshold land quality is increasing in GM effectiveness, output price, damage control input price, initial pest pressure at the threshold, and initial potential yield. The magnitude of the change is decreasing in the technology fee associated with GM seed adoption. The quantity of land recruited to production is a function of the distribution of land quality. If there is a substantial stock of land of quality just below the initial threshold, then even small changes in effective pest pressure, i.e. even marginal improvements in damage control, can lead to the recruitment of considerable land to production.

The extensive margin effects of GM seed have largely been overlooked in the extant literature on agricultural biotechnology impacts. Nevertheless, there is evidence that these effects may be quite large. Trigo and Cap [2004], for instance, estimated that the area planted to soybeans in 2001 would have been 40% smaller without the adoption of HT seeds. A principal aim of crop science is to make marginal land productive. This objective is important from a development standpoint as it affords poor countries opportunity to move beyond subsistence farming. It is also important in the context of rising food demand because it can alleviate hunger even if agricultural productivity growth stagnates. The expansion of farmland, however, is associated with environmental damage. Land-use change not only releases sequestered carbon and sacrifices future carbon sequestration, but it also destroys natural habitat, which jeopardizes biodiversity and ecosystem services. The value of these damages varies according to the ecological importance of natural land. The conversion of tropical forest to soybean production in Argentina, for instance, can diminish global social welfare even though agricultural expansion is optimal from the landowner's perspective. In other situations, however, the employment of land in crop production can be welfare improving if the land is marginal from an environmental perspective as well as an agricultural perspective. In future research, we intend to quantify the extent of GM seed-induced land expansion and present partial analysis of the food market effects of this extensive growth.

3.3.2 Virtual Land Expansion

While the principal purpose of HT crops is to permit the use of gyphosates and gluphosinates in order to reduce the costs of agricultural production, HT seeds also enable a virtual expansion of farmland. Because they allow the use of broad-spectrum herbicides that have lower residual activity than the more toxic and targeted alternatives used on conventional crops, they minimize restrictions on subsequent crops and reduce fallow periods between crops (Graef et al. 2007, Van Acker et al. 2003). HT seed adoption also makes it more profitable for farmers to adopt no-till practices, which also reduce fallow periods. Short fallow periods and low residual chemical activity permit greater use of multi-cropping–the practice of planting more than one crop per unit of land per year. This effect of HT seed adoption essentially makes more land available for the production of crops that can be grown in rotation with HT crops. Multi-cropping has grown considerably in regions that adopt HT varieties, especially HT soybeans. In Argentina, for instance, the double cropping of soybeans following wheat harvests has increased dramatically. In 2000, the adoption of wheat-soybean double-cropping resulted in a virtual increase of 3 million hectares of arable land in Argentina (Trigo and Cap 2004). Reliable data on the use of double cropping is scarce. Nevertheless, it is evident that a considerable benefit of GM seeds that is often overlooked, is the ability to farm land more intensively by growing more than one crop each year. In future research, we hope to quantify the output effects of GM-seed-induced multi-cropping and its welfare implications.

4 Estimating GM Seed Impacts

The wide-ranging estimates of GM seed impacts in the existing literature have engendered doubt as to whether genetic plant engineering can help resolve the challenges facing 21st century agriculture. The theory developed in the preceding section explains much of the variation in empirical estimates of GM seed impacts and should, therefore, reduce uncertainty about the efficacy of agricultural biotechnology. The antecedent literature, however, has also been criticized on methodological grounds. Attempts to estimate the average partial effect of GM seeds on farm outcomes like yield, input demand, and farmer profit are hindered by the characteristics of farm management decisions. In particular, agricultural technology adoption decisions are endogenous because they result from profit-maximizing behavior. Consequently, the likelihood of adopting technology is correlated with farm-level characteristics like access to information, credit availability, human capital, land quality, risk preferences, and labor constraints (e.g. Feder et al. 1985, Marra et al. 2003). These characteristics are likely also correlated with outcomes of interest and are usually unobservable to the econometrician. Because unobserved characteristics of GM adopters are correlated with farm outcomes and systematically differ from non-adopters, the "ignorability of treatment" is violated (Rosenbaum and Rubin 1983) and standard estimators will suffer from selection on unobservables.

The bulk of the existing empirical work has either ignored selection problems or responded to such concerns by randomizing adoption in controlled settings. Neither approach is completely satisfactory. Crost et al demonstrated that efficient farmers are more likely to adopt GM seeds than inefficient farmers. Studies that fail to account for selection, therefore, are likely to overstate the true average partial (or "treatment") effect (APE or PATE) of GM seed adoption. Studies that randomize treatment assignment, like Qaim and Zilberman (2003) and Huang et al. (2005), overcome selection bias, but have their own limitations. First, because randomized trials are costly, they are necessarily limited in duration and scope. They may estimate the APE with observations covering as little as one growing region and one season. To the extent that stochastic forces that affect farm outcomes, like pest pressure and weather, deviate from their means during the observation period, estimates of the APE will be inconsistent. Qaim et al. [2006] noticed that the yield effect of Bt cotton is stochastic, varying over time with changes in yield, pest pressure, and seed variety. Their analysis emphasizes the limitation of studies that are restricted to analysis of a few growing seasons, like Qaim and Zilberman [2003]. They suggested the value of studies like Crost et al. [2007], which employed panel data methods that exploit the dynamics of adoption and the time-series dimension of the data in order to eliminate heterogeneous farm-level effects. Using data covering Bt cotton adoption in India, they conclude after controlling for selection, that GM seed adoption generates significant yield gains and increases profits.

While most of the literature on impacts of GM crops has used regional data, limiting the external validity of analysis, we employ a panel of national-level data on production and GM trait adoption to determine the effect of GM trait adoption on output. The literature on agricultural productivity (e.g. Ball et al. 1997) has not estimated the impacts of specific seed varieties and relies on data and modeling different from ours. Our analysis applies the method of Just et al (1990) to country-level data. Just et al. [1990] modeled agricultural production assuming fixed coefficients that may vary across time and regions. The method is supported by the large body of literature relying on the von Liebig production function in agriculture (Paris 1992).

4.1 Data and Methods

The empirical strategy of this paper is motivated by the global pattern of GM seed adoption. By 2008, farmers in 25 countries had planted at least one of the four major GM crops. In most cases, the share of these crops planted to GM seed increased year over year in adopting countries from 1996 to 2008. In the U.S., for instance, 12% of cotton was planted to GM seeds in 1996, but by 2007 the GM share had reached 87%. Some countries adopted multiple GM crops and many others did not adopt any GM crops. Furthermore, countries that did adopt GM crops continued to plant other crops exclusively to conventional seed because GM alternatives did not exist or because regulation banned some GM crops. The variation in GM adoption across countries and across time permits identification of the population average partial effect of GM seed adoption on yields using a panel fixed effects approach that relies on assumptions similar to, but weaker than, those required for estimation in triple differencing procedures.

Motivated by Just et al. [1990], we observe that total output of crop j in country i at time t, Q_{jit}, is the sum of output produced by each seed technology, k, so that

$$Q_{jit} = \sum_{k=1}^{K} Q_{jitk}, \tag{4}$$

where Q_{jitk} is the unobserved quantity of crop j produced by country i at time t using seed technology k. Define L_{jitk} as the amount of land planted to crop j with seed technology k in country i at time t. Then $q_{jitk} = Q_{jitk}/L_{jitk}$ is the output of crop j per unit of land using seed technology k in country j at time t. The deterministic component of the q_{jitk}, which is denoted q^*_{jitk}, can be decomposed into a crop-specific average seed-technoogy effect, β_{jk}, a crop specific time effect, γ_{jt}, and a country-specific crop effect, δ_{ji}. Then q^*_{jitk} is given by:

$$q^*_{jitk} = \beta_{jk} + \gamma_{jt} + \delta_{ji}. \tag{5}$$

The β_{jk} are of interest and can be estimated by

$$Q_{jit} = \delta_{ji} L_{jit} + \sum_{k=0}^{K} [\beta_{jk}] L_{jitk} + \gamma_{jt} \mathbf{D_{jt}} + \epsilon_{jit} \quad (6)$$

where L_{jit} is total land planted to crop j in country i at time t,$\mathbf{D_{jt}}$ is a crop-specific time dummy (the time dummy for the year 2008 is omitted), andϵ_{jit} is a random deviation that is assumed normal and identically distributed. Equation (6) is estimated using fixed effects to control for country effects and secular trends. The fixed effects regression also controls for correlated random trends (Wooldridge 2005). Results are reported with White robust standard errors. The β_{jk} are interpreted as the marginal effect of seed technology adoption on per-acre output in tons per hectare.

We estimate two variations of the model in (6). The first permits identification of an aggregate GM-crop adoption effect. In this case, $K = 1$, where $k = 1$ denotes $k = 1$ denotes GM seed. In the alternative specification, GM-crop area is decomposed into the areas in each GM trait in order to separately estimate the yield effects of adopting seed expressing IR and HT traits, or both. In this case, $K = 3$, where $k = 1$ denotes IR seed, $k = 2$ denotes HT seed and $k = 3$ denotes "stacked" seed. Data on total crop output are reported in tonnes and come from the Food and Agriculture Organization of the United Nations (FAO). Total crop area is reported in hectares by FAO. The area of land planted to GM crops and specific traits was developed by Graham Brookes using data from the International Service for the Acquisition of Agri-Biotech Applications (ISAAA). The data cover the period 1990-2008. We include data on every country that adopted any GM crop from 1996-2008, as well as the top 100 gross producers of eight principal row crops during the period 1990-2008. For these 100 countries, we include observations on each of the four major GM crops (corn, cotton, soybean, and rapeseed) and each of four other principal row crops: wheat, rice, sorghum, and oats. These data comprise 10,717 annual country-level observations on crop output and GM seed area covering 627 country-crop groups. Because not all countries planted all eight crops in every year, the data constitute an unbalanced panel. Summary statistics are provided in Tables 2 and 3.

4.2 Results

In the first econometric analysis of the global yield effects of GM seed adoption, we find that agricultural biotechnology generally produces significant yield improvements relative to non-GM seed. Table 4 reports results from estimation of (6) for $K = 1$, which identifies the marginal yield effect of GM seed adopton in the aggregate.[4] In all cases, the coefficients of interest are statistically significant at the 99% level, and, for all crops, GM-seed increases yield relative to conventional seed. Row 1 of Table 10 reports the gain in yield from adoption of GM seed as a percent of total yield per acre.[5] Consistent with the theory introduced in the preceding section, the GM seed effect is greatest for crops with IR traits. Yield gains for GM cotton and maize–available in IR, HT and stacked varieties–are estimated to be 65% and 45.6%, respectively. Yield gains for HT rapeseed and soybean are 25.4% and 12.4%, respectively. These estimates reflect the fact, as theory suggests, that yield gains are larger for seeds expressing IR traits than for seeds expressing only HT traits because the HT trait largely permits substitution to cheaper and less toxic chemicals. The primary effect of HT seed, then, is to reduce production costs, not crop damage. As damage control

[4] Only coefficients of interest are reported. Full results are available from the authors by request.

[5] Determined as $100 \cdot \frac{\delta_{ji}}{\beta_{jk}}$.

Table 2: Summary Statistics: GM and Trait Shares

	All	Developing	Developed	Adopters	Non-adopters
			Cotton		
Yield	15521.02	14155.02	27981.82	19070.02	14492.22
	(9278.3)	(7954.58)	(11074.55)	(10174.24)	(8741.64)
GMO Seed Share	0.03	0.02	0.11	0.13	-
	(0.14)	(0.11)	(0.26)	(0.27)	
HT Seed Share	0.01	0.01	0.08	0.06	-
	(0.06)	(0.21)	(0.09)	(0.18)	
IR Seed Share	0.02	0.02	0.08	0.11	-
	(0.11)	(0.09)	(0.20)	(0.21)	
Observations	1326	1195	131	298	1028
			Maize		
Yield	34603.04	25987.91	68774.78	43716	31515.07
	(26844.58)	(17823.54)	(29293.47)	(25478.89)	(26601.66)
GMO Seed Share	0.01	0.01	0.03	0.05	-
	(0.09)	(0.07)	(0.13)	(0.17)	
HT Seed Share	0.00	0.00	0.01	0.01	-
	(0.03)	(0.01)	(0.07)	(0.07)	
IR Seed Share	0.01	0.00	0.02	0.05	-
	(0.07)	(0.06)	(0.09)	(0.14)	
Observations	1778	1420	358	450	1328
			Rapeseed		
Yield	16164.46	13623.73	20363.35	17313.31	15421.09
	(8082.97)	(6935.72)	(8104.34)	(7674.74)	(8259.82)
GMO Seed Share	0.02	0.01	0.05	0.05	-
	(0.11)	(0.07)	(0.18)	(0.18)	
Observations	756	471	285	297	459
			Soybean		
Yield	15760.13	14334.7	21177.71	18841.01	14559.26
	(8049.531)	(7789.70)	(6594.89)	(5634.42)	(8518.927)
GMO Seed Share	0.03	0.01	0.04	0.12	-
	(0.15)	(0.07)	(0.17)	(0.27)	
HT Seed Share	0.03	0.03	0.04	0.12	-
	(0.16)	(0.15)	(0.17)	(0.27)	
Observations	1469	1163	306	412	1119

Reported: means w/ standard deviatons in parentheses

Table 3: Summary Statistics: Harvest, GM and Trait Areas

	All	Developing	Developed	Adopters	Non-adopters
			Cotton		
Harvest Area	474349.9	428056	896649.6	1379338	212009.1
	(36980.19)	(37104.66)	(155609.4)	(145291.9)	(14420.28)
GM Area	68553.91	40843.28	321334.1	305041.9	-
	(13715.36)	(11320.57)	(90135.19)	(59087.57)	
HT Area	14809.95	794.3732	142662	65899.31	-
	(4238.486)	(326.7462)	(41290.66)	(18581.88)	
IR Area	45593.07	39889.99	97617.34	202873.9	-
	(10514.57)	(11313.96)	(25651.71)	(45686.3)	
Observations	1326	1195	131	298	1028
			Maize		
Harvest Area	1479825	1360254	1954099	4148485	575534.7
	(98446.21)	(88076.3)	(341315.7)	(355597.3)	(21051.8)
GM Area	109796.7	15909.59	482198.3	433819.1	-
	(30228.59)	(4282.138)	(147695.1)	(118219)	
HT Area	48679.08	2454.091	232029.6	192336.5	-
	(18522.17)	(861.1469)	(91386.47)	(72822.68)	
IR Area	97552.94	14295.37	427792.5	385442.5	-
	(29210.24)	(3861.429)	(143092.3)	(114434.1)	
Observations	1778	1420	358	450	1328
			Rapeseed		
Harvest Area	579795	586433.9	568823.4	1378898	62728.59
	(56032.14)	(78956.79)	(71337.53)	(129412.5)	(5906.965)
HT Area	56013.8	-	148584	142580.6	-
	(16089.23)	-	(42155.01)	(40484.63)	
Observations	756	471	285	297	459
			Soybean		
Harvest Area	955104.9	729134.4	1813940	3208778	76662.81
	(100410.5)	(78176.62)	(376048)	(333191.7)	(5633.527)
HT Area	324252.1	185842	850301	1156132	-
	(62136.7)	(42322.81)	(249257.4)	(216403.6)	
Observations	1469	1163	306	412	1119

becomes more cost effective, however, increased damage control effort will be undertaken, which boosts effective yields and may boost potential yield as well.

The yield effects of specific GM traits are estimated by Equation (6) for $K = 2$ and are reported in Table 5. For cotton, the HT trait is estimated to have a negative impact on yield that is significant at the 99% level. This estimate may reflect yield lag and yield drag, two effects that have been shown in the literature to reduce HT crop yields in some cases. Furthermore, HT seed availability leads to an expansion to more marginal farmlands, which may, at least partially, explain the negative yield effect observed in the data. The IR trait is estimated to nearly double yields of non-GM cotton varieties as is the stacked seed technology. Both effects are statistically significant at the 99% level. Estimated trait effects for maize are a bit more difficult to reconcile with theory. The HT and IR trait effects are significant both in magnitude, increasing yield 65% and 56%, respectively. The stacked seed, however, are shown to reduce yields nearly 160%, an effect that is significant at the 99% level. Given a high degree of correlation between stacked area and IT and HT area within crop, conditional on any GM trait area being positive, it may be difficult to separately estimate the trait effects. Trait specific estimates for rapeseed and soybean are as reported in Table 4 because only HT traits have been commercialized for each crop. The yield gains are 25% and 12%, respectively (see Row 1 of Table 11).

In order to test the theory that yield gains from GM crop adoption will be greatest in regions that suffer high pest pressure and have diminished access to chemical pest control agents, we estimate (6) separately for developed and developing countries. Because many developing countries effectively employ chemical pest control agents and because pest pressure is expected to be greatest in tropical regions, categorizing countries by economic status is admittedly crude. The development literature has struggled, however, to develop appropriate country classifications according to agro-ecological factors and doing so is beyond the scope of this paper. Nevertheless, estimated yield effects from the separate regressions of the developed and developing country samples does support the theory from Section 3. The separate estimation of "GM-seed" effects for developed and developing countries are reported in Tables 6 and 7, respectively. The magnitudes of these effects relative to conventional seed effects are summarized in Rows 2 and 3 of Table 10. The estimated yield gains associated with GM seed are greater in developing countries than in developed countries for each GM crop. These differences are statistically significant at the 95% level. The trait effects are also separately estimated by country-type and reported in Tables 8 and 9, and related to overall yields in Rows 2 and 3 of Table11. It is notable that stacked seed technology has no significant effect on yields in developing countries, a fairly large and significant effect on cotton yields in developed countries, and a large and significantly negative effect on maize yields in developed countries.

In general, we find effects of GM seed adoption that are statistically significant and large in magnitude. In some cases, the estimates are consistent with previous empirical work. In other cases, the results are considerably larger (both postive and negative) than the literature suggests. However, unlike studies based on field trials, we have not endeavored to estimate a "gene" effect, but rather the GM-adoption effect, which incorporates behavioral responses to GM adoption, including the adoption of other technologies and farming practices. These other responses are expected to boost yields, so that the adopton effect should dominate the gene effect. Large negative effects can perhaps be explained by the expansion of farming to less desirable land, which while profitable, may yield less output per hectare.

Table 4: GM Seed Adoption Effects

CROP	(1) Total Area	(2) GM Area
Cotton	1.313***	0.854***
	(0.220)	(0.130)
Maize	6.363***	2.902***
	(0.548)	(0.419)
Rapeseed	1.499***	0.382***
	(0.128)	(0.107)
Soybean	2.461***	0.307***
	(0.203)	(0.112)
Oats	1.202***	
	(0.0917)	
Rice	5.094***	
	(0.545)	
Sorghum	1.236***	
	(0.194)	
Wheat	2.257***	
	(0.254)	
Constant	-366994	
	(239633)	
Observations	10717	
Number of groups	627	
R-squared	0.728	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 5: GM Seed Adoption Effects by Trait

	(1)	(2)	(3)	(4)
CROP	Total Area	IR Area	HT Area	Stacked Area
Cotton	1.188***	1.151***	-0.991***	1.133***
	(0.212)	(0.217)	(0.218)	(0.213)
Maize	6.555***	3.674***	4.270***	-10.44***
	(0.541)	(1.236)	(1.641)	(3.744)
Rapeseed	1.499***		0.382***	
	(0.128)		(0.107)	
Soybean	2.461***		0.307***	
	(0.203)		(0.112)	
Oats	1.202***			
	(0.0917)			
Rice	5.094***			
	(0.545)			
Sorghum	1.236***			
	(0.194)			
Wheat	2.257***			
	(0.254)			
Constant	-405234*			
	(239773)			
Observations	10717			
Number of groups	627			
R-squared	0.733			

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 6: GM Seed Adoption Effects in Developed Countries

	(1)	(2)
CROPS	Total Area	GM Area
Cotton	1.407***	0.322***
	(0.267)	(0.105)
Maize	12.44***	1.890***
	(2.867)	(0.485)
Rapeseed	1.538***	0.370***
	(0.126)	(0.0994)
Soybean	2.784***	0.196
	(0.624)	(0.164)
Oats	2.149***	
	(0.115)	
Rice	5.381***	
	(1.154)	
Sorghum	4.572***	
	(0.366)	
Wheat	2.189***	
	(0.222)	
Constant	-453968*	
	(262868)	
Observations	2208	
Number of groups	150	
R-squared	0.848	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 7: GM Seed Adoption Effects in Developing Countries

CROP	(1) Total Area	(2) GM Area
Cotton	1.062***	1.163***
	(0.239)	(0.219)
Maize	5.404***	3.048***
	(0.508)	(0.409)
Rapeseed	1.476***	
	(0.210)	
Soybean	2.120***	0.640***
	(0.273)	(0.191)
Oats	1.123***	
	(0.0912)	
Rice	5.058***	
	(0.549)	
Sorghum	0.966***	
	(0.124)	
Wheat	2.250***	
	(0.390)	
Constant	-453968*	
	(262868)	
Observations	8509	
Number of groups	477	
R-squared	0.650	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 8: GM Seed Adoption Effects by Trait in Developed Countries

	(1)	(2)	(3)	(4)
CROP	Total Area	IR Area	HT Area	Stacked Area
Cotton	1.584***	1.137***	-1.123***	1.298***
	(0.320)	(0.304)	(0.182)	(0.163)
Maize	14.41***	3.139***	3.815*	-11.64***
	(2.384)	(1.131)	(1.946)	(3.511)
Rapeseed	1.538***		0.370***	
	(0.126)		0.0996)	
Soybean	2.784***		0.196	
	(0.624)		(0.164)	
Oats	2.149***			
	(0.115)			
Rice	5.381***			
	(1.155)			
Sorghum	4.572***			
	(0.366)			
Wheat	2.189***			
	(0.222)			
Constant	-1.368e+06*			
	(781999)			
Observations	2208			
Number of groups	150			
R-squared	0.875			

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 9: GM Seed Adoption Effects by Trait in Developing Countries

CROP	(1) Total Area	(2) IR Area	(3) HT Area	(4) Stacked Area
Cotton	1.047***	1.166***	-1.138**	-0.775
	(0.240)	(0.220)	(0.449)	(1.014)
Maize	5.413***	2.458***	7.140**	-4.811
	(0.511)	(0.597)	(3.520)	(5.982)
Rapeseed	1.476***			
	(0.210)			
Soybean	2.120***		0.640***	
	(0.273)		(0.191)	
Oats	1.123***			
	(0.0912)			
Rice	5.058***			
	(0.549)			
Sorghum	0.966***			
	(0.124)			
Wheat	2.250***			
	(0.390)			
Constant	-455689*			
	(262618)			
Observations	8509			
Number of cntry_crop_num	477			
R-squared	0.650			

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 10: Yield Gain from GM Seed as Percent of Yield

VARIABLES	(1) Cotton	(2) Maize	(3) Rapeseed	(4) Soybean
All Countries	65.042	45.607	25.484	12.475
Developed Countries	22.886	15.193	24.057	7.040
Developing Countries	109.510	56.403	-	30.189

Table 11: Yield Gain from GM Traits as Percent of Yield

VARIABLES	(1) Cotton	(2) Maize	(3) Rapeseed	(4) Soybean
HT All	-83.418	65.141	25.484	12.475
HT Dev'd	-70.896	26.475	24.057	-
HT Dev'g	-108.691	131.905	-	30.189
IR All	96.886	56.049	-	-
IR Dev'd	71.780	21.783	-	-
IR Dev'g	158.548	45.409	-	-
Stacked All	95.370	-159.268	-	-
Stacked Dev'd	81.944	-80.777	-	-
Stacked Dev'g	-	-	-	-

5 Biofuel Sustainability

In 2008, a global food crisis induced hunger and starvation in poor regions of the world as prices for grains rose dramatically and major food producing countries slashed exports to protect domestic markets. The crisis served a painful reminder after three decades of declining food prices that with a growing world population and complacency about crop science, a victory over hunger would only be temporary. The dramatic run-up in food prices in 2008 coincided with record biofuel production (Figure 2 shows the rapid growth in world biofuel production.), so much of the blame for food insecurity was leveled at the diversion of harvest from food to fuel-uses. At the same time as biofuel production was blamed for the food crisis, researchers began to question the conventional wisdom that biofuels provided at least some greenhouse gas savings relative to conventional fuel. In particular, attention to the land-use implications of growing demand for agricultural production yielded estimates that as biofuel production scaled-up to meet policy mandates, the conversion of natural land to cropland would induce a carbon debt that U.S. corn ethanol would not payoff for more than 100 years. Searchinger et al. [2008] noted that while biofuels were credited with sequestering CO2 in plant material until it was combusted as fuel in car engines, they were not charged for the carbon sequestration lost from land-use change or for the future carbon sequestration that is forsaken by the replacement of natural land with less absorptive cropland. Based on general equilibrium modeling, they found that scaled-up U.S. corn ethanol would double carbon emissions over 30 years because of the carbon impact from land-use change. That carbon debt would only be paid off over 167 years. Similar findings for other forms of biofuel were reported by Fargione et al. [2008].

The accumulation of reports showing dramatic food market effects of biofuel production and its medium-term increase in carbon emissions have fueled debate about the sustainability of biofuels and prompted governments around the world to reconsider support for the technology. The food market impacts of biofuels can be minimized and their carbon balance improved by greater adoption of agricultural biotechnology. As the preceding section showed, the first generation of genetically modified crops improves farm yields. This intensification of production reduces demand for extensive growth. In other words, yield gains from GM crops effectively reduce demand for land and other farm inputs, reducing costs of producing food, feed and fuel and reducing the conversion of natural land to productive uses.

The adoption of agricultural biotechnology, however, has been and remains constrained by regulation that precludes farmers in many countries from planting GM seed and closes off markets to farmers in other countries who can. While many papers (e.g. Bernauer and Meins [2003], Hoban [1998], Runge et al. [2001], Sheldon [2004]) have suggested the divergence in policy between aggressive adopters like the U.S. and Argentina and non-adopters like European and African countries reflects differences in consumer preferences, particularly risk preferences, others attribute it to political economy considerations (Prakash and Kollman 2003, Graff et al. 2009, Paarlberg 2008, Graff et al.). European non-adoption, in this context, is not an expression of social welfare maximization, but rather of rent seeking and protectionism. In African countries, non-adoption reflects influence from the former colonial powers in Europe and limited human and political capital. China, an aggressive adopter of GM cotton, has yet to approve production of GM crops for food or feed. Precautionary policies in Europe and many developing countries have resulted not just in their non-adoption of already developed GM traits, but also induced a global slowdown in development of second-generation traits (Graff et al. 2009). Patent applications and investment in research and development have fallen because constrained markets reduce the likelihood that the high costs of new seed registrations will be recouped. Even in the U.S., where GM traits have been approved for soybeans, maize, cotton, rapeseed, sugar beets, and potatoes, the regulatory burden facing seed manufacturers is considerable. New transgenic trait products must undergo a battery of ex-ante testing in order to ensure efficacy and human and environmental safety before they are commercially introduced (Zilberman 2006). After their introduction, transgenic trait products are routinely monitored and reevaluated. The cost of regulatory compliance for a single crop-trait combination ranges from $6 million to $15 million (Just et al. 2006).

5.1 What would have been (without GM crop adoption)

Food prices reached near-record levels in 2008, with some commodity prices nearly doubling over just a few-year window and food indexes climbing 56% in one year. Without the yield improvements afforded by agricultural biotechnology adoption, prices would have climbed even higher. Using partial equilibrium analysis, it is possible to consider what would have happened to food markets in 2008 if observed levels of biofuel production had prevailed and yield gains from GM seed adoption had not. To this end, we employ a multi-market framework to model the impacts of 2008 biofuel production on soybean, maize, wheat and rapeseed. We assume a global market for commodities and simulate three separate assumptions on own and cross-price elasticities of demand and supply. These scenarios are summarized in Table 12. Scenario 1 is characterized by reasonable elasticity assumptions based on estimated elasticities in the literature. Scenario 2 is characterized by more elastic demand and Scenario 3 incorporates greater substitutability among crop supply. We further parameterize the model based on observed prices and quantities in 2008. We then consider the price effect of biofuel production by subtracting biofuel demand and finding the new equilibrium price.

Global biofuel production in 2008 recruited 86 million tons (10%) of global maize production and 8.6 million tons of global vegetable oil, which we assume was equally drawn from soybean and rapeseed production to constitute 7% of the global rapeseed harvest and

Table 12: Simulation Scenarios

	Scenario 1	Scenario 2	Scenario 3
Own-price elasticity of demand	-0.30	-0.5	-0.30
Own-price elasticity of supply	0.30	0.30	0.30
Cross-price elasticities of demand	0.05	0.05	0.05
Cross-price elasticities of supply	-0.10	-0.10	-0.075

Table 13: Simulating Food Price Effects of Biofuel with and without Biotechnology

	2008 Price	No biofuel	No biotech	%Change No biofuel	%Change No biotech
Scenario 1: Base					
Corn	223.13	133.28	300.24	-40.27	34.56
Soybean	474.74	337.96	676.55	-28.81	42.51
Wheat	268.59	197.87	342.25	-26.33	27.42
Rapeseed	604.92	385.7	802.32	-36.24	32.63
Scenario 2: Elastic demand					
Corn	223.13	178.7	256.4	-19.91	14.91
Soybean	474.74	337.96	575.33	-28.81	21.18
Wheat	268.59	197.87	293.51	-26.33	9.27
Rapeseed	604.92	385.7	685.91	-36.24	13.38
Scenario 3: Increased substitutability					
Corn	223.13	157.19	274.76	-29.55	23.14
Soybean	474.74	390.711	623.64	-17.70	31.36
Wheat	268.59	227.95	310.92	-15.13	15.76
Rapeseed	604.92	451.37	732.85	-25.38	21.15

2% of the global soybean harvest. This increased demand for maize, soybean and rapeseed increased prices 67%, 40%, 36% and 57% for maize, soybean, wheat, and rapeseed, respectively. As reported in Table 13, world prices for these for commodities would have been between 26% and 40% lower without biofuel demand given the assumptions of Scenario 1. Without the yield gains of global biotechnology production, 2008 prices would have been considerably higher. Corn prices would have been 35% higher, soybean prices 43% higher, wheat prices 27% higher, and rapeseed prices 33% higher.[6] As is also shown in Table 13, even under the assumptions of more elastic demand (Scenario 2) and supply substitutability (Scenario 3), GM crop adoption in 2008 alone significantly reduced food prices. The cumulative effect of GM yield gains over the past 14 years is likely greater still. Given the degree of suffering near-record-high commodity prices in 2008 induced among poor populations, it is likely that agricultural biotechnology adoption helped to avert starvation and death. A more complete characterization of the welfare effects of biofuel and biotechnology adoption is the subject of ongoing research.

[6]An estimate of the global production gains attributable to biotechnology adoption was determined for each maize, soybean and rapeseed by multiplying observed country-level production in 2008 by the country-appropriate estimate of the GM-induced percentage increase in yield and the country-crop-year specific GM-crop share. These estimates determined GM-induced output gains to constitute 5%,11% and 4% of total output for maize, soybean, and rapeseed, respectively.

5.2 What could have been (with more GM crop adoption)

If GM crop bans in non-adopting countries were lifted, the yield-enhancing benefits of agricultural biotechnology could further improve the sustainability of biofuels by lessening food market impacts and reducing land-use change. Many estimates of the effects of scaled-up biofuel production on food security and environmental preservation assume current rates of crop yield growth persist. Searchinger et al. [2008], for instance, assumes any technology-induced increases in the rate of productivity growth are offset by yield losses resulting from expansion to marginal lands. But wider adoption of existing GM crops can dramatically increase yields today and encourage development of new genetically engineered traits. Using the yield gains from GM seed estimated in Section 4, we consider the extent to which greater GM crop adoption could have offset the food market and land-conversion effects of biofuel production in 2008. Mitchell [2008] estimated that 86 million tons of maize–11% of global maize production–were diverted in 2008 to worldwide production of ethanol. Global biodiesel production recruited 8.6 million tons of vegetable oil–7% of world production in 2008. The increase in demand for soybean and corn induced farmers to substitute away from production of wheat. Mitchell [2008] estimated biofuels reduced the world wheat harvest by 26 million tons and Searchinger projected a loss of 10.8 million hectares of natural land in order to boost U.S. biofuel production by 56-billion liters over 2016 baseline projections.[7]

If GM maize were fully adopted in the top-5 maize-producing countries in South Africa, namely Nigeria, Egypt, Ethiopia, Tanzania, and Malawi, at the same rate as adoption in the U.S. in 2008, the GM seed yield gains would have resulted in an additional 9 million tons of maize production in 2008, assuming average yield gains obtained. If yield gains in these developing countries matched the estimated average yield gain in developing countries, then maize production would have been 11 million tons higher. If China, a GM cotton adopter, were to adopt GM maize at the same rate as the U.S., the yield gains from GM maize would have boosted output by 60.5-75 million tons, depending on whether average or developing country average yield gains obtain. And similarly, U.S. rates of GM maize adoption in the top-5 maize producing countries in Europe would have generated an additional 17 million tons of maize in 2008, assuming average yields obtain. If developed country average yield gains obtained, production would have been 5.7 million tons higher. These results are reported in Table 14. A conservative estimate, then, is that complete adoption of GM maize in these 11 non-adopting countries, would have boosted maize production by 75 million tons in 2008, replacing 87% of the 86 million tons of maize that was consumed in ethanol production. This suggests that the near-tripling of maize prices from 2005-2007, which Mitchell ascribed largely to biofuel production, would have been mostly avoided had top maize producing countries around the world adopted GM maize at rates observed in the U.S.

If HT soybean and HT rapeseed had been more aggressively adopted by 2008, then output gains from GM-led productivity growth could have more than replaced the 8.6 million tons of vegetable oils recruited to energy production. For instance, if the top-10 non-adopting soybean producers had instead adopted GM soybeans at the same rate as the U.S. and achieved the global average yield gains estimated in Section 4, then total soybean output would have been 1.6 million tons higher. In addition, the ban on GM seed in Romania that accompanied the country's accession to the European Union, led to a precipitous 75% decline in area planted to soybean. If the 131,000 hectare-decline in soybean area following the

[7] S. Tokgoz et al, "Data files for revised 2015/16 baseline and scenario without E-85 constraint" (Center for Agricultural and Rural Development, Iowa State University, Ames, IA, 2007)

GM soybean ban had not occurred, Romanian soybean output alone would have been 0.29 million tons higher than it was in 2008. If the top-10 non-adopting rapeseed producers had aggressively adopted GM rapeseed at the same rate as the U.S., then total rapeseed output in 2008 would have been 9.46 million tons higher, assuming global average GM rapeseed yield gains obtained. Total adoption in China alone would have boosted 2008 output by 3 million tons. In total, adoption of GM rapeseed and soybean by the top rapeseed and soybean producing countries would have yielded 10.9 million tons more vegetable oil than was actually produced in 2008, enough to more than offset the vegetable oil diverted to biodiesel production. These results are summarized in Table 15

Finally, increased demand for maize and soybean for biofuels crowded out wheat production as farmers responded to record-high maize and soybean prices by substituting away from wheat production. Mitchell estimates world wheat production was 26 million tons lower in 2008 than it would have been absent biofuel production. Agricultural biotechnology could have helped offset foregone wheat production as well. Monsanto developed HT wheat varieties more than five years ago, but abandoned the commercial release of the seeds amid fractious protests by farmers and consumers. Estimating the output effect HT wheat could have had were it common use in 2008 is difficult because the seeds were never released so reliable yield data do not exist. But let us assume global average yield gains from HT wheat would equal the global average yield gains from HT soybean (12.48%). Then, if the top-10 wheat producers had adopted GM wheat on 20% of the land allocated to wheat in 2008 crop, output would have been greater by 12 million tons, as shown in Table 16. Under this scenario, relatively modest GM wheat adoption could offset nearly 50% of the wheat production lost to biofuels. Under more aggressive adoption, with 50% of top country crops planted to GM seeds, the entire wheat loss due to biofuels could have been replaced by intensive growth.

The foregoing analysis characterizes the significant capacity widespread GM crop adoption has to improve the sustainability of biofuel production. It shows that with sufficiently aggressive adoption, the biofuel demand for vegetable oils and maize could have been met with intensive growth, rather than an expansion of land planted to these crops. The land-use changes induced by biofuel production reduced land available for production of food crops and for environmental preservation. The GM crop adoption rates considered here are admittedly speculative. The adoption patterns presented here are not economic predictions based on the type of modeling in Section 3, but rather hypothetical scenarios. These calculations abstract away from the maximizing behavior that leads to technology adoption and also largely ignore general equilibrium effects, like the potential for higher margins on GM crops to induce expansion of land planted to GM crops or the potential for increased supply to lower prices and reduce land planted to GM crops. Still, the existing rates of adoption are constrained by non-economic factors like politics. Given the theory previously developed, there is ample reason to expect that farmers in most countries, if unconstrained by regulation, would adopt GM seeds at least as aggressively as U.S. farmers, who theory suggests stand to gain the least from adoption because of their exposure to relatively limited pest pressure and their access to chemical herbicides and insecticides. Recall benefits to GM technology adoption are expected to be greatest where pest pressure is high and where there are no affordable and effective substitutes. Furthermore, this analysis only considers the contribution of GM yield gains in the year 2008. Had GM seeds been adopted in these countries in previous years, the additional output would have boosted stocks and had a lowering effect on prices. While future research will include development of more economic adoption scenarios, this analysis shows that aggressive adoption of GM crops could have

Figure 2: World Ethanol and Biodiesel Production 2000-2008

Table 14: Maize Production Gains from GM Adoption

	2008 Production (Million Tons)	Potential Gain (Million Tons)
		Beta=45.61
Egypt	6.54	2.39
Ethiopia	3.77	1.38
Malawi	2.63	0.96
Nigeria	7.53	2.75
Tanzania	3.10	1.33
"Africa"	**24.14**	**8.81**
		Beta=45.61
China	166.04	60.58
		Beta=15.193
France	15.82	1.92
Germany	5.1	0.62
Hungary	8.96	1.09
Italy	9.49	1.15
Romania	7.85	0.95
"Europe"	**47.23**	**5.74**
TOTAL	**237.40**	**75.12**

averted the food crisis in 2008. The 42% increase in food prices from January 2007 to June 2008 (Mitchell 2008) could have been reduced or entirely avoided if GM technology had been more fully embraced.

6 Discussion and conclusions

Until recently, the world had grown complacent about crop science, believing that three decades of declining food prices meant the war on hunger had been won. But in 2008, food riots and the doubling of some food commodity prices in some regions served as a reminder that with slowing agricultural productivity growth and growing demand for farm output, the victory could only be ephemeral. Awakened to the inter-related challenges of feeding and fueling a global population that is at increasing both in size and wealth while simultaneously protecting the environment from climate change and biodiversity loss, policy makers nevertheless seem indifferent or opposed to a technology that theory and empirical evidence suggest can help to overcome each of the major challenges facing humanity today. Indifference toward agricultural biotechnology is, perhaps, partly motivated by conflicting reports on the economic effects of GM crop adoption and by the lack of a unifying theory to explain various GM crop experiences. This paper provides new econometric analysis of GM crop impacts on farm yields, drawing on recent data and spatial and temporal variation in adoption to overcome both the limitations of earlier studies. We find that, on a global scale, agricultural biotechnology has boosted farm yields for the four crops in which it has been introduced. Consistent with the theory developed in this paper, we find that the yield gains

Table 15: Vegetable Oil Production Gains from GM Adoption

	Production (Million Tons)	Potential Gain (Million Tons)		Production (Million Tons)	Potential Gain (Million Tons)
	Soybean			Rapeseed	
India	9.05	1.03	Czech Republic	1.05	0.26
Iran	0.21	0.024	China	12.1	2.98
Italy	0.35	0.039	France	4.72	1.16
Japan	0.23	0.026	Germany	5.15	1.27
Korea	0.35	0.039	India	5.83	1.44
Nigeria	0.59	0.068	Poland	2.11	0.52
Russia	0.75	0.086	Romania	0.67	0.17
Serbia	0.35	0.040	Russia	0.75	0.19
Ukraine	0.81	0.093	Ukraine	2.87	0.71
Vietnam	0.27	0.031	U.K.	1.97	0.49
Romania	0.091	0.29			
TOTAL	**12.94**	**1.75**	**TOTAL**	**37.23**	**9.20**

Table 16: Wheat Production Gains from GM Adoption

	2008 Production (Million Tons)	Potential Gain (Million Tons)
Australia	21.40	0.53
Canada	28.61	0.71
China	112.46	2.80
France	39.00	0.97
Germany	25.99	0.65
India	78.57	1.96
Pakistan	20.96	0.52
Russia	63.77	1.59
Ukraine	25.89	0.65
U.S.	68.03	1.70
TOTAL	**484.67**	**12.08**

are greatest in developing countries, which are generally characterized by high pest pressure and limited access to insecticides. While the magnitude of yield gains is significant, these findings are consistent with earlier work that has shown the GM yield advantage to reach 80% in a single season and average 60% over a four-year horizon (Qaim and Zilberman 2003). Furthermore, and it should be emphasized, that we have not estimated a gene effect, but rather a GM-seed adoption effect on yields. We do not control for the changes in optimizing behavior, which as we suggested in the theoretical model, will lead to yield improvements above and beyond the gene effect. It is this "aggregate" GM-seed adoption effect that is of importance n addressing the global challenges of the 21st century.

Agricultural biotechnology adoption improves the sustainability of biofuels, which had enjoyed strong political support until 2008, when high food prices were blamed on the diversion of food crops to energy production and Searchinger et al. reported in Science that scaled-up U.S.-produced corn ethanol increases carbon emissions over a 40-year period. Now the future of biofuel support programs depends on the ability of producers to meet sustainability criteria that seek to minimize food market impacts and maximize carbon savings. Subsidies in several OECD countries already target advanced biofuels, which perform better along sustainability measures than the commercialized technologies today. Agricultural biotechnology improves the sustainability of first and second-generation biofuels. GM-seed-induced productivity growth essentially frees land for production of biofuel feedstock, reducing the encroachment of biofuel production on natural land and land in food production. Food prices would have been 20-40% higher in 2008 had the additional output from GM-induced yield improvements not been available. With greater adoption of GM seed, much of the harvest diverted to energy production could have been replaced without farming additional land. These production gains are based nearly entirely on analysis of productivity gains. But GM crops don't just provide growth along the intensive margin. The also expand the stock of land that can be profitably farmed and enable a virtual expansion of farmland by permitting multi-cropping practices. In future research, we hope to quantify the additional crop output provided by such extensive margin growth.

This paper has demonstrated the potential for agricultural biotechnology adoption to compliment biofuel technology adoption and should inspire renewed attention to genetic plant engineering, particularly in the capitals of Europe and their one-time colonies. Even though Europe's de facto ban on GM crop imports and production ended in 2008, the European Union has been slow to approve new seed varieties. Heavy regulation and bans on GM technologies closed off markets, altering the expected returns to GM crop innovations. Consequently, R&D in agricultural biotechnology declined dramatically after 1998, when Europe stopped approving new seed technologies (Graff et al. 2009). It is likely that such policies have delayed the introduction of new seed technologies and caused seed companies to abandon others all together. The accumulated history of eighteen years of GM crop production in the U.S. stands as evidence against the environmental and food safety concerns that motivated a precautionary approach to genetic plant engineering. Given the obvious demands for food and fuel production and heightened concern about climate change and other environmental damages, it would perhaps be wise to give a second look at a technology that can provide a partial solution to the key challenges we face today.

While this analysis answers some questions about the economics of agricultural biotechnology, it raises others. Some results of the empirical analysis need to be better understood. For instance, why do stacked traits reduce yields whereas IR or HT traits separately increase yields? We also need to better understand what other technologies are adopted in conjunction with GM seed. In future work, we intend to improve the partial analysis of food market and land-use change effects of observed and hypothetical GM crop adoption scenarios and to quantify the magnitude of extensification made possible by GM seeds.

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Appendix

A Proofs of Propositions

A.1 Input-use effects

Proposition 4. *Damage control input-use intensity declines with adoption of GM seed.*

Define the change in input-use intensity from adoption of GM seed as $\Delta_i\tilde{x} = \tilde{x}_{1j} - \tilde{x}_{0j} = \frac{x_{1j}}{y_{1j}} - \frac{x_{0j}}{y_{0j}} = \frac{x_{1j}y_{0j} - x_{0j}y_{1j}}{y_{1j}y_{0j}}$. Then $\Delta_i\tilde{x} < 0 \Leftrightarrow x_{1j}y_{0j} - x_{0j}y_{1j} < 0$ or $\frac{x_{1j}}{x_{0j}} < \frac{y_{1j}}{y_{0j}} = \frac{g(x_{1j},n_1)f_j(z_{1j})}{g(x_{0j},n_0)f_j(z_{0j})} = \frac{g(x_{1j},n_1)}{g(x_{0j},n_0)} \cdot \frac{f_j(z_{1j})}{f_j(z_{0j})}$. Assume that GM seed is adopted but that potential yield is unchanged, i.e. technology does not change in the j dimension and z_{ij} is constant ($z_{0j} = z_{1j}$). The adoption of GM seed reduces pest pressure: $n_1 = \delta_1\eta < \delta_0\eta = n_0$. Then, given $g_{xn} > 0$, a reduction in pest pressure decreases the marginal product of x evaluated at the initial level of input, i.e. $MP(x_{0j}, n_1) = \frac{\partial g(x_{0j},n_1)}{\partial x} f_j(z_{0j}) < \frac{\partial g(x_{0j},n_1)}{\partial x} f_j(z_{0j}) = MP(x_{0j}, n_0)$. This implies that for equal input costs, the optimal quantity of input with GM seed is less than the optimal quantity of input with conventional seed, i.e. $MP(x_{0j}, n_1) < MP(x_{0j}, n_0) \Rightarrow x_{1j} < x_{0j}$ because $g_{xx} < 0$. A sufficient condition for damage control input intensity to decline, then, is that damage abatement is at least as great after the adoption of GM as it is before the adoption of GM, accounting for changes in x, i.e. $g(x_1, n_1) \geq g(x_0, n_0)$. In order for this condition to hold, it must be the case that the increase in damage abatement caused by the reduction in n is greater than the decrease in damage abatement caused by the decline in x, i.e. $[g(x_{1j}, n_1) - g(x_{1j}, n_0)] > [g(x_{0j}, n_0 - g(x_{1j}, n_0)]$ (See Figure A.1.). This is equivalent to:

$$[g(x_{0j}, n_1) - g(x_{0j}, n_0)] > [g(x_{0j}, n_0) - g(x_{1j}, n_0)] \tag{7}$$

Equation 7 always holds given $g_{xx} < 0$ and $g_{nn} > 0$. Therefore, damage will not be lower after adoption of GM seed.
If $f(\cdot)$ is no longer fixed and if damage abatement will not decrease, then potential yield will not decrease but may increase if (a) the change in technology along dimension j is such that $j : 0 \rightarrow 1$, (b) directly productive input-use increases because of a higher VMP for higher damage abatement, or (c) both j and z_{ij} increase with GM seed adoption. Importantly, potential yield cannot decline with the adoption of GM seed if damage abatement does not decline.

Proposition 5. *If $|g_{xx}g_n| > |g_x g_{xn}|$ holds, then holding all else constant, adoption of GM seed increases use of directly productive inputs.*

$\frac{\partial z^*}{\partial n} = \frac{\begin{vmatrix} pfg_{xx} & -pfg_{xn} \\ f_z g_x & -pf_z g_n \end{vmatrix}}{\begin{vmatrix} pfg_{xx} & pf_z g_x \\ pf_z g_x & pf_{zz} g \end{vmatrix}} = \frac{-fg_{xx}f_z g_n + ff_z g_x g_{xn}}{fgf_{zz}g_{xx} - f_z^2 g_x^2} > 0$ If this condition holds, then the change in directly productive inputs is given by:
$\Delta n \frac{\partial z^*}{\partial n} = (\delta_1 - \delta_0) \cdot n \cdot \frac{\partial z^*}{\partial n} > 0.$

Proof 2: For optimal use of directly productive inputs,

$$VMP_z = w,$$

where $VMP_z = pgf_z$. Assume that directly productive input demand does not change with GM adoption, i.e. $z_{0j} = z_{1j}$. Then $f_j(z_{0j}) = f_j(z_{1j})$.Therefore, it holds that $VMP_{z_{1j}} > VMP_{z_{0j}}$ as long as $g(x_{1j}, n_1) > g(x_{0j}, n_0)$.

A.2 Yield effects

Proposition 6. *For a given change in δ, the change in yield is increasing in initial potential output, $f_j(z_{0j})$.*

Proof. Let $\Delta_i g > 0$ denote a given change in damage abatement resulting from GM seed adoption. And let $\Delta_i f > 0$ denote the corresponding change in potential output. Then the change in yield, $\Delta_i y$, is:

$$\Delta_i y = \Delta_i g \cdot f_j(z_{0j}) + g(x_{ij}, n_1) \cdot \Delta_i f. \tag{8}$$

Therefore, $\frac{\partial \Delta_i y}{\partial f_j(z_{0j})} = \Delta_i g > 0$. □

Proposition 7. *For a given change in δ, the change in yield is increasing in the change in potential output.*

Proof. From Equation 8, it follows that $\frac{\partial \Delta_i y}{\partial \Delta_i f} = g(x_{ij}, n_1) > 0$. □

Proposition 8. *For a given change in δ, the change in yield is increasing in initial pest pressure.*

Proof. From Equation 8, observe that $\Delta_i y$ is increasing in $\Delta_i g$. Further, note that$\Delta_i g \approx \frac{\partial g}{\partial n}\Delta n$, where $\frac{\partial g}{\partial n} < 0$ and $\Delta n = (\delta_1 - \delta_0) \cdot \eta < 0$. As initial pest pressure grows, i.e. η increases, $|\Delta n|$ increases and $\Delta_i g$ increases. Hence, $\Delta_i y$ increases. □

Proposition 9. *As δ_1 decreases, the change in yield increases.*

Proof. Observe $\frac{\partial |\Delta n|}{\partial \delta_1} > 0$. The rest of the proof follows the proof for Proposition 6. □

Proposition 10. *The change in yield is decreasing in initial damage control input use, x_{0j}.*

Proof. From Equation 3, it follows that $\frac{\partial \Delta_i y}{\partial x_{0j}} = -g_x(x_{0j}) < 0$. □

Proposition 11. *The reduction in conventional damage control input use is increasing in the level of initial use of conventional damage control inputs.*

Proof. TBD □

A.3 Extensive margin effects

Proposition. *For given prices, let $\bar{\eta}_0$ denote the minimum land quality (e.g. pest pressure) at which profit maximizing agricultural production with conventional seeds yields non-negative profits, so that for $n < \bar{\eta}_0$, profits are negative. Then, if it is profitable to adopt GM seed at $\bar{\eta}_0$, then $\bar{\eta}_1$ is minimum land quality at which profit maximizing agricultural production with GM seed yields non-negative profits, where $\bar{\eta}_1 < \bar{\eta}_0$.*

Proof. Let $\bar{\eta_{ij}}$ be defined as the level of pest pressure at which maximum profits per acre under technology ij are zero, i.e. $\pi_{ij}(x^*_{ij}, z^*_{ij}, p, w, v, n_i) = 0$, where $n_i(\bar{\eta_{ij}}) = \delta_i \bar{\eta_{ij}}$. Then $\bar{\eta_{0j}}$ is the threshold level of initial pest pressure at which it is profitable to farm with conventional seed and $\bar{\eta_{1j}}$ is the threshold level of pest pressure at which it is profitable to farm with GM seed. Assume $\pi_{1j}(x^*_{ij}, z^*_{ij}, p, w, v, n_1(\bar{\eta_{0j}})) - \pi_{0j}(x^*_{ij}, z^*_{ij}, p, w, v, n_0(\bar{\eta_{0j}})) > T_{1j}$, i.e. it is optimal to adopt GM seed at the quality threshold. Given $\frac{\partial \pi}{\partial n} = pfg_n + pfg_x \frac{\partial x}{\partial n} + pgf_z \frac{\partial z}{\partial n} < 0$, land is not farmed under technology $0j$ for $n > n_0(\bar{\eta_{0j}})$ because negative profits would obtain. Therefore, land of quality $\eta > \bar{\eta_{0j}}$ is not farmed, and $\bar{\eta_{0j}}$ defines the external margin under technology $0j$. Effective pest pressure under technology $1j$ given $\bar{\eta_{0j}}$ is $n_1(\bar{\eta_{0j}})$. Given $\delta_1 < \delta_0$, it holds that $n_1(\bar{\eta_{0j}}) < n_0(\bar{\eta_{0j}})$. Thus $\pi_{1j}(x^*_{1j}, z^*_{1j}, p, w, v, n_1(\bar{\eta_{0j}})) > \pi_0(x^*_{0j}, z^*_{0j}, p, w, v, n_0(\bar{\eta_{0j}})) = 0$. Then, because $\frac{\partial \pi}{\partial n} < 0$, $\exists n_1(\bar{\eta_{1j}})$, for $\bar{\eta_{1j}} > \bar{\eta_{0j}}$, s.t. $\pi_{1j}(x^*_{ij}, z^*_{ij}, p, w, v, n_1(\bar{\eta_{1j}})) = 0$. Therefore, adoption of GM technology permits profitable farming of land that is too marginal to be profitably farmed under traditional technology. GM technology adoption increases the range of land qualities over which production occurs by $\bar{\eta_{1j}} - \bar{\eta_{0j}}$. □