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Evaluation of Economic, Land Use, and Land-use Emission Impacts of Substituting Non-GMO Crops for GMO in the United States

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The main objective of this study was to evaluate potential economic and environmental consequences of losing GMO traits in the United States for the major crops of corn, soybeans, and cotton. The first step was to obtain from the literature a range of estimates of the yield losses if we move away from GMO traits in the United States. The second step was to calculate the weighted average GMO and non-GMO area to get the overall shock value. The third step was to introduce the yield losses obtained into a well-known CGE model, GTAP-BIO, to quantify the land use and economic impacts of banning GMO traits in the United States. Absent the GMO technology, more land would be needed to produce corn, soybeans, and cotton. That land comes from switching from other crops and conversion of cropland pasture, pasture, and forest in many global areas. The land expansion likely is similar to the entire US ethanol program. Furthermore, induced land-use emissions were significantly larger than the corresponding figure for US corn ethanol. We evaluated three cases representing different levels of yield shocks. The price changes for corn were as high as 28% and for soybeans as high as 22%. In general, the price increases for two of the three cases were higher than those observed previously for the US ethanol mandate shocks. Food cost changes in the United States amount to $14-$24 billion per year. As expected, welfare falls both in the United States and globally.

Key words: GMO crops, productivity, computable general equilibrium, economic impacts, land use, land use emissions.

Introduction

Production, consumption, and trade of genetically modified organism (GMO) crops have always been controversial. Some countries such as members of the European Union and Japan banned production and consumption of GMO crops due to health concerns. On the other hand, many other countries have produced and used these crops. In 2014, 18 million farmers in 28 countries planted more than 181 million hectares of GMO crops (James, 2014). The United States is a leading country in producing GMO crops, with 40% share in the global area planted to GMO crops in 2014 (James, 2014). In the same year, 94% of soybeans, 91% of cotton, and 89% of corn produced in United States were GMO crops (US Department of Agriculture [USDA], Economic Research Service [ERS], 2014b).

More recently there has emerged increased opposition against GMO crops. GMO crops have been widely produced and used in the United States and also exported to other countries. GMO crops are usually more productive than the non-GMO crops, so imposing restriction on production and or consumption of these crops could lead to lower crop production on the exiting cropland base as yields drop. It could also lead to reduction in the net exports of US agricultural products, higher crop prices at the national and global scales, some increases in food prices, and increases in use of pesticides and other inputs that would be needed without GMO traits (not examined in this article). These impacts jointly harm the United States and global economy and generate welfare losses. In addition, moving away from GMO crops could induce major land-use changes and increase GHG emissions through this channel. If the United States were to cease using GMO technology, then lower yield on the existing US cropland will increase demand for cropland anywhere in the world. This could cause deforestation at the global scale to satisfy higher demand for cropland, which leads to expansion in GHG emissions due to land-use changes. This article examines the economic and land-use impacts of banning three main GMO crops (corn, soybeans, and cotton) produced in the United States.

To accomplish this task, the article first determines the expected yield reductions for corn, soybeans, and cotton if GMO crops were not produced in the United States. The expected yield contributions of GMO crops are determined based on the existing literature, which measured and compared the GMO and non-GMO yields at the farm level. Then, a well-known computable general equilibrium (CGE) model, GTAP-BIO, is used to examine the economic and land-use impacts of banning three main GMO crops (corn, soybeans, and cotton) produced in the United States. Our results show that eliminating GMO crops in the United States would have significant impacts on land use and associated GHG emissions and would cause a meaningful increase in commodity and food prices. There would also be associated economic welfare losses.

Literature Review

The existing literature on the economic and environmental impacts of GMO crops is considerable and can be divided into two broad categories. The first category focuses on farm-level impacts and issues surrounding farmer adoption of these crops. This includes determining factors associated with farmer adoption, effects on pesticide and insecticide use, and the GMO yield contributions and their impacts on farm incomes (Brookes & Barfoot, 2012, 2014; Fernandez-Cornejo, Weschsler, Livingston, & Mitchell, 2014; Klumper & Qaim, 2014; Nolan & Santos, 2012; Qaim, 2009; Sankula, 2006a, 2006b; Verhalen, Greenhagen, & Thacker, 2003). We basically rely on this part of the literature to determine the yield contributions of the GMO technology to corn, soybeans, and cotton produced in the United States.

The second group of papers examines the economy-wide impacts of the GMO technology. Qaim (2009) comprehensively reviewed earlier publications in this area and divided this part of the literature into two groups. The first group covers papers that mainly estimated the welfare gains of adopting GMO crops using partial equilibrium models. These papers indicate that whenever GMO crops are adopted, yields and crop supplies have increased, and that generates welfare gains. However, the magnitude of the welfare gains vary by case. These partial equilibrium analyses usually evaluate the impacts of a particular GMO trait on the supply side of a single commodity, assuming production and prices of other commodities are fixed. The second group of papers in this category examines the economy-wide impacts of adopting GMO crops using CGE models. Unlike the partial equilibrium models, the CGE models take into account forward and backward linkages across economic activities, allow price adjustment across markets, explicitly impose resource constrains, and trace trade across regions. Hence, these models are more suitable to capture the overall economy impacts of major improvements in biotechnology with key global consequences. As mentioned in the Qaim review, this group of studies that used the standard GTAP model (developed by Hertel, 1999) also examined the welfare and price impacts of adopting individual GMO traits. Similar to the partial equilibrium analyses, the CGE studies also confirm that adoption of GMO crops generates considerable gains. In addition, these studies provide major insights on the price and trade impacts of GMO crops. These analyses also recognized that adoption of GMO crops has major land-use impacts. However, they did not quantify these impacts, as the standard GTAP model they used does not trace land-use changes across the world.

In a recent work Stevenson, Villoria, Byerlee, Kelley, and Maredia (2013) used a more advanced version of the GTAP model (known as GTAP-AEZ), augmented to trace land-use changes due to economic and biophysical factors, to estimate global saving in land conversion into agricultural production due to germplasm improvement in the major staple crops (wheat, rice, and coarse grains) between 1965 and 2004. These authors simply assigned changes in observed total factor productivity[1] (TFP) in crop production to germplasm improvement due to agricultural research. However, improvement in germplasm is not the only factor that affects TFP.

More recently, the existing literature on the impacts of GMO crops has been extended by a set of papers that combine econometric methods and partial equilibrium analysis to determine the economic impacts of GMO crops (more recent publications include Barrows, Sexton, & Zilberman, 2014; Sexton & Zilberman, 2011). These papers indicate that GMO varieties (mainly cotton, corn, soybeans, and rapeseed) significantly improve yields compared with non-GMO varieties in developed and developing countries. However, the impacts vary by crop, region, and the implemented estimation method. By developing counterfactual partial equilibrium analysis built on the estimated yield gains of GMO crops, these papers conclude that agricultural biotechnology made significant contribution in lowering food prices, preserving deforestation, and saving greenhouse gas (GHG) emissions associated with land-use changes. For example, Barrows et al. (2014) calculated price increases of 5-19% for corn, 19-33% for cotton, and

1. *These authors relied on crop TFP estimated by Everson (2003), who assigned unexplained growth in crop outputs to TFP, while the control variables were growth rates in land, labor, capital (animal and mechanical power), and fertilizer. Many other variables explain changes in crop outputs at the aggregate and farm level, and these were not included.*

either 3-4% (without the extensive margin) or 50-66% (with the extensive margin) for soybeans in the absence of GMO technology. These authors also estimated that at least 11 million ha of cropland has been saved due to using GMO technology. They convert the land saving into 150 million metric tons of GHG emissions averted due to yield contributions of GMO crops. The counterfactual land-use analyses provided in these papers offer useful information on the land-use impacts of GMO crops in the absence of a full CGE analysis (Barrows et al., 2014). In this article, for the first time we estimate the economic and land-use impacts of using GMO crops in the United States using an advanced CGE model.

Research Methodology

The research methodology consists of three steps. In the first step using the existing literature, we estimate the expected yield reductions for corn, soybeans, and cotton if GMO crops were not produced in the United States. We do not examine production of GMO crops in other regions which currently produce these crops. In the second step, we calculate the weighted average yield loss for each crop using the fraction of total area that is in the three GMO crops in the United States. In the third step, we introduce yield losses into the GTAP-BIO model by crop as exogenous yield shocks. These steps are described briefly below and in detail in Appendix A.

Yield Contribution of GMO Crops

We used the official information on GMO and non-GMO acreages provided by the National Agricultural Statistics Services (NASS) and the exiting literature to quantify yield losses due to banning GMO crops. Several studies have estimated the average yields for GMO and non-GMO crops in the United States (e.g., Fernandez-Cornejo et al., 2014; Nolan & Santos, 2012; Sankula, 2006a, 2006b; Verhalen et al., 2003). While these publications indicate that in general GMO crop yields are higher than the non-GMO crops, they provide a range of estimates for yield contributions of GMO crops. Given the uncertainty in these estimates, we developed ranges of yield reductions if we switch to non-GMO crops. We divided the yield reductions obtained from the literature for each crop into two categories of “reference” and “conservative,” which represent upper and lower bounds of GMO yield contributions, respectively. In addition, we developed an *average* case for each crop, which represents simple averages of upper and lower cases. The results are presented in Table 1 and details are explained in Appendix A.

Table 1. Estimated negative productivity shocks due to banning GMO crops in the United States (% decrease in yield).

Description	Crop	Reference	Conservative	Average
Original shocks calculated for individual crops	Corn	17.1	5.2	11.2
	Cotton	23.1	14.1	18.6
	Soybeans	10.3	0.0	5.2
Modified shocks calculated for GTAP	Coarse grains	15.64	4.76	10.24
	Other crops	0.27	0.16	0.22
	Soybeans	10.3	0.0	5.2

Table 1 indicates that in the reference cases, switching to non-GMO crops reduces the average yields of corn, cotton, and soybeans by 17.1%, 23.1%, and 10.3%, respectively, in the United States. The corresponding figures for conservative case are 5.2%, 14.1%, and 0.0%, and for the average case are 11.2%, 18.6%, and 5.2%, respectively. Our CGE model represents crops in 10 different crop categories of paddy rice, wheat, sorghum, coarse grains (including corn and excluding sorghum), soybeans, palm, rapeseed, other oilseeds, sugar crops, and other crops (including cotton). These GTAP shocks are presented in the bottom panel of Table 1.

GTAP-BIO Model

To quantify the economic and land-use impacts of switching to non-GMO crops in the United States, we use the GTAP-BIO model. This model has been developed and frequently used to examine the economy-wide impacts and land-use consequences of agricultural, energy, trade, and environmental policies (Hertel et al., 2010; Liu, Hertel, Taheripour, Zhu, & Ringler, 2014; Taheripour, Hertel, & Tyner, 2011). A most recent version of this model, which has been reported in Taheripour and Tyner (2013) and adapted by the California Air Resources Board (CARB) for use in determining induced land-use changes due to biofuels, is implemented in this paper. This allows us to do some comparisons of the GMO withdrawal impacts with ethanol impacts. This advanced version of the GTAP-BIO model includes improvements made in recent years to properly trace the land-use impacts of changes in economic and biophysical variables within the GTAP modeling framework. The model has been extensively modified to trace allocation of land resources (including forest, pasture, and cropland) by country and agro-ecological zone (AEZ) at the global scale and to model biofuel industry interactions with other land-using activities. Unlike the earlier version of the model, the new version uses a two-nest land cover (one for the mix of cropland and pasture land and one for the mix of these two with forest) and distinguishes between the extensive and intensive margins. This version of the model uses regional land transformation elasticities which are tuned according to recent observations on changes in land cover and crop-harvested areas. In other words, regions that experience little change in land cover (like the United States and EU) now have much lower change in GTAP, and other regions like Sub-Saharan Africa have higher changes. In addition, it uses a set of regionalized extensive margins, which are obtained from a biophysical model and used to evaluate the productivities of new and existing cropland in the land conversion process. The model is enhanced to trace demands for and supplies of animal feeds (including biofuel by-products and oilseed meals) and substitution among these items in response to changes in their relative prices, in connection with competition for land among livestock, crop, and forest sectors. Unlike other versions of the GTAP model, the new model takes into account substitution among alternative vegetable oils at the demand side and allows consumers to switch among different types of vegetable oils in response to their relative prices. With these modifications, the GTAP-BIO model can trace and quantify the impacts of major changes in commodity markets.

Major changes in commodity markets, induced by supply shocks (like banning GMO crops) or by a demand shock (like expansion in demand for biofuels), generate a series of market-mediated responses that affect many markets across the world. The key market-mediated responses include changes in relative crop prices; changes in demands for and supplies of crops; changes in the allocation of cropland among crops; changes in demand for cropland, which leads to changes in extensive and intensive margins that affect land cover (including changes in forest, pasture, and cropland, which lead to changes in markets of forestry and livestock products); and finally, changes in international trade, which in turn spread these market-mediated responses across the world. The GTAP-BIO model implemented in this article captures and quantifies all of these changes along with induced changes in other markets. It is important to note that the experiments that we examined in this article (either the GMO or ethanol shocks) only reflect the changes induced by the applied shock to the model, e.g., ethanol or GMO loss yield reductions. Impacts of other changes that might occur in the real world are not captured. The intent is to isolate the impact of the applied shock from the impacts of all other factors that might affect the world economy.

GTAP-BIO Database

The latest version of GTAP-BIO database represents the global economy in 2004. This database divides the global economy into 19 regions and aggregates goods and services into 48 categories, including biofuels and their by-products, as shown in Appendix B. Since this database represents the world economy in 2004, it does not reflect the expansion in demand for corn and oilseeds for biofuels produced in the United States in recent years. To capture the current market environment for these crops, we upgraded our database to represent 15 billion gallons of ethanol and 1 billion gallons of biodiesel according the US biofuel mandates. This helps us to measure the impacts of binding GMO in the presence of biofuels more accurately. Actual US production levels in 2015 are near these values.

Experiments

We designed and implemented several experiments to cover the consequences of moving away from GMO crops under several alternative conditions and assumptions. First, we developed three cases to represent the joint impacts of reduction in corn, cotton, and soybeans yields for the reference, average, and conservative negative yield shocks presented in Table 1. Henceforth, we refer to these experiments as the *base cases*.

In the second set of simulations, we repeat the base cases while we assume that the US exports of affected crops (corn, cotton, and soybeans) remain constant. We refer to these scenarios as *fixed trade cases*. These cases tend to proxy a case where GMO traits disappeared across the world. In our base case, when US production falls, exports are likely to fall, and production elsewhere in the world could increase, dampening the impacts of the 'US only' shock. However, if there were a global GMO ban, production would be affected in all regions with GMO crops, so there would be higher demand for US exports. By fixing US exports, we come closer to what would happen if we had a global GMO ban. Hence, this experiment is a sort of proxy for the experiment with more complete information that we could not accomplish within the scope of this project.

Table 2. Estimated land-use changes for base cases (figures are in 1,000 hectares).

Cases	Land type	US	EU	Brazil	Rest of world	Total
Reference	Forest	-49.5	-27.2	-75.3	-494.9	-646.9
	Cropland	161.4	59.0	246.0	1,411.6	1,878.0
	Pasture	-111.9	-31.7	-170.7	-916.7	-1,231.1
	Cropland pasture	-1,886.5	0.0	-723.7	0.0	-2,610.2
Average	Forest	-32.3	-16.8	-44.0	-295.0	-388.2
	Cropland	101.8	36.2	143.4	842.7	1,124.1
	Pasture	-69.5	-19.3	-99.4	-547.7	-735.9
	Cropland pasture	-1,173.6	0.0	-415.2	0.0	-1,588.8
Conservative	Forest	-13.1	-6.1	-11.8	-102.8	-133.7
	Cropland	39.9	13.0	41.1	292.3	386.3
	Pasture	-26.8	-6.9	-29.3	-189.6	-252.6
	Cropland pasture	-443	0	-116	0	-559

The third set of simulations repeat the base cases with food consumption held constant at the global scale. We refer to these scenarios as *fixed food cases*. These cases are designed to determine what would be the land-use change, production, and price impacts of banning GMO crops if food consumption were not allowed to change. In other words, it aims to determine the impacts of GMO shocks while not allowing food consumption to fall. Finally, the last group of simulations repeat the base cases with both trade and food consumption being fixed. We refer to these experiments as *trade and food fixed cases*.

Simulation Results

While our simulation results represent changes in a wide range of economic and land-use variables at the sectoral, household, and national levels by county/region, in what follows we mainly present the key impacts, including impacts on land-cover change, induced land-use emissions, price and production impacts, and changes in welfare.

Land-use Impacts

Here, we first examine the land-use consequences for the base cases in more detail, and then we highlight the key differences between the base cases and other experiments. Table 2 provides induced land-use changes for the reference, average, and conservative base cases. Changes are reported for forest, cropland, pasture, and cropland pasture for United States, EU, Brazil, Rest of World, and total. Cropland pasture exists in the database only for the United States and Brazil. This type of land refers to lands which have been cultivated in the past for crop production and are now used as pasture land. USDA includes this type of land in the cropland category, and GTAP follows this approach. Conversion of this land to crop production does not count as converted natural land, as would forest or pasture converted to cropland.

As shown in Table 2, moving away from GMO crops induces land-use changes in the United States and other regions across the world. Banning US GMO crops in the reference base case, which represents a higher level of yield losses, increases area of cropland by 1,878 thousand hectares at the global scale with 647,000 and 1,231,000 hectare reductions in forest and pasture areas, respectively. In this case, area of cropland pasture falls by about 1,886,000 and 724,000 hectares in the United States and Brazil. The share of US cropland expansion is about 8.6%. The share of US cropland expansion is small because in this country, farmers convert a portion of their cropland pasture (which is in the cropland base) to crop production when more cropland is needed. The expansion in global cropland falls to 1,124,000 and 386,000 hectares in the average and conservative base cases, respectively. These figures indicate that moving away from GMO crops could generate major land-use changes, in particular in the reference and average cases. This means that adopting GMO technology avoided conversion of natural land (forest and pasture) to cropland.

To highlight the scale of avoided land conversion, we now compare these results with the induced land-use changes due to expansion in US corn ethanol, as a major driver of land-use changes in recent years. Many papers have estimated induced land-use changes due to corn ethanol. Here, we use a projection made by Taheripour and Tyner (2013) using the modeling framework implemented in this article and adopted by the CARB—that

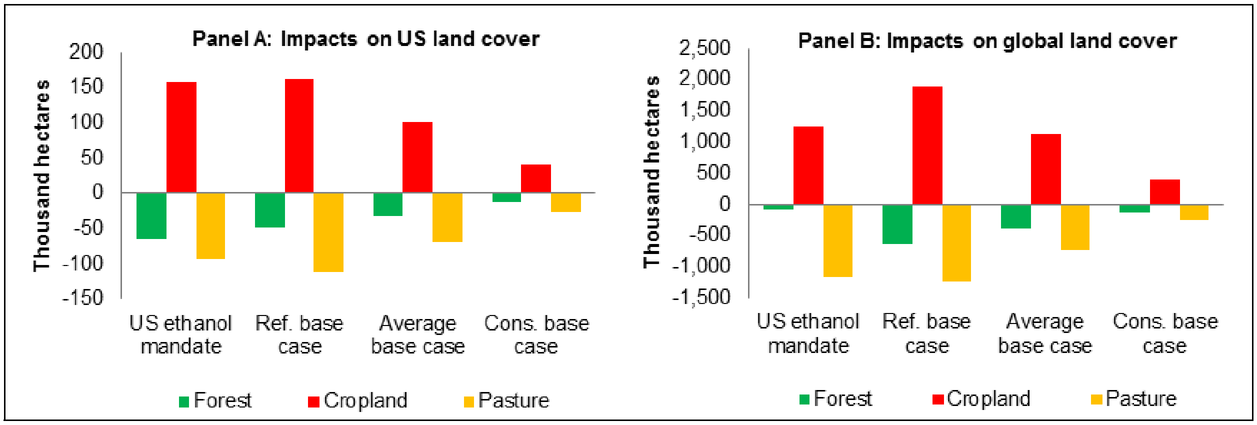

Figure 1. Induced land-use changes for corn ethanol and for reference, average, and conservative base cases.

is, the results of Case D reported by these authors. This case represents an expansion in US corn ethanol from its 2004 level of 3.41 billion gallons to 15 billion gallons and obtained from the same modeling framework. Figure 1 compares induced land-use changes (i.e., changes in forest, pasture, and cropland) due to corn ethanol with the corresponding result for the reference, average, and conservative base cases.

In general, Figure 1 shows that the land-use changes associated with the corn ethanol experiment are within the range of the GMO estimated changes for the conservative and reference cases. The cropland needed to be added in the United States for corn ethanol is 157 thousand hectares, and it falls between 40 and 161 thousand hectares for the GMO shocks. Globally, the expansion in corn ethanol adds 1,243,000 hectares to cropland, while the corresponding figures for the GMO cases range between 386,000 and 1,878,000 hectares. The global conversion of forest and pasture to cropland is quite similar for the ethanol and average GMO shocks. The loss in pasture land tells a similar story. Less forest is converted in the United States due to the ethanol shock, but much more is converted globally. In fact, even the conservative GMO shock leads to more forest conversion than the ethanol shock. One reason for this result is that the ethanol expansion produces distillers dried grains with solubles (DDGS), which is a livestock feed that substitutes to some extent for pasture and other crops. The GMO cases do not, so it creates more pressure to covert land to cropland, a good part of which globally is forest.

In conclusion, while there are differences in every category, results from the GMO average base cases are closest to the case of expansion in corn ethanol. We believe the GMO conservative case may be unrealistically low, so it is interesting that the GMO average base case results most closely resemble the expansion in corn ethanol results, while the GMO reference case generally has larger land-use change impacts than corn ethanol.

We now compare the induced land-use changes obtained from the reference, average, and conservative base cases with their corresponding results for all other scenarios, including the fixed trade, fixed food, and fixed both food and trade cases, as presented in Table 3. From the results presented in this table, we can describe the following major differences among the alternative cases:

- Compared with the base cases, fixed trade cases represent higher land-use changes in the United States and lower figures at the global scale. In this case, land use goes up in the United States because it produces more crops to avoid reduction in US crop exports. Exports are not allowed to fall, so more US land must be converted to crops, but in other countries there is no GMO shock, so less conversion is needed. Clearly, the fixed trade case is only a partial proxy for having a global GMO shock.
- Compared with the base cases, fixed food cases represent higher land-use changes in the United States and even higher figures at the global scale. In this case, land use goes up everywhere to keep food consumption constant.
- When both trade and food consumptions are fixed, land-use changes fall in between the corresponding figures for the fixed trade and fixed food cases.
- When both trade and food consumptions are fixed, land-use changes are larger than the corresponding figures for the base cases in the United States and at the global scale.

Table 3. Estimated land-use changes for all alternative scenarios (figures are in 1,000 hectares).

Cases	Land type	Base cases	Fixed trade	Fixed food	Fixed trade and food
US					
Reference	Forest	-49.5	-86.3	-65.4	-111.3
	Cropland	161.4	266.4	169.0	276.6
	Pasture	-111.9	-180.1	-103.6	-165.3
	Cropland pasture	-1,886.5	-3,054.3	-1,891.3	-3,048.7
Average	Forest	-32.3	-56.4	-41.9	-71.1
	Cropland	101.8	166.2	106.8	173.3
	Pasture	-69.5	-109.9	-64.9	-102.2
	Cropland pasture	-1,173.6	-1,856.3	-1,179.2	-1,859.1
Conservative	Forest	-13.1	-18.6	-16.6	-23.0
	Cropland	39.9	53.9	41.6	56.0
	Pasture	-26.8	-35.3	-25.1	-33.0
	Cropland pasture	-443.3	-563.5	-443.5	-561.3
Whole world					
Reference	Forest	-646.9	-583.6	-912.6	-841.6
	Cropland	1,878.0	1,611.2	2,304.3	2,007.4
	Pasture	-1,231.1	-1,027.7	-1,391.7	-1,165.8
	Cropland pasture	-2,610.2	-3,475.1	-2,747.7	-3,577.9
Average	Forest	-388.2	-338.2	-544.6	-481.9
	Cropland	1,124.1	930.8	1,374.9	1,149.7
	Pasture	-735.9	-592.6	-830.3	-667.8
	Cropland pasture	-1,588.8	-2,090.6	-1,670.5	-2,151.5
Conservative	Forest	-133.7	-110.5	-187.2	-154.4
	Cropland	386.3	303.5	470.4	369.8
	Pasture	-252.6	-193.0	-283.2	-215.3
	Cropland pasture	-559.5	-657.0	-581.2	-674.8

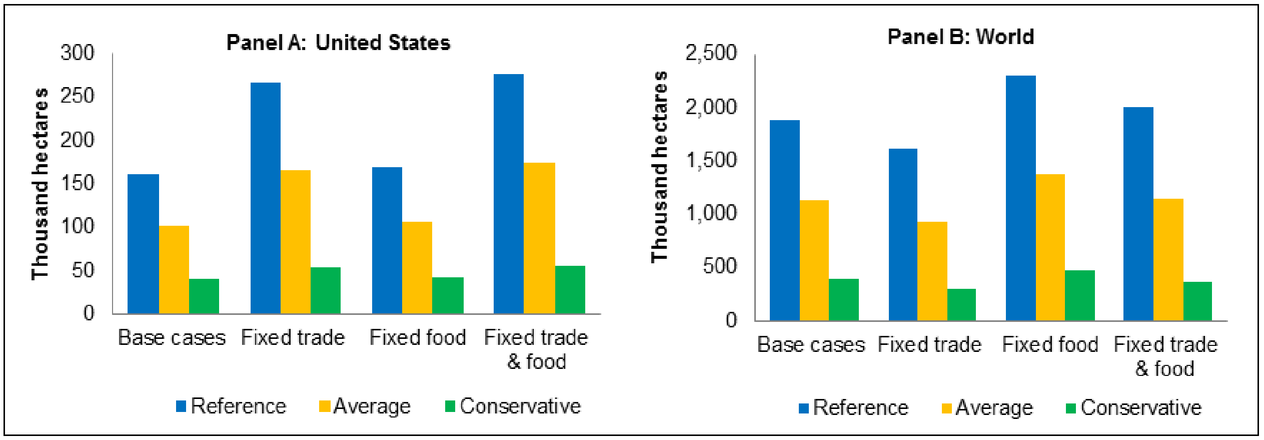

Figure 2. Changes in cropland for all examined scenarios.

Figure 2 represents changes in cropland for all of the examined scenarios.

Induced Land-use Change Emissions

To calculate the induced land-use emissions associated with each experiment, we used the land-use emission model developed by Plevin, Delucchi, and Creutzig

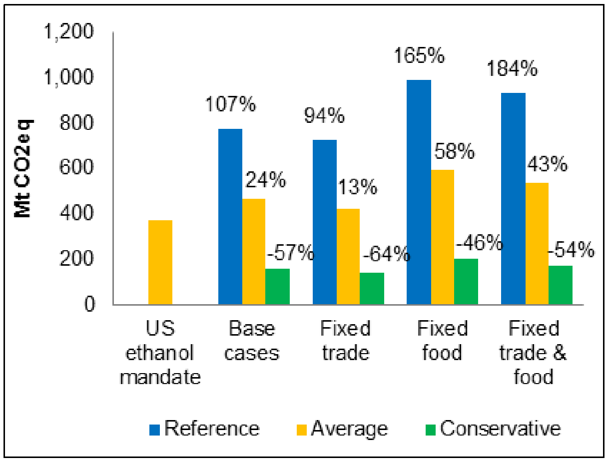

Figure 3. Induced land-use change emissions for corn ethanol and for reference, average, and conservative base cases under alternative scenarios.

Figures over the bars represent percent difference between every case and the case of ethanol. For example, the emission level associated with the reference base case is 107% larger than emissions associated with the corn ethanol.

(2014) and adopted by the CARB. The induced land-use-change emissions for the corn ethanol case and all the GMO experiments examined in this article are presented in Figure 3. As shown in this figure, the expansion in corn ethanol from 3.41 billion gallons (its 2004 level) to 15 billion gallons generates 375 metric tons CO_2 equivalent (Mt CO_2eq) emissions.

Figure 3 shows that for all the reference and average scenarios examined in this article, induced land-use emissions due to banning GMO crops in the United States are significantly larger than the corresponding figure for corn ethanol. For example, the induced land-use emissions associated with the reference and average base cases are 777 Mt CO_2eq and 465 Mt CO_2eq emissions, respectively. These figures are 107% and 24% higher than the corn ethanol emissions as shown in Figure 3. For the conservative cases, emissions are lower than the ethanol case. Among all alternative scenarios, the fixed food consumption cases represent higher induced land-use emissions. Therefore, using GMO crops in the United States made significant contributions to avoiding induced land-use emissions.

Production and Price Impacts

Here we analyze the production and price impacts for the United States. As mentioned earlier in this article, our database classifies corn within the coarse grains category and cotton in the other crops category. The shares of corn and cotton in harvested areas of their corresponding categories are about 92% and 1.1%, respectively. Since the coarse grains crop category mainly represents corn, we will refer to it as corn in this section. Moving away from GMO crops reduces crop outputs under all alternative cases, as shown in Table 5. The only exception is sorghum, whose production increases, but from a relatively small base. Sorghum production increases because it is a substitute for corn in demand for feeds, and corn production is negatively impacted by the GMO shocks.

Table 4. Saving in land-use emissions due to using GMO crops in the United States as a fraction of total global emissions and agricultural emissions (figures are in %).

Description		Base cases	Fixed trade	Fixed food	Fixed trade and food
Global emissions	Ref.	1.7	1.6	2.1	2.0
	Avg.	1.0	0.9	1.3	1.2
	Cons.	0.3	0.3	0.4	0.4
Agricultural emissions	Ref.	12.9	12.1	16.6	15.5
	Avg.	7.8	7.0	9.9	8.9
	Cons.	2.7	2.3	3.4	2.9

In all scenarios examined in this article, corn, soybeans, and cotton yields and therefore supplies of these commodities fall in the absence of GMO technology. This leads to higher prices for these crops. In response, farmers switch their land from other crops to these crops, and that leads to reductions in production of other crops produced in the United States due to competition for land among crops. As shown in Figure 4, in the reference, average, and conservative base cases supply of corn goes down by 7.7%, 4.7%, and 1.9%, respectively. The corresponding figures for soybeans are 10.1%, 5.5%, and 0.8%, respectively. In the fixed trade and fixed food scenarios and their combination we observe smaller rates of reductions across crops. In general, Table 5 shows that in the absence of GMOs, the United States loses a significant portion of its crop outputs; however, the reduction rates vary across crops and scenarios.

Reductions in crop supplies reduce commodity prices by relatively large rates, as shown in Table 6. For example, in the reference, average, and conservative base cases the supply price of corn goes up by 17.1%, 9.8%, and 3.8%. The corresponding figures for soybeans are 10%, 5.7%, and 0.9%, respectively. As shown in Table 6, in the fixed trade, fixed food, and their combinations scenarios, the price impacts are higher. Figure 4 highlights the price impacts for corn and soybeans under all experiments examined in this article. For

Table 5. Production impacts of moving away from GMO crops for all alternative scenarios.

Cases		Rice	Wheat	Sorghum	Coarse grains	Soybeans	Rapeseed	Other oilseeds	Sugar crops	Other crops
		Crops								
Base cases	Reference	-3.5	-4.9	23.6	-7.7	-10.1	-3.2	-1.1	-0.3	-3.5
	Average	-2.1	-3.1	14.2	-4.7	-5.5	-2.1	-0.9	-0.2	-2.1
	Conservative	-0.8	-1.2	5.9	-1.9	-0.8	-1.0	-0.8	-0.1	-0.8
Fixed trade	Reference	-7.4	-10.7	25.8	-6	-5.3	-8.8	-7.8	-0.6	-3.7
	Average	-4.4	-6.4	15.2	-3.6	-2.8	-5.4	-4.8	-0.3	-2.1
	Conservative	-1.3	-2	5.9	-1.3	-1.2	-1.6	-1.3	-0.1	-0.6
Fixed food	Reference	-3.4	-5	24.3	-7.6	-10	-3.4	-1.3	-0.1	-3.5
	Average	-2.1	-3.1	14.6	-4.6	-5.4	-2.2	-1.0	0.0	-2.2
	Conservative	-0.8	-1.2	6	-1.9	-0.8	-1.1	-0.8	0.0	-0.8
Fixed trade & food	Reference	-7.6	-11.2	26.8	-5.9	-5.1	-9.4	-8.3	-0.2	-3.6
	Average	-4.5	-6.7	15.7	-3.5	-2.7	-5.7	-5.1	-0.1	-2.1
	Conservative	-1.3	-2	6	-1.3	-1.2	-1.7	-1.4	0.0	-0.6

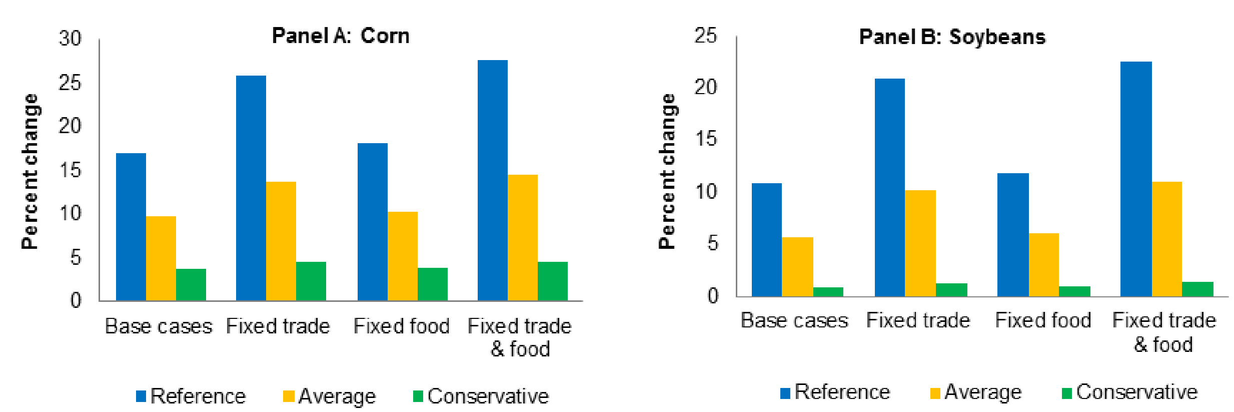

Figure 4. Changes in corn and soybeans prices for reference, average, and conservative cases under alternative scenarios.

example, in the reference case, the price of corn goes up by 17.1%, 25.8%, 18.1%, and 27.6%. The corresponding figures for soybeans are 10.9%, 20.9%, 11.8%, and 22.6%. In the average case, the price impacts drop by half, but remain still relatively large.

The increases in crop prices affect food prices (including all types of livestock products and processed food items). Of course, it is well known that agricultural commodities represent only a small part of total food costs, with the rest being processing, labor, transport, etc. For example, according to our simulation results, the US food price index increases by about 1%, 0.6%, and 0.2% for the reference, average, and conservative base cases, respectively. While these numbers may seem small, a 1% increase in food costs for all Americans amounts to billions of dollars per year. In 2012-13, US total food consumption was about $1.4 trillion per year (USDA ERS, 2014a). Therefore, a 1% increase would be about $14 billion per year, and it increases if we take into account higher commodity prices in the fixed trade, fixed food, and their combination cases. The higher crop prices will negatively affect livestock and food processing industries as well.

Welfare Impacts

We now examine the overall welfare impacts of moving away from GMO crops at the US and global levels. The welfare impact measures changes in economic wellbeing in monetary terms. The welfare impacts for all examined cases are presented in Table 7 for the United States and at the global scale. In the reference, average, and conservative base cases, banning GMO crops reduces US welfare by $1.1 billion, $0.6 billion, and $0.2 billion, respectively. The corresponding figures for these cases at the global level are $4.3 billion, $2.5 billion, and $0.8 billion. The negative wel-

Table 6. Price impacts of moving away from GMO crops for all alternative scenarios.

Cases		Crops								
		Rice	Wheat	Sorghum	Coarse grains	Soybeans	Rapeseed	Other oilseeds	Sugar crops	Other crops
Base cases	Reference	3.6	2.9	11.4	17.1	10.9	3.6	3.8	5.7	5.2
	Average	2.1	1.8	6.4	9.8	5.7	2.1	2.2	3.3	3.1
	Conservative	0.8	0.6	2.4	3.8	0.9	0.7	0.7	1.2	1.1
Fixed trade	Reference	6.3	4.7	17.2	25.8	20.9	5.4	5.3	10.7	10.0
	Average	3.6	2.7	9.0	13.8	10.2	3.0	3.0	5.9	5.6
	Conservative	1.0	0.8	2.8	4.5	1.2	0.9	0.9	1.7	1.6
Fixed food	Reference	4.1	3.4	12.2	18.1	11.8	4.0	4.3	6.4	5.8
	Average	2.4	2.0	6.9	10.3	6.1	2.3	2.4	3.8	3.5
	Conservative	0.9	0.7	2.5	3.9	1.0	0.8	0.8	1.4	1.3
Fixed trade & food	Reference	7.1	5.2	18.8	27.6	22.6	6.0	5.9	12.0	11.2
	Average	4.0	3.0	9.7	14.6	11.0	3.3	3.3	6.6	6.3
	Conservative	1.1	0.9	2.9	4.6	1.4	1.0	1.0	1.8	1.8

Table 7. Welfare impacts of banning GMO crops in the United States for all alternative scenarios (figures are in million $ at 2004 prices).

Description		Base cases	Fixed trade	Fixed food	Fixed trade & food
United States	Reference	-1,139.9	-4,664.8	-1,201.2	-4,875.9
	Average	-624.3	-2,524.8	-652.9	-2,616.6
	Conservative	-189.2	-622.4	-194.6	-633.7
World	Reference	-4,319.3	-5,695.6	-4,425.7	-5,946.8
	Average	-2,495.7	-3,149.6	-2,546.9	-3,268.3
	Conservative	-826.3	-896.8	-836.5	-917.9

fare impacts grow as we move to the fixed trade, fixed food, and their combinations. For example, when both trade and food consumption are fixed, US welfare drops by $4.9 billion, $2.6 billion, $0.6 billion in the reference, average, and conservative cases, respectively. The corresponding figures at the global scale are $6 billion, $3.3 billion, and $0.9 billion. The welfare losses reflect all the substitution that occurs in a general equilibrium analysis. In addition, it must be remembered that commodity and food price changes represent a very small portion of the total consumer budget in the United States.

Conclusions

The main objective of this study was to evaluate the potential economic and GHG emissions consequences of losing GMO traits in the major crops of corn, soybeans, and cotton in the United States. We obtained from the literature a range of estimates of the yield loses if we move away from GMO traits in the United States. Then we introduced the yield losses into a well-known CGE model, GTAP-BIO, adopted by the CARB for use in determining induced land-use changes due to biofuels, to quantify the land-use and economic impacts of banning GMO traits in the United States.

Our analyses confirms that if we do not have access to the GMO technology, more land would be needed for corn, soybeans, and cotton. Some of it would come from crop switching, and the rest from conversion of cropland pasture, pasture, and forest. Of course the land-use changes vary by case and by level of yield shock. However, results from the GMO average base case is closest to the case of expansion in corn ethanol from its 2004 level of 3.41 billion gallons to 15 billion. In other words, loss of GMO technology would result in an increase in GHG emissions equivalent to or higher than the land-use change emissions from the entire US ethanol program. The logic of the land-use emissions increase is straight-forward. Without GMO technology, more land would be needed to meet the food, feed, fuel, and fiber demands. Some of this land would come from converted forest or pasture, and that land conversion releases GHG emissions.

As would be expected, production of the affected commodities falls pretty much proportional to the size of yield loses in the absence of GMO crops. The production changes are less for the fixed trade and fixed food consumption cases because the model is required to meet export levels and/or food consumption levels.

Commodity prices for the shocked commodities increased. In general, commodity price changes in general equilibrium models like GTAP are lower than those for partial equilibrium models. However, the price changes for corn were as high as 28% and for soybeans as high as 22%. These are very high price increases for a general equilibrium model. In general, the price increases for the reference and average cases were higher than those observed previously for US ethanol shocks.

The food price impacts for the fixed trade case (perhaps the case that best represents what might actually happen) were 1% for the average shock and 1.7% for the reference shock. Since commodity prices make up a small part of total food cost, these food price increases can be considered as large. Given that in 2012-13 total US food consumption was about $1.4 trillion, these food price changes amount to $14-$24 billion per year.

Losing the GMO productivity also would have negative economic welfare impacts for the US and global economy. The reference cases change in US welfare range between -$1.1 and -$4.9 billion, and the global changes range between -$4.3 and -$5.9 billion. For the average cases, the US range was -$0.6 to -$2.6 billion, and the global range was -$2.5 to -$3.3 billion.

Clearly, if we lost the GMO technology, there would be significant land-use change and GHG emissions, important commodity price increases, food price increases, and economic welfare losses.

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Appendix A

Impacts of GMO Traits on US Corn, Soybeans, and Cotton Yields

In order to calculate the total negative productivity shock for each crop under investigation, we took the yield differential between the genetically engineered (GE) crop and the conventional crop from relevant sources. We then weight it by the percentage of total US acreage planted to the GE crop.

The literature used in this article provides estimates of yield improvement of GMO crops over conventional varieties. In order to convert these yield improvement to proper yield shocks for the GTAP model, we followed three steps. The first is to derive yield shocks in terms of yield improvement from the exiting literature. Then we weight the shocks by planted area. Finally we group the shocks and weight them according to the GTAP crop categories.

In order to derive the yield shocks in terms of the yield improvements in the literature, we begin by stating the relation between GMO and conventional yields. Equation 1 gives the relationship between conventional yields, GMO yield improvement, and GMO yield.

$$Y_g = Y_c \times (1 + g), \tag{1}$$

where Y_c is conventional yield, g is the GMO yield improvement, and Y_g is the GMO yield. Dividing both sides by $(1 + g)$ gives

$$Y_c = [Y_g / (1 + g)]. \tag{2}$$

Equation 2 gives the conventional yield in terms of the GMO yield and the GMO yield improvement. We divide each side by the GMO yield in order to derive the ratio of conventional yield to GMO yield. This is given by Equation 3.

$$Y_c / Y_g = 1 / (1 + g) \tag{3}$$

To derive the yield gap, we subtract 1 from the conventional to GMO yield ratio. For example, if the ratio of conventional to GMO is 0.9, then the yield shock (or yield loss) associated with switching from conventional to GMO is 10% (0.9 − 1 = -0.1). Subtracting 1 from each side gives

$$(Y_c / Y_g) - 1 = -g / (1 + g). \tag{4}$$

Thus, we convert the yield improvement given by g to a yield shock. The yield shock is weighted by the proportion of total planted area that is planted to the GMO variety. This is represented as

$$S = [-g / (1 + g)] \times A_g / A, \tag{5}$$

where S is the weighted shock, A_g is the area planted to the GMO variety, and A is the total area planted to the crop (GMO and conventional).

The area data used in our calculations comes from the National Agricultural Statistics Service (NASS) acreage report for 2014. We include percentages rather than total area, since the purpose of these areas is to weight our yield differentials. In 2014, the total area planted to corn with only *Bacillus thuringiensis*, or insect-resistant traits (Bt), was 4% of total corn area planted in the United States. The total area planted to corn with only herbicide-tolerant traits (Ht) was 13%, and the total area planted to corn with stacked traits (Bt&Ht) was 76%.

In 2014, the total area planted to cotton with only Bt traits was 5% of total cotton area planted in the United States. The total area planted to cotton with only Ht traits was 12%, and the total area planted to cotton with Bt&Ht traits was 79%. However, in the case of cotton,

Table A1. Estimated negative productivity shocks in the United States (% decrease in yield).

Crop	Reference	Conservative	Average
Corn	17.1	5.2	11.2
Cotton	23.1	14.1	18.6
Soybeans	10.3	0.0	5.2

there is little evidence of a significant change in yield as a result of stacking the Bt trait with an Ht trait. In fact as noted in Verhalen et al. (2003), despite Ht traits occasionally resulting in a negative yield differential relative to conventional varieties, the yield increase from the Bt traits in stacked Bt&Ht cotton overcomes the impact of these deficits. Thus we will consider the Bt planted acreage and the Bt&Ht planted acreage as one and weight our observed differentials appropriately. In 2014, 94% of soybeans planted in the United States had Ht traits. That was the major GE option used by farmers.

Table A1 provides a summary of the results of this analysis for the three target crops. The sources for the data and the calculations are in the material that follows. From reviewing the literature, we developed reference and conservative cases below. The reference cases represent studies that estimated higher yield impacts for genetically engineering crops. The conservative case represents those studies that estimated lower yield impacts for GE crops. The third column represents the simple average of the two cases. We perform the GTAP simulations with these three yield shocks.

The GMO yield shocks summarized in Table A1 must be translated into the appropriate shocks in GTAP. The reason that a translation is necessary is because commodities are combined into groups in GTAP. Of the three crops being considered here, only soybeans are in a group by themselves. So the soybean shocks in Table A1 translate directly into the shocks applied in GTAP. Corn is included in coarse grains, but it is the vast majority of that category, representing 91.5% of the coarse grains area. Thus, the corn shocks in Table A1 are multiplied by 0.914 to get the shocks applied in GTAP. This is represented as

$$M = 0.914 \times S_m \,, \tag{6}$$

where M is the GTAP coarse grains shock and S_m is the weighted yield shock for corn.

The biggest problem is for cotton. Cotton in the GTAP aggregation used for all the biofuels research is in the commodity group that contains plant-based fibers (PBF); vegetables, fruits, and nuts (V_F); and crops not included elsewhere (OCR). In the United States, cotton represents only 1.1% of the area of all the crops in that group. Thus the original shocks in Table A1 are multiplied by 0.011 to get the shocks applied in GTAP. This is represented as

$$\mathrm{P} = 0.011 \times S_c \,, \tag{7}$$

where P is the GTAP shock and S_c is the weighted yield shock for cotton.

Table A2 summarizes the percentage shocks applied in GTAP based on the logic described here. Because cotton represents such a small share of the total area of the plant-based fiber category, and because we have somewhat less confidence in the cotton results for that reason, we report the land-use change simulation results with and without the cotton shocks included for the base case. For the production and price changes, the differences were very small, so we only report the 'with cotton' results. The 'without cotton' results are available from the authors.

Corn

In the case of GE corn in the United States, there are two major types of modified corn with significant yield differences when compared to conventional corn—Bt corn, and stacked Bt$Ht corn. Though a certain percentage of the GE corn planted in the United States is just herbicide resistant, there appears to be little evidence that herbicide tolerance increases yield. Its economic benefits and reasons for adoption are not directly increased to productivity, but rather other gains to the farmer (e.g., cost reduction) which indirectly improves their profitability. While we recognize that Ht crops improve profitability and that indirectly means higher productivity, we do not include this effect in our analyses. Thus, our productivity shock estimate for corn is the weighted average of the estimated productivity shock for Bt corn and the estimated productivity shock for stacked-trait corn. In the case of some estimates, the Bt productivity data is separated into corn-rootworm-resistant (CRW) and corn-borer-resistant (ECB) corn. In such cases, we will consider the ECB and the ECB/CRW stack as the more relevant number.

Reference Case for Corn: Fernandez-Cornejo et al. (2014)

Our first estimate comes from "Genetically Engineered Crops in the United States" (Fernandez-Cornejo et al., 2014). This paper is not primarily focused on productivity shocks, but rather on the overall economic impact of

Table A2. Original yield shocks and GTAP applied shocks (%).

Crop	Area share of GTAP commodity	Reference		Average		Conservative	
		Original shock	GTAP shock	Original shock	GTAP shock	Original shock	GTAP shock
Corn	91.5	17.1	15.64	11.2	10.24	5.2	4.76
Cotton	1.1	23.1	0.27	18.6	0.22	14.1	0.16
Soybeans	100	10.3	10.3	5.2	5.2	0	0

GE crops in the United States. It provides a qualitative overview of much of the literature on the impacts of GE crops in the United States to date, with regard to yields, pesticide use, and net returns. It also provides some quantitative data itself on yield differences. The productivity information provided by Fernandez-Cornejo et al. (2014) for Bt corn comes from USDA Agricultural Resource Management Survey (ARMS) data for corn in 2010. In 2010, average yields for non-Bt corn were 132.6 bu/ac, while yields for Bt corn were 159.2 bu/ac. The percentage difference is calculated from the GM yields because that is the yield realized with GM varieties, and we want to estimate the loss if those varieties did not exist. Thus, the drop in yield is (132.6/159.2 – 1)*100 = -16.7%. For purposes of simplicity we will ignore various potential biases (self-selection, most importantly), but we note here that they inevitably have some impact on this data. In our reference case, we will therefore adopt a negative productivity shock of 16.7% for Bt planted acres.

The same paper provides an estimate for stacked-trait corn as well, using the same methodology—that is, simply looking at USDA ARMS data on yields for stacked trait vs. conventional yields in 2010. Here, the difference is even more striking: the stacked trait corn had average yields of 171 bu/ac, compared to the 134 bu/ac yields of conventional corn. The drop in yield is -21.6%. We weighted the yield differentials by the percentage of total area:

Weighted corn yield shock = [0.04 × (-0.1671) + 0.76 × (-0.2164)] × 100 = -17.1%.

Thus, our reference case for a weighted productivity shock is a 17.1% decrease in corn productivity for GMO acreage in the United States.

Conservative Case for Corn: Nolan and Santos (2012)

Nolan and Santos' (2012) article uses a large dataset collected from university extension trials to produce estimates for the effects of specific, as well as stacked, GE traits on yield. In this article, yield differentials are given on a trait-by-trait basis. The first group of traits we will consider are the Bt-only traits: ECB, CRW, and stacked ECB&CRW. In the fixed-effects specification, yields for corn with the relevant trait are compared to conventional yields. The conventional comparison yields differ from trait to trait. Here again, the percentage difference is calculated from the GM yields because that is the yield realized with GM varieties.

In the case of the ECB trait, the yield for conventional corn is 179.3 bu/ac, compared to ECB corn, which has a yield of 187.2. The drop in yield is (179.3/187.2 − 1)*100 = -4.2%. Comparing conventional corn to the CRW trait, conventional yield is given as 192.3 bu/ac, while CRW corn yield is 195.7 bu/ac. The drop in yield is (192.3/195.7 – 1)*100 = -1.7%. Finally, for ECB&CRW stacked corn, the conventional yield is 185.9 bu/ac, while the ECB&CRW corn yield is 193.1 bu/ac. The drop in yield is (185.9/193.1 – 1)*100 = -3.7%. Adoption rates for the CRW trait are generally lower than the adoption rates for ECB, and are about equivalent to adoption rates for ECB&CRW. We will therefore adopt 4% as a negative productivity shock for the Bt corn acreage.

Three stacked (Bt/Ht) yield differentials are provided—ECB/Ht vs. conventional, CRW/Ht vs. conventional, and ECB/CRW/Ht vs. conventional. In the first case, ECB/Ht vs. conventional, the conventional yield is 174.2 bu/ac, while the ECB/Ht corn yield is 184.6 bu/ac. The drop in yield is (174.2/184.6 – 1)*100 = -5.6%. For CRW/Ht vs. conventional, the conventional yield is 185.9 bu/ac, while the CRW/Ht average yield is 199.7 bu/ac. The drop in yield is (185.9/199.7 – 1)*100 = -6.9%. Finally, CRW/ECB/Ht average yield is 200.6 bu/ac, while conventional yield is 187.3 bu/ac. The difference is (187.3/200.6 – 1) = -6.6%. Given the prevalence of CRW/ECB/Ht corn, we will adopt 6.6% as our productivity shock for Bt/Ht corn acreage. We weighted the yield differentials by the percentage of total area:

Weighted corn yield shock = [0.04 × (-0.0400) + 0.76 × (-0.0660)] × 100 = -5.2%.

Thus, our conservative estimate for a weighted productivity shock is a 5.2% decrease in corn productivity in the United States. We consider this quite conservative as the conventional yields in this data set seem high.

Cotton

As mentioned earlier, the positive yield impacts for stacked-trait cotton are attributable to the Bt trait. In the United States, by far the most dominant Bt trait in cotton is the Bollgard II (BG2) trait. Thus our estimates have focused on the yield impact of this trait when compared to conventional cotton. We have assumed that, though the herbicide tolerance provides no positive yield impact itself, it does not hinder the improved productivity of the BG2 trait.

Reference Case for Cotton: Sankula (2006a)

Sankula (2006a) provides an overview of GE crops focused on the primary types of traits (Bt and Ht) for the primary crops (cotton, soybeans, and corn). The chapter uses both USDA survey data and other studies to survey the many economic and agronomic impacts of GE crops. The chapter was written in 2006, before the mainstream commercialization of the BG2 gene. Most of its discussion about Bt cotton is therefore focused on the Bollgard I (BG1) gene. The improvement in yield of BG1 over conventional yields is given as 7% to 12%. The paper also provides some data on BG2 yields: in particular, it cites multi-state trials from 2003 showing 26% yield increases for BG2 compared to BG1. In order to determine the yield impact of switching from BG2 to conventional cotton, we must first calculate the yield impact of switching from BG2 to BG1. Since the yield differential is given in the paper as a percentage improvement over BG1, some straightforward algebra is required.

BG2/BG1 = 1.26 BG1/conv = 1.095
BG2/1.095conv = 1.26
BG2/conv = 1.3797 conv/BG2 = 0.7248
Negative yield shock = 0.2752

We weighted the yield differential by the percentage of total area.

Weighted corn yield shock = 0.84 × (-0.2752) × 100 = -23.1%

Thus, we obtain a negative productivity shock of 23.1% for cotton yields for the reference case.

Conservative Case for Cotton: International Cotton Advisory Committee (2003)

The conservative estimate is derived from an article published in the March 2003 edition of the International Cotton Advisory Committee's (ICAC) Recorder (2003). The paper is a meta-analysis of a number of agronomic studies of BG2 cotton. These include a number of studies not especially relevant to our purpose here (effects on pest pressure, nature of the toxin and its expression, etc.). However, the paper also includes a summary of some data on yields for BG1, BG2, and non-Bt cotton. This data looks at yields in unsprayed and sprayed trials of non-Bt, BG1, and BG2 genotypes. We assume the relevant yield differential is from the sprayed trial. In those trials, the yields observed were 833 kg/ha for non-Bt cotton, and 1,001 kg/ha for BG2 cotton. This is a drop of (833/1001 − 1)*100 = -16.8% in yield between BG2 and non-Bt cotton. We weighted the yield differential by the percentage of total area.

Weighted corn yield shock = 0.84 × (-0.1678) × 100 = -14.1%

Thus, we obtain a negative productivity shock of 14.1% for the conservative case for cotton yields in the United States.

Soybeans

As mentioned before, the literature on yield improvements for Ht soybeans is thin, and there seems to be little consensus that there is any significant yield effect. The substantial rates of adoption of the GE varieties (the most substantial, in fact, of the three crops presented here) is usually attributed to lowered input costs and benefits to farmers other than yield improvements. We therefore provide the estimate below as an upper bound. The lower bound is zero.

Reference Case for Soybeans: Fernandez Cornejo et al. (2014)

This number also comes from the Economic Research Service report, produced by Fernandez-Cornejo et al. (2014). As with the corn yield differentials provided in the same, this productivity difference comes from ARMS data—this time from the 2006 soybean survey. In that survey, Ht adopters had average yields of 45.6 bu/ac, while conventionally planted acres had average yields of 40.6 bu/ac. Thus the difference is (40.6/45.6 – 1)*100 = -11%. We weighted the yield differential by the percentage of total area.

Weighted corn yield shock = 0.94 × (-0.1096) × 100 = -10.3%

Thus, we obtain a productivity shock of 10.3% for soybean yield reference case. As indicated before, the conservative case for soybeans is no yield increase associated with GMO traits.

Appendix B

Commodity and Geographical Aggregation Schemes

Table B1. Regions and their members in GTAP BIO model.

Region	Description	Corresponding countries in GTAP
USA	United States	usa
EU27	European Union 27	aut, bel, bgr, cyp, cze, deu, dnk, esp, est, fin, fra, gbr, grc, hun, irl, ita, ltu, lux, lva, mlt, nld, pol, prt, rom, svk, svn, swe
Brazil	Brazil	bra
Canada	Canada	can
Japan	Japan	jpn
China	China and Hong Kong	chn, hkg
India	India	ind
C-America	Central and Caribbean Americas	mex, xna, xca, xfa, xcb
S-America	South and other Americas	col, per, ven, xap, arg, chl, ury, xsm
E-Asia	East Asia	kor, twn, xea
Mala-Indo	Malaysia and Indonesia	ind, mys
R-SE-Asia	Rest of South East Asia	phl, sgp, tha, vnm, xse
R-S-Asia	Rest of South Asia	bgd, lka, xsa
Russia	Russia	rus
E-Europe-RFSU	Other East Europe and rest of former Soviet Union	xer, alb, hrv, xsu, tur
Other Europe	Rest of European countries	che, xef
M-East-N-Africa	Middle Eastern and North Africa	xme,mar, tun, xnf
Sub-Saharan Africa	Sub-Saharan Africa	bwa, zaf, xsc, mwi, moz, tza, zmb, zwe, xsd, mdg, uga, xss
Oceania	Oceania countries	aus, nzl, xoc

Table B2. List of industries and commodities in the new model.

Industry	Commodity	Description	Name in the GTAP_BIOB
Paddy_Rice	Paddy_Rice	Paddy rice	pdr
Wheat	Wheat	Wheat	wht
Sorghum	Sorghum	Sorghum	A portion of gro
Oth_CrGr	Oth_CrGs	Cereal grains except sorghum	A portion of gro
Soybeans	Soybeans	Soybeans	A portion of osd
Palmf	Palmf	Palm fruit	A portion of osd
Rapeseed	Rapeseed	Rapeseed	A portion of osd
Oth_Oilseeds	Oth_Oilseeds	Other oilseeds	A portion of osd
Sugar_Crop	Sugar_Crope	Sugar cane and sugar beet	c-b
OthAgri	OthAgri	Other crops	ocr, pfb, v_f
DairyFarms	DairyFarms	Dairy Products	Rmk
Ruminant	Ruminant	Cattle & ruminant meat production	Ctl, wol
NonRum	Non-Rum	Non-ruminant meat production	oapl
ProcDairy	ProcDairy	Processed dairy products	Mil
ProcRum	ProcRum	Processed ruminant meat production	Cmt
ProcNonRum	ProcNonRum	Processed non-ruminant meat production	Omt
Forestry	Forestry	Forestry	Frs
Bev_Sug	Bev_Sug	Beverages, tobacco, and sugar	b_t, sgr
Proc_Rice	Proc_Rice	Processed rice	Pcr
Proc_Food	Proc_Food	Processed food products	A portion of ofd
Proc_Feed	Proc_Feed	Processed animal feed products	A portion of ofd
OthPrimSect	OthPrimSect	Other primary products	fsh, omn
Coal	Coal	Coal	Coa
Oil	Oil	Crude oil	Oil
Gas	Gas	Natural gas	gas, gdt
Oil_Pcts	Oil_Pcts	Petroleum and coal products	p-c
Electricity	Electricity	Electricity	Ely
En_Int_Ind	En_Int_Ind	Energy-intensive industries	crpn, i_s, nfm, fmp
Oth_Ind_Se	Oth_Ind_Se	Other industry and services	atp, cmn, cns, ele, isr, lea, lum, mvh, nmm, obs, ofi, ome, omf, otn, otp, ppp, ros, tex, trd, wap, wtp
NTrdServices	BTrdServices	Services generating non-C02 emissions	wtr, osg, dwe
PastureCrop	PastureCrop	A dummy sector to model cropland pasture	New
Vol_Soy	VOl_Soy VOBPS	Soy vegetable oil Soy meal	New, a portion of vol New, a portion of vol
Vol_Palm1	VOl_palm VOBPP	Palm vegetable oil Palm meal	New, a portion of vol New, a portion of vol
Vol_Rape1	VOl_Rape VOBPR	Rapeseed vegetable oil Rapeseed meal	New, a portion of vol New, a portion of vol
Vol_Oth1	VOl_Oth VOBPO	Other vegetable oil Other meals	New, a portion of vol New, a portion of vol
EthanolC	Ethanol1 DDGS	Ethanol produced from grains Dried Distillers Grains with solubles	New New
Ethanol2	Ethanol2	Ethanol produced from sugarcane	New
EthanolS	Ethanol3 DDGSS	Ethanol produced from sorghum Sorghum DDGS	New New
Biod_Soy	Biod_Soy	Biodiesel produced from soy oil	New
Biod_Palm	Biod_Palm	Biodiesel produced from palm oil	New
Biod_Rape	Biod_Rape	Biodiesel produced from rapeseed oil	New
Biod_Oth	Biod_Oth	Biodiesel produced from other vegetable oil	New