Assessing Environmental Impacts of Genetically Modified Seeds in Brazilian Agriculture

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Using a farm-level dataset on genetically modified (GM) seed adoption and pesticide application in Brazil, we find that Insect Resistant (IR) cotton reduces the environmental impact of insecticides but Herbicide Tolerant (HT) soybeans increase the environmental impact of herbicides due to weak substitution among herbicides of different toxicity levels.

Genetically modified (GM) seeds have been considered one of the major technological innovations for agricultural systems and have been promoted as an effective tool for controlling agricultural pests and expanding food supply. Their relevance can also be measured by the wide span of controversial issues that have been raised by the related literature, such as: intellectual property rights over organisms, productivity effects, economic returns, consumer safety, welfare and income distribution, and environmental effects.

On the environmental front, benefits from adoption of GM seeds have been argued based on findings about pesticide use and agricultural practices. Insect Resistant (IR) cotton has been found to reduce the use of insecticides and therefore produce environmental, health and safety gains. Herbicide Tolerant (HT) soybeans have been found to change the mix of herbicides applied towards less toxic chemicals and to allow the use of no-till cultivation techniques, leading researchers to conclude that they also produce environmental benefits.

This article addresses the environmental impacts, associated with pesticides use, resulting from adoption of GM seeds in Brazil. We innovate relative to previous works on this topic by employing a broader measure of environmental impact that takes into account toxicity levels and risk of exposure in evaluating the effects of pesticides for different dimensions of agricultural systems. Hence, we are able to uncover environmental impacts that have been hidden by the qualitative nature of the change in the mix of pesticides used.

GM Seeds and Pesticides Use

Since the mid 1990's, when first-generation GM seeds were commercially introduced, adoption by farmers has grown steadily in industrialized and developing countries as they provide an alternative and more convenient way of controlling pest damage. By 2008, 13.3 million farmers dedicated 8% of total cropland (12.5 million ha) to the cultivation of GM seeds. The leading countries in terms of share of cultivated area in 2009 were the United States (50%), Argentina (17%), Brazil (13%), India (6%), Canada (6%), and China (3%).

In Brazil, the most recent nationwide survey on agricultural biotechnology adoption indicates that GM seeds account for 91.8% (27.4 million ha) of soybean cultivated area, 81.6% (12.4 million ha) of maize, and 65% (0.71 million ha) of cotton-cultivated area. The main traits that have been introduced in first-generation GM seeds correspond to HT and IR technologies. The focus of this article relies on HT soybeans and IR cotton.

IR seeds are engineered to produce a natural toxin found in the soil bacterium *Bacillus thuringiensis* (Bt), which is lethal to a number of bollworm pests but not to mammals. In other words, the IR trait works as a substitute for insecticides that control bollworm infestations. IR crops have been considered technically and economically efficient for producers, allowing savings in labor and machinery used in insecticide applications. This potential is higher in regions with high infestations—typically, less-developed countries in tropical weather regions with high rates of insecticide use. Besides, it has also been considered a more efficient tool for managing risk of pest attack, allowing reduced expenditure on crop insurance. The result in terms of the outcome of interest is straightforward: less insecticide usage reduces associated environmental impact.

Weeds are strong competitors with soybean plants for nutrients, water, and sunlight. Weed control techniques have evolved from traditional mechanical methods to herbicide applications, which were introduced in the 1960's. Soybean seeds engineered with HT traits were introduced in 1996 under the commercial name *Roundup Ready*®. They are the result of the transfer of part of the genetic code of a soil bacterium, *Agrobacterium tumefaciens*, which allows the plant to metabolize the herbicide glyphosate (Roundup). In 1998 soybean varieties tolerant to the herbicide glufosinate were introduced under the commercial name *Liberty Link*®. These herbicides are considered less toxic than others and

Table 1. Estimates of Impact of IR Cotton and HT Soybeans on Quantity of Pesticides (Insecticides and Herbicides) and Environmental Impact (EIQ)

	Insecticies (Kg/ha)	Insecticides + (EIQ)	Herbicides (Kg/ha)	Herbicides+ (EIQ)
IR Cotton	-0.242***	-0.234***	-	-
	[0.037]	[0.035]	-	-
HT Soybean	-	-	0.442***	0.356***
	-	-	[0.056]	[0.049]
N	120	120	170	170
r^2	0.913	0.918	0.755	0.790

+ Robust standard errors. *$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$*

Coefficients multiplied by 100 indicate approximate percentage variation.

target a large variety of broad-leaf and grass weeds species, but cause severe damage to conventional crops when applied after germination.

By making the soybean plant less susceptible to damage caused by those chemicals, the HT trait induces farmers to apply more of them. The resulting environmental impact is ambiguous though: farmers are induced to apply more of less toxic herbicides, but the net effect depends on how much they substitute for more toxic ones. Hence, increasing the share of less toxic herbicides in the quantity of pesticides applied is not enough to guarantee a reduction in environmental impacts associated with these chemicals.

This discussion suggests that measuring environmental impacts associated with pesticide use is not straightforward. For HT traits, specifically, the net effect on environmental impact is an open issue. Economists who studied it have focused on the change in the mix of herbicides to conclude that there are environmental gains allowed by the use of HT traits. Nevertheless, we argue that weak substitution might undermine this conclusion, as we show in the analysis that follows on the next section.

Empirical Strategy

In the empirical analysis, we use a unique farm-level dataset originated from a survey conducted by a private firm in Brazil. The survey collected data on production, revenue, costs, biotechnology adoption, and pesticides used. Information on pesticide use was collected for harvest seasons 2009–2011 and covers 839 farms.

The dataset is disaggregated by fields, within a farm, cultivated with conventional or GM seeds. In other words, for each farm, we have potentially multiple observations related to fields cultivated with conventional or GM seeds. This setup allows us to use *within-farm* variation for farmers who plant both conventional and GM seeds to identify the effect of adoption on the environmental impact of pesticides. This empirical strategy holds constant all farm-level characteristics that might simultaneously affect the choices of pesticide use and biotechnology adoption, such as management skills, input/output prices, location, weather shocks, etc.

The farms surveyed represent large operations with potentially large environmental impacts associated with the scale of production and pesticide use. For cotton growers, the average total planted area is 2,521 ha, ranging from 60 ha to 28,374 ha. For soybean growers, the average total planted area is 1,240 ha, ranging from 8 ha to 13,500 ha. In terms of experience, farmers report an average of 22.4 and 29.4 years for cotton and soybeans, respectively.

We measure the environment impact as two outcome variables: quantity (Kg/ha) of active ingredients of chemicals, and the Environmental Impact Quotient (EIQ) index. This measure of environmental impact of pesticides was designed to capture risks associated with both toxicity levels and exposure to chemical pesticides on three components of agricultural systems: farmworker, consumer, and ecological. Hence, the EIQ index provides a more complete picture than just the composition of the mix of pesticides used, allowing for an adequate weighting of pesticides with different toxicity levels.

The use of the EIQ index represents a big advancement over previous studies, which relied on an increased share of less toxic chemicals of the total quantity (Kg/ha) of herbicides applied in HT soybeans fields, since this measure cannot capture environmental effects due to substitution between herbicides. If the increase in the use of less toxic herbicides is not accompanied by a sufficient decrease in more toxic ones, the new mix of herbicides induced by HT seeds can be more harmful than the one

Table 2. Estimates of Effects of HT Trait on Quantity of Herbicides per Toxicity Level

	Herbicides 1 (Kg/ha)	Herbicides 2 (Kg/ha)	Herbicides 3 (Kg/ha)	Herbicides 4 (Kg/ha)
HT Trait	-0.084***	-0.005	0.635***	0.438***
	[0.021]	[0.054]	[0.098]	[0.090]
N	168	168	168	168
r2	0.887	0.777	0.855	0.845

Robust standard errors in brackets. *$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$*

Note: toxicity levels 1-4 in decreasing order (from more to less toxic). Herbicides based on glyphosate are considered of lower toxicity level.

induced by conventional seeds. The EIQ index calculated for field operations allows us to adequately weight pesticides of different toxicity levels and gets around the difficulties of looking only at the quantity mix of pesticides used.

Findings

Our findings are summarized in Table 1. The dependent variables are logs of quantity (Kg/ha) of pesticides and of the EIQ index. The independent variable of interest is a dummy indicator for adoption of IR cotton or HT soybeans. Results show that adoption of IR cotton reduces the amount of active ingredients of insecticides used by 24.2%, and the environmental impact index by 23.4%, when compared with fields cultivated with conventional seeds. In absolute terms, this is equivalent to a reduction of approximately 0.956 Kg/ha of active ingredients.

For HT soybeans, although farmers use more of less toxic herbicides, we estimate that the net environmental impact is higher than for conventional seeds. We find that adoption of HT seeds causes an increase of 44.2% of active ingredients (Kg/ha), and a corresponding 35.6% increase in the EIQ index when compared with fields cultivated with conventional seeds. In absolute terms, this corresponds to an increase of 0.996 Kg/ha of active ingredients.

Table 2 sheds light on the mechanism that drives the results for HT soybeans. It shows estimates of the impact of HT seeds on the quantity of active ingredients (Kg/ha) of herbicides of different toxicity levels. The reductions in higher toxicity herbicides (columns 1 and 2) are very modest when compared to the increases in lower toxicity ones (columns 3 and 4). In absolute terms, we estimate that the increase in the later is *twelvefold* the decrease in the former. This result indicates that weak substitution among herbicides of different toxicity levels causes a net increase in the environmental impact associated with herbicides.

Our results confirm the environmental gains from IR cotton but suggest that the prior findings on the environmental effects of HT soybeans have been misled by relying solely on the change in the mix of herbicides used.

Conclusions

In this article, we analyze the environmental effects related to the use of pesticides arising from adoption of IR cotton and HT soybean seeds. Using *within-farm* variation across fields treated with conventional and GM seeds, we find that IR cotton reduces the amount of insecticides applied to cotton crops. HT soybeans, on the other hand, leads to more use of herbicides.

Analysis using the EIQ index shows that IR cotton reduces the environmental impact by about 23% in the treated fields compared to fields cultivated with conventional seeds. This is consistent with the previous result on Kg/ha of insecticides, and confirms the environmental impact-saving nature of the IR technology. The resulting environmental effects for HT soybeans, on the other hand, are found to be negative. The estimates imply that the impact of herbicides is increased by 35.6% compared to fields cultivated with conventional seeds.

Looking at quantities of herbicides of different toxicity levels, we see increases in the use of lower toxicity herbicides and very small reductions in higher toxicity ones. This finding indicates very weak substitution among herbicides, which explains the higher environmental impact associated with these chemicals caused by adoption of HT soybeans.

We believe this to be an important result for three reasons. First, it contributes to uncover environmental effects that have been hidden by the qualitative nature of the mix of herbicides induced by the HT trait. Second, environmental policy makers designing policies for biotechnology adoption might consider this new evidence to differentiate among GM traits that produce positive or negative externalities. Finally, as the composition of the EIQ index suggests, the environmental impact of pesticides can have multiple dimensions that might involve farmworker health and safety, consumer safety, and ecological impacts. Hence, the results on HT soybeans suggest additional avenues of work that should be taken to evaluate each of these possible channels since they can also affect other important outcomes.

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For additional information, the authors recommend:

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