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Bt cotton and pesticide use in Argentina: economic and environmental effects

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ABSTRACT. This article analyzes effects of insect-resistant Bt cotton on pesticide use and agricultural productivity in Argentina. Based on farm survey data, it is shown that the technology reduces application rates of toxic chemicals by 50 per cent, while significantly increasing yields. Using a damage control framework, the effectiveness of Bt versus chemical pesticides is estimated, and technological impacts are predicted for different farm types. Gross benefits could be highest for smallholder farmers, who are not currently using the technology. The durability of the advantages is analyzed by using biological models to simulate resistance development in pest populations. Rapid resistance buildup and associated pest outbreaks appear to be unlikely if minimum non-Bt refuge areas are maintained. Thus, promoting a more widespread diffusion of Bt cotton could amplify the efficiency, equity, and environmental gains. Conclusive statements about the technology's sustainability, however, require longer-term monitoring of possible secondary effects and farmers' behavior in maintaining refuges.

1. Introduction

Bt cotton was among the first genetically modified (GM) crops to be used in commercial agriculture. A gene from the soil bacterium *Bacillus thuringiensis* (Bt) was transferred to the cotton genome. This gene encodes the production of a protein that is toxic to certain lepidopteran insects. Cotton is attacked by a variety of insect species, and the crop is the single largest insecticide consumer worldwide (Matthews and Tunstall, 1994). Thus, cotton production is associated with considerable negative environmental externalities. As an inbuilt pest resistance mechanism, Bt could cause significant economic and ecological benefits, provided that pest populations would not rapidly overcome this resistance.

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In the USA and China, Bt cotton was commercialized in the mid 1990s, and today the technology covers about 30–40 per cent of the cotton area in both countries. Recent studies show that USA and Chinese Bt adopters realize significant pesticide and cost savings in most cotton-producing regions (Carpenter *et al.*, 2002; Pray *et al.*, 2002; Huang *et al.*, 2002a). Preliminary benefits of Bt cotton have also been reported for South Africa (Thirtle *et al.*, 2003; Ismaël *et al.*, 2002) and Mexico (Traxler *et al.*, 2001). Nonetheless, relatively little is known about Bt–insecticide interactions and productivity effects under different agroecological conditions (GRAIN, 2001). The broader impacts of GM crops in general, and Bt cotton in particular, are still a matter of controversy, especially with respect to long-term environmental implications and sustainability (Batie and Ervin, 2001; Benbrook, 2001; UK Soil Association, 2002). This holds true both in developed and developing countries.

This article adds to the discussion by empirically analyzing the economic, social, and environmental repercussions of Bt cotton in Argentina, where the technology was commercialized by Monsanto starting in 1998. So far, two Bt varieties containing the Cry1Ac gene have been released. These varieties were not specifically developed for the Argentine market and are used in a number of other countries. Due to a relatively high technology fee charged for Bt by the monopoly seed supplier, adoption in Argentina is still comparatively low (Qaim and de Janvry, 2003). Independent of the seed price, however, we examine the technology's impacts on pesticide use and productivity at the farm level. This analysis is based on a comprehensive survey of cotton farmers carried out in 2001. The data set covers both adopters and non-adopters of Bt technology and, for adopters, both Bt and non-Bt cotton plots.

Furthermore, we examine possible Bt resistance development in pest populations, which would influence the technology's sustainability. Although significant resistance buildup has not been observed so far in commercial cotton production, entomological studies indicate a high risk of rapid insect adaptation to the Bt toxin (Gould, 1998). Resistance development is also one of the main concerns of environmentalists with respect to Bt crops. It would not only render the transgenic technology useless, but would also imply loss of Bt as an ecologically friendlier microbial insecticide which is widely used in organic agriculture. We use biological models to simulate Bt cotton–pest interactions and resistance development in Argentina.

The remainder of this article is structured as follows. Section 2 briefly explains the farm survey and examines the impact of Bt cotton on pesticide use. Since Bt has not yet been widely adopted, different techniques are used to reduce a possible non-random selection bias. Descriptive statistics and econometric models both confirm that the technology has a net pesticide-reducing effect. At the same time, Bt entails a significant yield advantage, which is higher in Argentina than in many other countries. In section 3, different specifications of the micro-level production function are used to analyze and explain these productivity effects. The effectiveness of Bt versus chemical insecticides in pest management is modeled using a damage control specification. The damage control framework is also used for predicting likely technology impacts on different types of non-adopters. This is particularly interesting because the Argentine cotton sector is very heterogeneous in terms of farm sizes, and small-scale producers are not yet using GM varieties. Simulations of Bt resistance development in pest populations are carried out in section 4. Since resistance buildup appears to depend on maintenance of non-Bt refuge areas, different scenarios are considered. The last section discusses the main findings and concludes.

2. Data basis and pesticide use

2.1. Farm survey

An interview-based survey of 299 cotton farms was carried out in 2001 in collaboration with Argentina's *Instituto Nacional de Tecnología Agropecuaria* (INTA). The survey covered the two major cotton-growing provinces, Chaco and Santiago del Estero, which together account for almost 90 per cent of the Argentine cotton area. Because the number of Bt adopters is still comparatively small, we employed a stratified random sampling procedure, differentiating between adopters and non-adopters of the technology. Complete lists of adopters – defined as farmers who had used Bt at least once during the previous two cropping seasons – were provided by the seed-supplying company. The total sample consists of 89 adopters and 210 non-adopters.

In order to account for heterogeneity in the Argentine cotton sector, we subdivide the sample into two groups according to overall farm size. Following a classification commonly used in Argentina, small-scale producers are those who own less than 90 hectares of agricultural land. They are mostly liquidity constrained farmers who cultivate cotton with low input intensities and a low to medium degree of mechanization. Large-scale producers, with more than 90 hectares of agricultural land, are comparatively better off. Although the majority of these farms can still be labeled family businesses, farmers often live in the nearby town and employ one or more permanent workers. Large-scale farmers produce around 70 per cent of the Argentine cotton but account for only 15 per cent of all cotton producers (SAGPYA, 2000). This corresponds almost exactly to the share of large farms in our sub-sample of non-adopters. With an average farm size of 730 hectares, Bt adopters are fairly representative of the group of large-scale farmers. Indeed, none of the interviewed adopters had a land holding of less than 90 hectares.

Apart from eliciting general farm and household characteristics, the survey included detailed questions about input–output relationships in cotton cultivation for two cropping seasons – 1999/2000 and 2000/2001. As all Bt adopters were also cultivating at least some conventional cotton, they were asked the same questions for both their Bt and conventional plots. This allows us to make with and without technology comparisons not only across but also within farms. Accordingly, the number of observations on plots is somewhat larger than the number of farmers interviewed in both cropping seasons.

2.2. Effects of Bt cotton on pesticide use

Bt cotton provides strong resistance to the tobacco budworm (*Heliothis virescens*) and fairly good resistance to the cotton bollworm (*Helicoverpa gelotopoeon*), which together are often referred to as the bollworm complex. This complex is a major pest in Argentina. Furthermore, the Bt toxin protects against the cotton leafworm (*Alabama argillacea*), the pink bollworm (*Pectinophora gossipiella*), and to a lesser extent to armyworms (*Spodoptera* spp.), all of which occur in the country. We will refer to these lepidopteran species as Bt target pests. Cotton pests in Argentina to which the technology does not provide resistance include plant bugs (*Dysdercus* spp. and *Jadera* spp.) and various sucking pests, especially aphids (*Aphis gossypii*) and thrips (*Frankliniella* spp.). Therefore, Bt cotton does not completely eliminate the need to spray chemical insecticides in order to avoid pest damage. Since expression of the Bt toxin declines in aging plants (Greenplate, 1999), even sprays against Bt target pests are sometimes necessary when there is heavy infestation late in the cropping season.

Patterns of insecticide use with and without Bt technology are shown in table 1 for the 1999/2000 and 2000/2001 cropping seasons. Column (1) shows mean values for all Bt plots, whereas column (2) refers to all conventional plots in the sample. As expected, the number of sprays and insecticide amounts are lower for Bt, but the differences are relatively small. The reason is the big heterogeneity in the sample, and the fact that so far only large farms have adopted Bt. Columns (3) and (4) reveal that large-scale farmers use significantly more insecticides on their conventional plots than their smaller counterparts. This is mainly due to financial constraints and limited knowledge about pest infestation in the small farm sector. In 2000/01, around 15 per cent of smallholders were not using any pesticides at all. This is reflected in sizeable crop damage and lower average yields. A comparison of Bt plots (column 1) with conventional large farm plots (column 4) reduces the systematic bias and reveals the significant pesticide savings effect of the technology.

Since the data set also includes conventional plot observations for Bt adopters, a within-farm evaluation is instructive as well. Thus, the disturbing influence of unobservable farmer characteristics is removed. A comparison of columns (1) and (5) reveals that Bt cotton was sprayed over twice less often than conventional cotton, while insecticide amounts were reduced by 55 per cent and 43 per cent in 1999/2000 and 2000/2001, respectively. These insecticide savings become even more pronounced when commercial product concentrations are converted into amounts of active ingredients. Table 1 demonstrates that most of the reductions occur in hazardous chemicals of toxicity classes I and II, such as organophosphates, carbamates, and synthetic pyrethroids. These broad-spectrum pesticides are highly disruptive to beneficial insects and cause significant residue problems. Apart from cost savings and productivity gains, Bt technology can therefore be associated with major environmental benefits.[1]

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[1] Substituting Bt for broad-spectrum pesticides could possibly lead to a higher incidence of non-Bt target pests. Indeed, a few technology adopters reported

Table 1. *Insecticide use and crop yields on Bt and conventional cotton plots (Mean–standard deviation)*

		Conventional plots			
	(1) *Bt plots*	(2) *All conv. plots*	(3) *Only small farms*	(4) *Only large farms*	(5) *Only Bt adopters*
1999/2000 cropping season					
Number of sprays	2.14	3.74**	3.02**	4.75**	4.52**
	(1.13)	(2.01)	(1.83)	(1.81)	(1.24)
Amount of insecticide	1.85	2.43*	1.41*	3.88**	4.15**
(kg/ha)	(1.11)	(1.92)	(1.32)	(1.71)	(1.61)
of which in:					
Toxicity class I	1.52	1.60	0.89**	2.62**	2.87**
	(1.15)	(1.53)	(1.18)	(1.40)	(1.33)
Toxicity class II	0.27	0.78**	0.52**	1.15**	1.20**
	(0.42)	(0.73)	(0.53)	(0.82)	(0.92)
Toxicity classes III & IV	0.05	0.05	0.00**	0.12*	0.08
	(0.10)	(0.13)	(0.00)	(0.18)	(0.14)
Amount of active ingredient	0.64	1.15**	0.69	1.79**	1.90**
(kg/ha)	(0.35)	(0.82)	(0.76)	(0.87)	(0.87)
Yield of raw cotton (kg/ha)	2,032	1,291**	1,111**	1,546**	1,537**
	(580)	(505)	(464)	(449)	(364)
Number of observations	29	276	162	114	29
2000/01 cropping season					
Number of sprays	2.84	3.70**	2.90	4.81**	5.07**
	(1.19)	(2.10)	(1.97)	(1.74)	(1.91)
Amount of insecticide	2.30	2.35	1.25**	3.87**	4.03**
(kg/ha)	(0.78)	(1.94)	(1.14)	(1.78)	(1.86)
of which in:					
Toxicity class I	1.77	1.46	0.73**	2.48**	2.57**
	(1.12)	(1.50)	(1.01)	(1.48)	(1.62)
Toxicity class II	0.48	0.82**	0.51	1.25**	1.34**
	(0.72)	(0.83)	(0.48)	(1.00)	(1.04)
Toxicity classes III & IV	0.05	0.06	0.00**	0.14**	0.12**
	(0.10)	(0.14)	(0.00)	(0.19)	(0.19)
Amount of active ingredient	0.78	1.08**	0.59**	1.77**	1.80**
(kg/ha)	(0.45)	(0.97)	(0.64)	(0.93)	(0.94)
Yield of raw cotton (kg/ha)	2,125	1,285**	1,080**	1,570**	1,606**
	(566)	(515)	(446)	(468)	(459)
Number of observations	73	298	173	125	73

Notes: * Significantly different from mean value on Bt plots at 10% level.
** Significantly different at 5% level.

In order to estimate the technology's net effect on pesticide use, insecticide amounts in kilogram per hectare (*INS*) are regressed on different

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more problems with plant bugs and sucking pests. Longer-term monitoring is necessary to analyze whether this will entail a decline in Bt-induced pesticide reductions over time.

explanatory variables as follows

$$INS = \alpha + \beta_1 Bt + \beta_2 P + \beta_3{}' PEST + \beta_4{}' A + \beta_5{}' H + \varepsilon \qquad (1)$$

where *Bt* is a dummy which takes a value of one for Bt plots and zero otherwise. *P* is the insecticide/cotton price ratio. In spite of cross-section data, there is price variation because farmers buy inputs from different sources. Insecticide prices are converted into dollars per kg of active ingredient, to account for possible quality disparities. *PEST* is a vector of plot-level variables describing the degree of pest pressure *ex ante* to spraying decisions. *A* includes different agroecological factors, and *H* captures farm and household characteristics. ε is a random error term with mean zero. The estimation results are shown in table 2 for both growing seasons (columns 1 and 2), including all plot observations with complete sets of explanatory variables.

The coefficients for the *Bt* dummy in the two cropping seasons confirm that the technology decreases insecticide use significantly. In both seasons, the net effect is a saving of 1.2 kg per hectare. Unsurprisingly, higher insecticide prices also have a reducing effect on use. In order to quantify levels of pest pressure, farmers were asked to assess the incidence of different insect species and, related to this, the expected damage they would have incurred without spraying. Pest pressure was recorded separately for both growing seasons on a scale from 1 to 10. Because the incidence of Bt target pests is strongly correlated with technology use, we replaced the pressure of lepidopteran species on Bt plots with values observed for conventional plots on the same farms. This approach is justified, since conventional and Bt cotton is generally grown on adjacent plots. Evidently, bollworm pressure has the most notable impact on insecticide use, which underlines the high destructive capacity of this pest. Plant bug pressure led to higher insecticide use in 2000/2001 but not in 1999/2000. The negative coefficients associated with other lepidopteran insects, including pink bollworm and armyworm, are somewhat surprising. Since collinearity with other species might be expected, we tried to remove individual variables, but the results remained robust. Discussions with farmers and local entomologists confirmed that pink bollworm in particular is not considered a serious production constraint in Argentina.

More favorable climatic, soil, and water conditions entail higher pesticide use on account of higher yield expectations.[2] Likewise, education has a positive effect on application rates. Each additional year that the farmer attended school led to an increase in the amount per hectare of 0.1 kg in 2000/2001 and 0.2 kg in 1999/2000. In an international comparison, rates of pesticide use in Argentina are relatively low, and, indeed, quite a few farmers are not well aware of pest-related crop losses and how to avoid them.

As was already done for the descriptive statistics in table 1, the econometric analysis can also be confined to the sub-sample of Bt adopters

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[2] Pest infestation in irrigated cotton is somewhat higher than on rainfed plots. Analysis of correlation and variance inflation factors (VIF), however, showed that multicollinearity is not a problem. Mean VIFs were 1.62 and 1.53 for the 1999/2000 and 2000/2001 regressions, respectively, and none of the individual VIFs was bigger than 2.4.

Table 2. *Estimated insecticide use and insecticide reduction functions*

	(1) *Insecticide use 1999/2000 kg/ha* ($n = 294$)		(2) *Insecticide use 2000/01 kg/ha* ($n = 358$)		(3) *Insecticide reduction 2000/01 kg/ha* ($n = 70$)	
	Coefficient	*t-statistic*	*Coefficient*	*t-statistic*	*Coefficient*	*t-statistic*
Constant	−1.580	−2.29	−0.852	−1.34	2.596	2.92
Bt (dummy)	−1.227	−3.07	−1.171	−5.85		
Insecticide/cotton price ratio	-2.4×10^{-4}	−3.10	−0.005	−4.21	−0.024	−3.88
Bollworm pressure	0.199	5.53	0.200	6.33	0.181	2.94
Leafworm pressure	0.044	0.99	0.046	1.22	[a]	
Other lepidopteran pressure	−0.069	−1.26	−0.203	−4.23	[a]	
Plant bug pressure	0.009	0.21	0.142	4.19	[a]	
Sucking pest pressure	0.083	1.31	−0.049	−0.88	−0.141	−1.47
Irrigated (dummy)	−0.058	−0.14	1.161	3.86	[a]	
Climate (1–5 scale)	0.390	2.80	0.304	2.49	[a]	
Good soil quality (dummy)	0.548	2.11	0.977	4.08	[a]	
Farm size (owned land)	4.0×10^{-4}	3.89	3.7×10^{-4}	3.96	2.7×10^{-4}	1.97
Education	0.163	6.00	0.098	4.07	[a]	
Age	0.002	0.28	−0.005	−0.74	−0.026	−1.77
Adjusted R^2	0.412		0.434		0.272	

Notes: [a]Coefficients had absolute t-statistics smaller than one, so that variables were removed from the regression to save degrees of freedom.

to control for unobserved farmer characteristics and avoid a possible selection bias. We use an approach similar to the one suggested by Shaban (1987) in his paper on inefficiencies of sharecropping, and estimate the following relationship

$$\Delta INS = INS^{conv} - INS^{Bt} = \alpha + \beta_1 P + \beta_2{}' PEST + \beta_3{}' A + \beta_4{}' H + \varepsilon \qquad (2)$$

Pest pressure levels for Bt target species refer to the adopters' conventional plots, while they refer to Bt plots for non-target pests. We decided not to use plot-level differences in infestation levels, because this could cause problems of reverse causality: as was mentioned earlier, Bt-related reductions in broad-spectrum insecticides may lead to a higher incidence of plant bugs and sucking pests.

The number of Bt adopters in the sample for 1999/2000 is too small to derive any meaningful estimates. For the 2000/2001 season, results are shown in the third column of table 2. The constant term is positive and significant. This has to be interpreted as the net Bt effect. Due to the smaller heterogeneity in this sub-sample, the effect is even larger than was suggested by the insecticide use model with all observations. The coefficient for the insecticide/cotton price ratio is significantly negative, implying that absolute pesticide reductions tend to be bigger for those farmers with access to cheaper chemical products. This is not surprising, because insecticide prices are negatively correlated with initial application rates. Bollworm pressure has a clearly positive effect on insecticide reductions: the higher the bollworm pressure, the bigger the technological benefits. In contrast, high infestation of sucking pests can lower pesticide savings, albeit the coefficient is not significant. Because of the small sample size, variables associated with t-statistics smaller than one were removed from the regression to save degrees of freedom. When all variables are included, the constant term is 2.48, which is very similar to the one shown in table 2, but its t-statistic is only 1.05.

3. Productivity and damage control

3.1. Production function analysis

As can be seen in table 1, Bt cotton in Argentina not only reduces insecticide applications, but also increases yields to a significant extent. These yield advantages are larger than in many other countries. The net yield effect can be estimated econometrically by using a production function approach, where Bt is included as an explanatory variable. We use a quadratic specification, which generally shows a good fit in empirical studies at the micro level.[3] In particular, we estimate the following relationship

$$Y = \alpha + \beta Bt + \sum_i \gamma_i X_i + \sum_i \lambda_i X_i Bt + \sum_i \sum_j \phi_{ij} X_i X_j + \delta' A + \varphi' H + \varepsilon \qquad (3)$$

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[3] The often used Cobb–Douglas specification was also tried with similar general results but a much smaller number of observations. The problem with estimating a linearized Cobb–Douglas is that it leads to an exclusion of zero input observations, because their logarithm is not defined. The same holds true for the translog. As was already mentioned, many smallholders in Argentina do not use pesticides and other chemical inputs.

where Y is the yield of raw cotton, and X is a vector of inputs used – all expressed in per-hectare terms. The other variables are defined as before.

One problem with production function estimates based on farm survey data is the possible endogeneity of inputs. Insecticides, in particular, may be problematic if they are applied as a response to high pest pressure (Widawsky *et al.*, 1998). Accounting for this possible bias, we use an instrumental variable approach. Instead of including insecticides directly in the production function, we use predicted insecticide amounts (INS^{pred}). Predictions are based on the insecticide use functions in equation (1). A Hausman specification test confirms that this instrumental variable estimator is consistent and more efficient than the least squares estimator: the chi-square test statistic is 12.09. In principle, the endogeneity problem might also apply to other inputs for which suitable instruments are not available. However, since removing labor, fertilizer, and other chemicals from the production function has little effect on the remaining coefficients, we infer that there is no serious correlation with the error term.

The first column in table 3 shows the results of the production function estimate for 2000/2001, including all observations.[4] Evidently, Bt has a positive effect on output. All other things being equal, Bt increases cotton yields by 506 kg per hectare, which corresponds to a yield effect of 32 per cent for adopters. The technology is incorporated in cotton varieties which are not otherwise being used in Argentina, so we cannot control for a general germplasm effect. Since the Bt varieties have not been specifically developed for Argentine conditions, we would expect the germplasm effect to be small or even negative. Thus, most of the yield advantage is probably due to the Bt gene itself. If domestically bred varieties are better adapted to the local conditions, our model would underestimate the yield effect of Bt technology.

Insecticides also contribute substantially to higher yields. This underlines the destructive capacity of insect pests, especially the bollworm complex. The sample also comprises a number of farmers who did not use any insecticides at all, and whose fields are located in low-pesticide environments. Hence, we conclude that the bollworm complex is a real primary pest in Argentina – that is, one that causes significant crop damage also in the absence of system disruptions through chemical pesticides. Relatively high pest pressure and low amounts of insecticides used are also the reasons why yield effects of Bt cotton are bigger than in some other countries. In the USA and China, for instance, yield gains are smaller than 10 per cent on average (Carpenter *et al.*, 2002; Pray *et al.*, 2002; Huang *et al.*, 2002a).

Labor has a positive effect on cotton output. The impact of fertilizers is also positive, but not statistically significant. Only 13 per cent of all farmers used fertilizers on their cotton plots. Other chemicals basically comprise growth regulators and herbicides. Input interactions were excluded,

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[4] The same regression was also run with the 1999/2000 data and with pooled data for both seasons, using a season fixed effect. The results are similar to those shown, although slightly less efficient. Since the survey was carried out in 2001, farmers' responses are probably more accurate for the 2000/2001 season.

Table 3. *Estimated production functions*

	(1) *Quadratic specification, all observations* (*n* = *358*)		(2) *Quadratic specification, only large farm plots* (*n* = *185*)		(3) *Damage control specif., all observations* (*n* = *358*)	
	Coefficient	*t-statistic*	*Coefficient*	*t-statistic*	*Coefficient*	*t-statistic*
Constant	−9.65	−0.04	133.44	0.34	600.25	1.99
Bt (dummy)	506.29	6.66	482.28	5.08		
Insecticide (predicted)	216.79	3.46	213.70	2.49		
Square of insect. (pred.)	−33.01	−2.51	−36.50	−2.17		
Labor	5.88	2.36	11.07	2.14	4.82	1.96
Square of labor	−0.05	−2.40	−0.15	−1.97	−0.04	−1.52
Fertilizer	3.27	0.83	3.61	0.81	3.57	0.53
Square of fertilizer	−0.02	−0.51	−0.02	−0.48	−0.03	−0.37
Other chemicals	117.84	2.85	183.61	2.31	63.06	1.03
Square of other chemicals	−9.65	−1.58	−19.27	−1.97	−0.38	−0.04
Certified seeds (dummy)	162.70	2.83	30.73	0.32	293.47	3.65
Irrigated (dummy)	278.18	2.99	446.52	2.73	241.36	1.94
Climate (1–5 scale)	54.70	1.47	52.60	0.80	79.13	1.55
Good soil (dummy)	111.97	1.29	−41.61	−0.20	44.17	0.34
Farm size (owned land)	0.09	3.03	0.09	2.60	0.07	1.23
Education	23.41	2.61	21.82	1.86	33.41	2.56
Age	4.69	1.93	5.96	1.53	6.04	1.74
Damage control function						
μ					0.22	0.87
Insecticide (predicted)					0.50	3.98
Bt (dummy)					2.42	1.93
Adjusted R^2	0.54		0.39		0.51	

because the coefficients were individually and jointly insignificant.[5] Likewise, Bt interaction terms resulted in low t-statistics, suggesting that the technology has no systematic effect on the yield responsiveness of inputs. For insecticides, this is actually surprising. As Bt is a substitute in pest control, we would expect the technology to reduce the marginal productivity of insecticides. We will return to this issue in the next subsection, using a different model specification.

Use of certified seeds leads to an average yield gain of 163 kg. Usually, certified seeds have higher germination capacity and produce more vigorous plants, especially at the early growth stages. About 40 per cent of the interviewed farmers in 2000/2001 used seeds from their own reproduction or other uncertified sources. More favorable agroecological conditions, especially irrigation, are associated with higher yields, as is the farm size and the farmer's level of education. Interacting education with Bt did not produce a significant coefficient. Obviously, technological effects do not depend on human capital endowments. That age has a slightly positive effect in the production function might be attributable to the older farmers' longer experience with cotton cultivation.

Due to significant heterogeneity among cotton farmers, one might question the approach of pooling all observations in a single production function. Given different cultivation practices and intensities, it is possible that large farms do not have the same production function as their smaller counterparts. Inclusion of farm size as a fixed asset variable relaxes this assumption to some extent. Nonetheless, we re-estimated equation (3) by only using the large farm observations, in order to test for consistency with the full sample regression. The results are shown in the second column of table 3. Most of the input coefficients are quite similar to those in column (1). Yet, the goodness-of-fit is inferior to the full sample model. Obviously, large and small farms operate on different parts of the same or a similar production function, so that pooling all observations appears to be a valid approach.

3.2. Damage control framework

Including pest control agents such as insecticides and Bt into a standard production function implicitly assumes that their mode of action is the same as that of other inputs. However, while normal inputs such as fertilizer and labor tend to increase output directly, pest control agents rather reduce potential crop losses. This can lead to overestimation of the productivity of damage control agents in traditional specifications. Lichtenberg and Zilberman (1986) proposed a framework that takes better account of this phenomenon in empirical estimation. They propose using a separate damage control function, G, which is linked to the production function in a multiplicative fashion

$$Y = F(X)G(Z) \tag{4}$$

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[5] With input interaction terms included, the coefficient for Bt is 506.07, and also the other results are fairly robust.

where X denotes normal inputs and Z pest control agents. $G(Z)$ possesses the properties of a cumulative distribution function, with values defined in the (0, 1) interval. Thus, $F(X)$ is the potential maximum yield to be obtained with zero pest damage or maximum pest control. Lichtenberg and Zilberman (1986) showed analytically that using the damage control framework in econometric estimation produces more accurate results and is more appropriate for predictions.

This framework has been used by different authors to estimate pesticide productivity (e.g., Babcock *et al.*, 1992; Carrasco-Tauber and Moffit, 1992). Huang *et al.* (2002b) have used a damage control function for the first time in the context of host-plant resistance, for estimating the effectiveness of Bt cotton in China. The advantage is that, apart from the level of damage control, interactions between Bt and chemical insecticides can be modeled more appropriately than with a standard production function. For $F(\cdot)$ we use the same quadratic functional form as before, whereas for $G(\cdot)$ we use a logistic specification

$$G(Z) = [1 + \exp(\mu - \sigma_1 INS^{pred} - \sigma_2 Bt)]^{-1} \tag{5}$$

where μ has to be interpreted as a fixed damage effect. The logistic specification has been used in the pesticide literature, and it generally represents the pest abatement relationship quite well (Lichtenberg and Zilberman, 1986). An alternative exponential specification revealed that the results are fairly robust to the choice of functional form. Equation (4) was estimated using non-linear techniques. The results are shown in the third column of table 3.

The coefficients for the normal inputs and farm and household characteristics are mostly similar to those in the standard production function model (compare with column 1). The constant term is much larger, however. This should not come as a surprise because $F(X)$ is potential output without crop damage, which is higher than the actual yields obtained. Without any pest control inputs, crop damage would have been around 56 per cent. The coefficients in the damage control function demonstrate that both insecticides and Bt contribute significantly to crop protection. Yet, evaluated at sub-sample means, actual crop losses are still around 29 per cent on the conventional plots, while they are less than 5 per cent on the Bt plots. Even large farmers would have to increase their application rates in conventional cotton by 50 per cent, in order to achieve the same output per hectare as with Bt technology.

In order to determine economically optimal levels of pest control, we derive the value marginal product (*VMP*) of insecticides with and without Bt. *VMP* can be calculated by inserting equation (5) into equation (4), taking the partial derivative with respect to insecticides, and multiplying by the price of raw cotton (P^{cot}):

$$VMP(INS^{pred}) = P^{cot} F(X) \frac{\sigma_1 \exp(\mu - \sigma_1 INS^{pred} - \sigma_2 Bt)}{[1 + \exp(\mu - \sigma_1 INS^{pred} - \sigma_2 Bt)]^2} \tag{6}$$

Using the estimated parameters reveals that Bt notably reduces the marginal productivity of insecticides. At sample means, *VMP* is \$32 for conventional

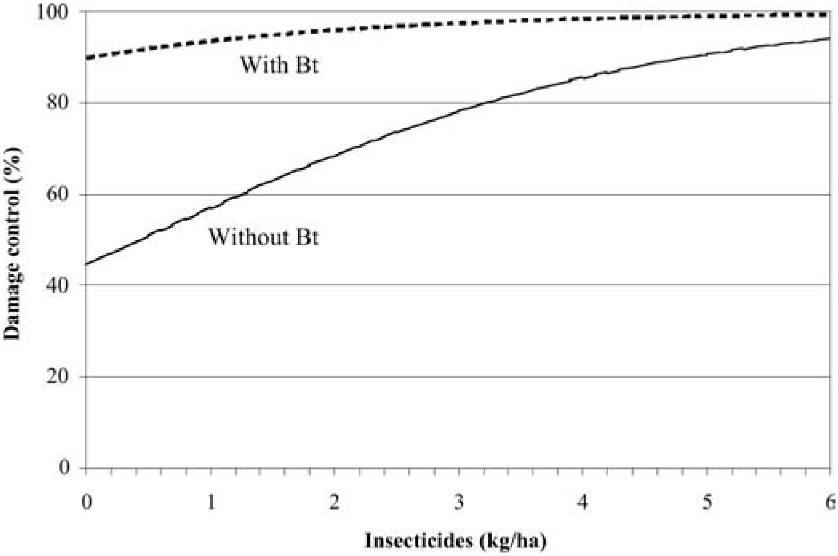

Figure 1. *Estimated relationship between insecticide use and damage control with and without Bt*

cotton, while it is only $6 on the Bt plots. Given that the average insecticide price is around $11 per kg, conventional farmers could improve their results by using more insecticides. Bt adopters, in turn, could further decrease their application rates. According to our model, profit-maximizing insecticide levels would be 5.5 kg and 1.0 kg per hectare for average conventional and Bt plots, respectively.

Figure 1 helps to establish the linkages between insecticide use, Bt, and yield levels. The curves shown are based on the econometric estimates of the damage control function. When insecticides are under-used in conventional cotton, adoption of Bt causes a significant yield effect, as actually observed in Argentina. Yet, the distance between the curves diminishes gradually with increasing pesticide use; this is why yield effects are smaller in the USA and China.[6] In these countries, yield losses in conventional cotton are low, so that Bt is mainly pesticide reducing at constant output levels. These relationships support Qaim and Zilberman's (2003) hypothesis that Bt yield effects will be higher in situations where crop damage is not effectively controlled through chemical pesticides. Similar results were also obtained by Thirtle *et al.* (2003) for South Africa and by Qaim (2003) for India.

Given that Bt technology in Argentina has so far been adopted only by some large-scale cotton farmers, it is instructive to use the damage control framework for predicting technology-related productivity effects for current non-adopters. Such predictions are shown in table 4, disaggregated by farm size. The insecticide reductions assume that farmers would adjust

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[6] Especially in China, pesticides are often heavily over-used (Huang *et al.*, 2002a; Huang *et al.*, 2002b).

Table 4. *Predicted mean insecticide use and yield effects of Bt cotton on conventional plots* [a]

	All conventional plots ($n = 288$)	*Conventional plots of large farms* ($n = 115$)	*Conventional plots of small farms* ($n = 173$)
Reduction in amount of insecticides (kg/ha)	1.7	2.3	1.2
Reduction in amount of insecticides (%)	73.0	71.9	75.4
Insecticide saving (US$/ha)	18.2	25.6	13.6
Yield gain (kg/ha)	381.4	271.6	447.7
Yield gain (%)	29.5	16.8	41.8
Yield gain (US$/ha)	70.0	49.8	82.2
Total gross benefit (US$/ha)	88.2	75.4	95.8

Notes: [a]Predictions are based on the damage control estimates, using mean values of explanatory variables for each sub-sample. It is assumed that adopting farmers would reduce their insecticide amounts from currently predicted levels (INS^{pred}) without Bt to economically optimal levels with Bt. Potential monetary gains are based on market prices in 2001.

their application rates from currently predicted levels to economically optimal levels with Bt technology (i.e., *VMP* equal to insecticide price). On average, pesticide amounts across farms could be reduced by 73 per cent, or 1.7 liters per hectare. Extrapolating this to Argentina's total cotton area in 2000/2001 would imply a reduction of around 700 thousand liters of pesticides. Absolute savings potentials are bigger for larger producers, because chemical application rates are positively correlated with farm size. Yet, relative pesticide reductions are similar across farm groups. At the same time, predicted yield gains due to Bt adoption are much more pronounced for smaller than for larger farms, both in absolute and relative terms.

This is a typical situation in many developing countries: owing to financial and human capital constraints, smallholder farmers invest less in chemical pest control, so that their crop damage is relatively high. Pest-resistant GM crops can be associated with significant yield effects and overall economic gains in such situations. While gross benefits of Bt technology in Argentina are predicted at $75 per hectare for large farms, they could be around $96 for small-scale cotton producers. These findings suggest that a wider dissemination of Bt cotton technology at reasonable seed prices could lead to considerable productivity gains and income increases in smallholder agriculture.[7]

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[7] As was stated before, a high technology fee charged by the monopoly seed supplier is currently the major adoption constraint. For details on intellectual property protection and corporate pricing strategies in Argentina, see Qaim and de Janvry (2003).

4. Resistance simulation

Just as susceptibility of insect populations to specific chemical pesticides decreases over time, insects can also develop resistance to the Bt toxin expressed by GM crops. This is a serious concern with respect to the technology's economic and ecological sustainability. If resistance were to build up in a short period of time, then the productivity gains and environmental benefits would only be of short duration. Instead, Bt technology would perpetuate the pesticide treadmill that GM crops actually promise to ease. Before the introduction of GM crops, Bt had been used for a long time as a biological insecticide without reports of substantial resistance. However, as a foliar application, Bt is degraded rapidly by ultraviolet light, a fact which lowers selection pressure in pest populations. This is different in GM crops, which express the toxin continuously (Tabashnik *et al.*, 2003).

To reduce selection pressure for Bt resistance, a refuge strategy is implemented for GM crops in the USA and a number of other countries, including Argentina. Farmers are required to plant a certain fraction of their cotton area with conventional varieties. On these non-Bt refuges, Bt-susceptible insects will remain unharmed, so they can mate with the resistant individuals that survive on the nearby Bt plot. This way, a rapid increase in the frequency of resistance might be avoided. Yet, relatively little is known about long-term effectiveness. Although there is some evidence that the strategy works, observation periods are still relatively short (Tabashnik *et al.*, 2003). Also, the effects will vary according to ecological and agronomic conditions. In this article, we are interested to assess possible resistance buildup in Argentina, in order to predict how far the benefits of Bt cotton technology may be sustained over time.

4.1. Physiologically based models

Physiologically based, age-structured models of the cotton system and interactions with pest and natural enemy populations have been developed and tested in different environments (e.g., Gutierrez *et al.*, 1975; Stone and Gutierrez, 1986). Recently, such models were extended to include the genetics of resistance to the Bt toxin for cotton bollworm (*Helicoverpa zea*), beet armyworm (*Spodoptera exigua*), and pink bollworm (*Pectinophora gossipiella*) (Gutierrez and Ponsard, 2002; Gutierrez *et al.*, 2002). We employ these models to simulate resistance development in Argentina over a 15-year period, using different assumptions about non-Bt refuges.[8]

While for algebraic details reference is made to the literature, the following paragraphs briefly outline some of the more general features of the models. The cotton system model simulates a cotton field under the assumption that all plants are growing identically. The pattern of development is in part determined by weather, initial planting density, varietal characteristics, and soil conditions. Expression of the Cry1Ac toxin

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[8] Although *H. zea*, which is the bollworm in North-American cotton systems, is slightly different from *H. gelotopoeon*, the South-American counterpart, both are closely related, and there are no significant differences in their ecologies (Matthews and Tunstall, 1994). Likewise, *Heliothis virescens* has a similar ecology, so we assume that the *H. zea* model is representative of the bollworm complex.

in Bt crops declines in aging plants and plant sub-units and varies according to geographic location.

Age-structured models are used to simulate the number and mass population dynamics of bollworm, beet armyworm, and pink bollworm. Resistance to the Bt toxin is assumed monogenic and recessive with Mendelian inheritance.[9] This assumption is common in the literature (Tabashnik *et al.*, 2003). Homozygous susceptible, homozygous resistant, and heterozygous populations are modeled separately throughout each season for the three insect species. Survival, developmental times, and fecundity of each population vary with time and age as well as the toxicity of the plant parts attacked (Ashfaq, 2000). Immigration of insects to the Bt cotton field occurs proportional to the size of the refuge area, whereby random mating is assumed following the Hardy–Weinberg approach (Gould, 1998). Successive seasons are linked through the surviving number of over-wintering larvae or pupae or, in the case of pink bollworm, individuals emerging from diapause. The frequency of the resistance gene is determined endogenously, depending on the initial level of resistance, selection pressure on the Bt plot, and dilution through immigration from refuge areas. These models are more sophisticated than previous tools to simulate resistance development (Gutierrez and Ponsard, 2002; Gutierrez *et al.*, 2002). Earlier models neglected sub-lethal effects of Bt on pest development and time-varying toxin levels in different parts of the cotton plant.

4.2. Simulation results

The models were calibrated using agroecological and entomological data from INTA's experiment station in Sáenz Peña, located within the major cotton-growing region of Chaco, Argentina. With a southern latitude of 26° 52′, Sáenz Peña belongs to the sub-tropics with an altitude of 90 meters above sea level. Meteorological data on a daily basis were available from 1996 to 2001. To obtain a 15-year series for our simulations, these data were extrapolated using a random procedure that allowed variations in an interval of plus and minus 10 per cent of the mean. The initial frequency of resistance in pest populations is not known for Argentina. Also for the USA, the literature does not provide uniform values. Recent studies show that the initial frequency is likely to be higher than the conventional expectation of 10^{-6} (Tabashnik *et al.*, 2000; Gould, 1998). As a conservative estimate, we assume an initial resistance level of 0.1 for the three pest species considered.

Figure 2 shows the simulated development of bollworm, beet armyworm, and pink bollworm populations on a Bt cotton plot, assuming a non-Bt refuge area of 20 per cent. This is the official refuge requirement in

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[9] A gene locus for a monogenic trait consists of two alleles. An allele is one of two alternate forms of a gene; a single allele for each locus is inherited from each parent. The alleles for the Bt resistance locus can be susceptible (S) or resistant (R). Hence, possible combinations are SS (homozygous susceptible), RR (homozygous resistant), and SR (heterozygous). That Bt resistance is recessive means that heterozygous insects are phenotypically susceptible; only the RR gene is actually encoding resistance.

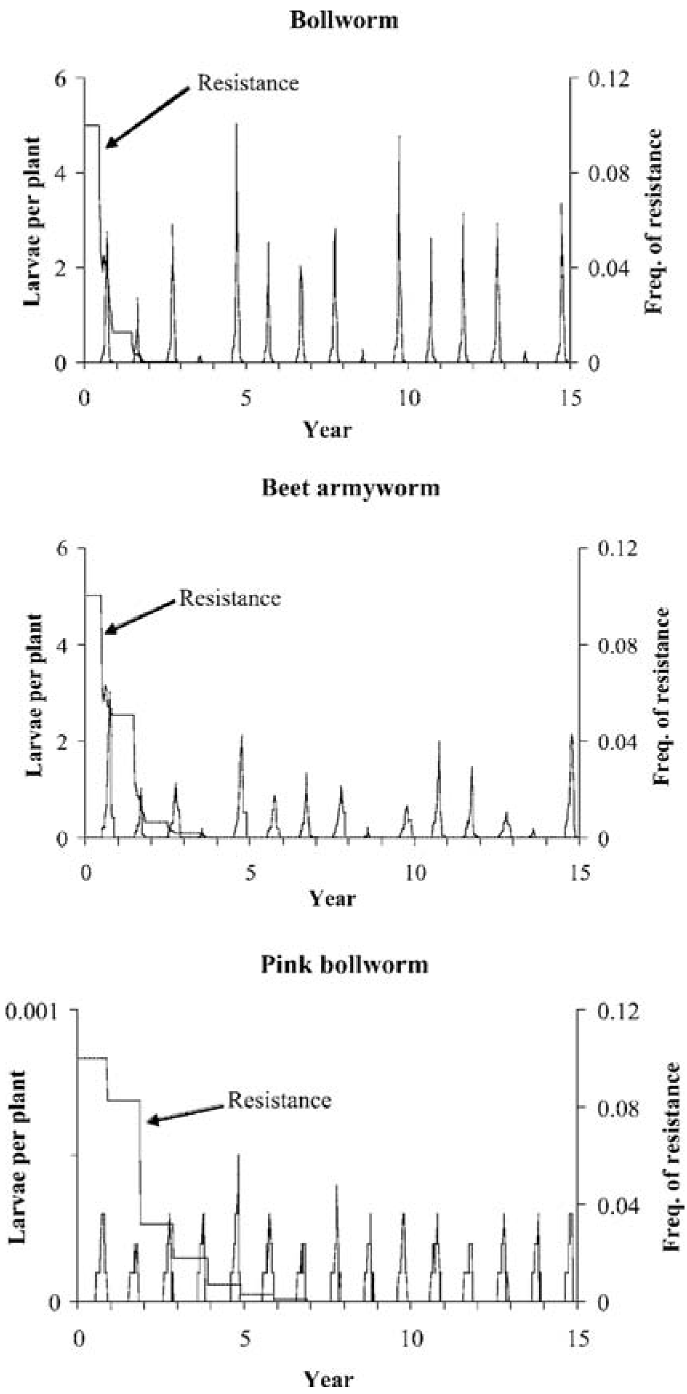


Figure 2. *Simulation of pest populations and development of Bt resistance with 20 per cent refuge area*

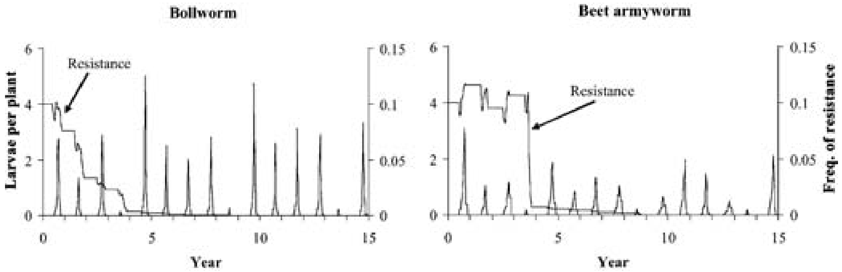
Argentina. The oscillating lines in each graph denote pest infestation, measured as the number of larvae per plant. Infestation peaks during the growing season and declines to zero during fallow periods, albeit larvae and pupae can over-winter in the soil and plant residues. Overall, infestation levels are relatively low. Differences between the species reflect the pests' relative importance under local conditions and their susceptibility to the Bt toxin. Bt mortality is higher in pink bollworm than in the other two species. Yet, additional model simulations revealed that pink bollworm pressure is low even without Bt, which is consistent with field observations. Under photoperiod and temperature conditions in Argentina, many pink bollworm larvae enter diapause during the cotton season, so that plant infestation levels usually remain below economic thresholds.

The marked lines in figure 2 indicate the simulated development of resistance. As can be seen, the frequency of the resistance gene declines to zero within a couple of years. Sufficient immigration of susceptible insects from the refuge areas leads to a dilution of the resistance trait. Therefore, a breakdown of Bt technology is very unlikely, if official refuge requirements are followed. The decline in resistance is somewhat slower in pink bollworm, which can once again be explained with the species' different susceptibility to Bt. The higher the degree of susceptibility, the bigger is the selection pressure for resistance.

An important question, however, is whether farmers will follow the 20 per cent refuge requirement. Furthermore, Argentine cotton farmers are permitted to use chemical pesticides on their refuges, a circumstance which is likely to decrease migration of susceptible insects to the Bt plots (cf. Hurley *et al.*, 2001). Against this background, additional simulations were run, testing the sensitivity of results with respect to changes in the size of spatial refuges. For an effective refuge area of 10 per cent, resistance development in bollworm and beet armyworm is similar to that in the 20 per cent scenario, that is, the frequency of resistance declines to zero within a short period of time. For pink bollworm, the resistance level increases gradually, yet staying below one within the 15 year horizon. Given the low importance of pink bollworm in Argentina, resistance buildup would have minor effects on pest infestation levels.

Simulation results with 5 per cent refuge and no spatial refuge assumptions are shown in figure 3 for bollworm and beet armyworm. In the 5 per cent scenario (panel a), resistance declines in both species but with more within-season variability than before. This variability is due to the declining concentration of the Bt toxin in aging plants, which can be interpreted as a temporal refuge towards the end of any particular season. The smaller the spatial refuge is, the bigger is the relative effect of this temporal refuge (Gutierrez *et al.*, 2002). In spite of its lower susceptibility to Bt, beet armyworm exhibits a slower decrease in resistance than bollworm. This phenomenon can be explained by the higher overall fecundity of armyworms. The no refuge area scenario (panel b) shows a relatively rapid resistance buildup for bollworm and beet armyworm. In both pests, the frequency of resistance increases to one within 6–7 years. This undermines the technology's effectiveness, as is reflected in higher numbers of larvae per plant.

(a) 5% refuge area



(b) No refuge area

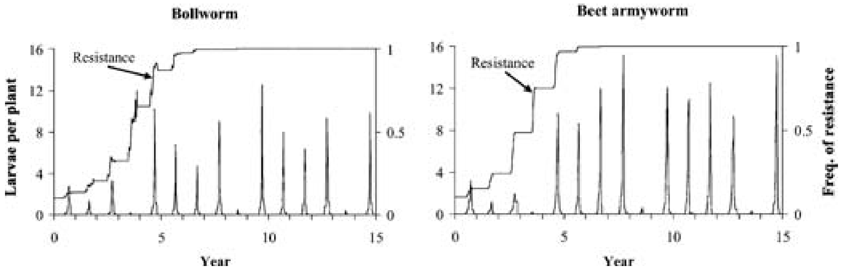


Figure 3. *Simulation of pest populations and development of Bt resistance with varying refuge areas*

The scenario comparisons demonstrate the importance of refuge areas to prevent buildup of resistance in pest populations. The findings are consistent with laboratory experiments and field observations from other countries (Tabashnik *et al.*, 2003). In Argentina, all survey respondents who had purchased Bt cotton seeds from the official supplier followed the refuge area requirements. Farmers have to sign respective purchase contracts, which are monitored by the seed-supplying company. However, some farmers who used Bt seeds from own reproduction or other unofficial sources did not fully comply with these regulations. Monitoring and enforcement can be difficult in developing countries, especially in the small farm sector. On the other hand, bollworm and beet armyworm also feed on a number of other plants, including corn, soybean, sorghum, and various vegetables, all of which are commonly grown in Argentina. Seventy-eight per cent of the interviewed cotton producers, including small and large farms, grew at least one of the other host plants on their land. Since bollworm and beet armyworm are migratory, these other species could provide additional non-Bt refuges. This was not explicitly accounted for in our simulations. Thus, even if farmers complied only partially with official refuge requirements, a rapid resistance buildup might not occur under current Argentine conditions. In the medium-run, pyramiding two or more dissimilar insecticidal genes in GM plants might further delay resistance development (Zhao *et al.*, 2003).

These are no arguments in favor of lax environmental regulations, however. Establishment of effective biosafety systems and proper enforcement are important for responsible biotechnology management, including in developing countries. In settings where pink bollworm has a higher economic significance, or where Bt cotton is grown as a monoculture, problems of resistance buildup are likely to be more severe. Also, it should be stressed that not all possible effects were considered in the simulations. For instance, the cotton leafworm, which is a Bt target pest in Argentina, could not be included because physiologically based models do not exist. Although adult leafworms are flyers and have a wide range of host plants, resistance buildup might possibly be different than in other lepidopteran species. There are also non-target pests with relevance in Argentina, for which no appropriate biological models exist, especially *Dysdercus* and *Jadera* plant bugs. A Bt-induced reduction in broad-spectrum insecticides could lead to increasing problems with secondary non-target pests over time. More research is needed, before conclusive statements about the technology's sustainability can be made.

5. Discussion and conclusion

In this article, we have empirically analyzed the effects of Bt cotton on pesticide use and productivity in Argentina. The farm survey reveals that the technology leads to a considerable decline in pesticide application rates. On average, adopting farmers use 50 per cent less insecticides on their Bt plots than on plots grown with conventional cotton. Almost all of these reductions occur in highly toxic chemicals, with concomitant positive effects for the environment. Moreover, Bt adopters benefit from significantly higher yields, which is due to insufficient pest control in conventional cotton. In an international comparison, Argentine farmers use relatively little amounts of pesticides, so the yield gains of Bt cotton are higher than in many other countries.

So far, only relatively few large-scale farmers have adopted Bt cotton in Argentina, which is due to a substantial technology fee charged for GM seeds. To obtain a broader picture of potential technological effects, we used econometric models to predict the impacts of Bt on different types of non-adopters. Our data set is suitable for such predictions, because it comprises a representative sample of farmers with a large degree of heterogeneity. As pesticide use is positively correlated with farm size, potential savings are bigger for large than for small farms. For cotton output, however, the opposite is true. Many smallholders do not use insecticides at all, so that they suffer significant pest-related yield losses. Potential yield effects of Bt are higher for this group of farmers. While the net yield gain is predicted at 17 per cent for average large-scale growers, for small producers the gain could be around 42 per cent. Also, total gross benefit per hectare of Bt cotton is predicted to be higher for smaller than for larger farms. Therefore, promoting wider technological diffusion at reasonable prices would not only extend the aggregate economic and environmental advantages, but could also entail desirable social effects. These findings should be of interest to other developing countries which are currently considering the commercial approval of pest-resistant GM crops.

The durability of benefits has been analyzed by simulating the development of resistance to the Bt toxin in different pest populations. For this purpose, physiologically based models of Bt cotton–pest interactions have been calibrated, using agroecological and entomological data from Argentina. Scenario results demonstrate that rapid resistance buildup and associated pest outbreaks are unlikely if minimum non-Bt refuge areas are preserved. Apart from conventional cotton, other host plants of Bt target pests are commonly grown in the local setting and might contribute to the dilution of resistance. These results suggest that the economic and ecological advantages of Bt cotton in Argentina could be maintained also in the medium to long run if current circumstances continue to prevail. Nonetheless, some caution is warranted with respect to far-reaching generalizations. More research is needed into the complex interactions with environmental systems and farmers' longer-term behavior in preserving refuges before conclusive statements about the technology's sustainability can be made.

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