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Agronomics and Sustainability of Transgenic Cotton in Argentina

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Transgenic Bt cotton can halve pesticide application rates in Argentina while significantly increasing yields. Yield effects are bigger than in other countries, due to the current low levels of insecticide use. Although smallholder farmers are not currently using the technology, gross benefits are predicted to be highest for them. Biological model simulations show that rapid resistance buildup in pest populations appears to be unlikely if minimum non-Bt refuge areas are maintained.

Key words: Bt cotton, damage control, pesticides, pest resistance, yield effect.

Introduction

Bt cotton was among the first transgenic crops to be used in commercial agriculture. A gene from the soil bacterium *Bacillus thuringiensis* (Bt) has been transferred to the cotton genome. This gene codes for production of a protein that is toxic to the cotton bollworm, a severe insect pest in most cotton-growing regions of the world. In the United States and China, Bt cotton was commercialized in the mid-1990s, and today, the technology covers around 30-40% of the cotton area in both countries. Recent studies demonstrate that US and Chinese Bt adopters realize significant pesticide and cost savings (Carpenter et al., 2002; Pray, Huang, Hu, & Rozelle, 2002). Benefits of Bt cotton have also been reported for South Africa (Shankar & Thirtle, 2003) and Mexico (Traxler, Godoy-Avila, Falck-Zepeda, & Espinoza-Arellan, 2001). Nonetheless, there is still uncertainty related to the technology's impacts and sustainability under different agroecological and socioeconomic conditions.

This article analyzes the implications of Bt cotton in Argentina, where the technology was commercialized by Monsanto in 1998. Unlike other Bt-growing countries, where cotton is a heavily subsidized crop, Argentina is producing under free-trade conditions, with comparatively low input intensities and production costs. This might influence the technology's agronomic outcome. Apart from a comparative analysis of pesticide use and yields with and without Bt, productivity effects are modeled econometrically using a damage control specification. This analysis is based on a comprehensive survey of Argentine cotton farmers in 2001 done jointly with Argentina's National Institute for Farming and Livestock Technology (INTA).

Although short-run gains of the technology are increasingly recognized (Qaim & Zilberman, 2003), long-run effects associated with pest resistance remain in doubt. We address this issue by using biological models to simulate possible resistance development in bollworm populations. Although resistance buildup has not been observed in the field so far, biochemical studies indicate a high risk of rapid insect adaptation to the Bt toxin (Gould, 1998). Resistance development is one of the main concerns of environmentalists with respect to Bt crops. It would not only challenge the technology's sustainability, but would also imply loss of Bt as an ecologically friendly microbial insecticide that is widely used in organic agriculture.

Data Basis

An interview-based survey of 299 cotton farms was carried out in 2001. The survey covered Argentina's two major cotton-growing provinces, Chaco and Santiago del Estero, which together account for almost 90% of total cotton area. Because the number of Bt adopters is still comparatively small, a stratified random sampling procedure was employed, differentiating between adopters and nonadopters. Adopters were defined as those farmers who had used Bt technology at least once during the previous two cropping seasons. The total sample consists of 89 adopters and 210 nonadopters; the subsample of nonadopters is representative of the Argentine cotton sector as a whole (Secretary of Agriculture, Livestock, Fisheries and Food [SAGPyA], 2000).

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. Because all Bt adopters had also cultivated at least some conventional cotton, they were asked the same questions for both their Bt and conventional plots. This allows with- and without-technology comparisons not only across but also within farms.

Table 1. Insecticide use and yields on Bt and conventional cotton plots.

	1999/2000		2000/01	
	Bt (*n* = 29)	Conventional (*n* = 29)	Bt (*n* = 73)	Conventional (*n* = 73)
	Mean (standard deviation)			
Number of sprays	2.14* (1.13)	4.52 (1.24)	2.84* (1.19)	5.07 (1.91)
Amount of insecticide (kg/ha)	1.85* (1.11)	4.15 (1.61)	2.30* (0.78)	4.03 (1.86)
of which in:				
Toxicity class I	1.52* (1.15)	2.87 (1.33)	1.77* (1.12)	2.57 (1.62)
Toxicity class II	0.27* (0.42)	1.20 (0.92)	0.48* (0.72)	1.34 (1.04)
Toxicity class III & IV	0.05 (0.10)	0.08 (0.14)	0.05* (0.10)	0.12 (0.19)
Amount of active ingredients (kg/ha)	0.64* (0.35)	1.90 (0.87)	0.78* (0.45)	1.80 (0.94)
Seed cotton yield (kg/ha)	2,032* (580)	1,537 (364)	2,125* (566)	1,606 (459)

** Mean value on Bt plots is different from that on conventional plots at 5% significance level.*

Effects on Pesticide Use

Bt cotton provides resistance to the cotton bollworm (*Helicoverpa gelotopoeon* and *H. zea*, usually occurring together with *Heliothis virescens*), which is a primary pest complex 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.). Cotton pests in Argentina to which the technology does not provide resistance include tropical plant bugs and various sucking pests. Patterns of insecticide use with and without Bt are shown in Table 1 for the 1999/2000 and 2000/01 cropping seasons. To reduce the effect of non-technology-related factors, this comparison is confined to the subsample of Bt adopters who also cultivate conventional cotton—that is, Bt and conventional plots are compared on the same farms.

In both growing seasons, Bt cotton was sprayed about half as often as conventional cotton, while insecticide amounts were reduced by 55% and 43% in 1999/2000 and 2000/01, respectively. These effects become even more pronounced if commercial product concentrations are converted into amounts of active ingredients. Most of the reductions occur in hazardous chemicals, such as organophosphates, carbamates, and synthetic pyrethroids, which mainly belong to international toxicity classes I and II. These broad-spectrum pesticides are highly disruptive to most beneficial insects and cause significant residue problems. Bt technology can therefore be associated with major environmental and health benefits. It should be noted, though, that even in conventional cotton, pesticide use in Argentina is relatively low in an international comparison. This is partly related to the fact that unlike cotton producers in most other countries, Argentine farmers do not receive any input or output subsidies. Against the background of low cotton prices on the world market, they have to keep production costs low. Hence, although relative pesticide savings through Bt are similar to those in other countries, they are much lower in absolute terms.

In order to estimate the technology's net effect on pesticide use, insecticide amounts per hectare were regressed on different explanatory variables, including Bt as a dummy. The estimation results for both growing seasons are shown in Table 2. The Bt coefficients confirm that the technology decreases insecticide use significantly. In both seasons, the net effect is a saving of about 1.2 kg/ha. Higher insecticide prices also have a reducing effect. Perceived pest pressure ex ante to insecticide sprays was elicited from farmers for both growing seasons separately on a scale from 1-10. Unsurprisingly, bollworm pressure has a positive impact on insecticide use, whereas the coefficients for sucking pests are not statistically significant. More favorable climatic, soil, and water conditions entail higher pesticide use because of higher yield expectations. Likewise, education has a positive effect on application rates. Especially in the small farm sector, many farmers are not well aware of pest-related crop losses and how to avoid them. This also contributes to relatively low average pesticide application rates.

Yield Effects

Apart from pesticide reductions, Table 1 showed that Bt technology in Argentina is also associated with significant yield gains. This is different from the experience in most other countries. In the United States and China especially, average yield effects are below 10% (Carpenter et al., 2002; Pray et al., 2002), whereas in Argentina they have been 32% in two consecutive growing

Table 2. Estimated insecticide use functions.

	1999/2000 (n = 294)		2000/01 (n = 358)	
	Coefficient	t-statistic	Coefficient	t-statistic
Constant	-1.580	-2.29	-0.852	-1.34
Bt (dummy)	-1.227	-3.07	-1.171	-5.85
Insecticide price ($/kg of active ingredients)	-2.4×10^{-4}	-3.10	-0.005	-4.21
Bollworm pressure (1-10 scale)	0.199	5.53	0.200	6.33
Sucking pest pressure (1-10 scale)	0.083	1.31	-0.049	-0.88
Irrigated (dummy)	-0.058	-0.14	1.161	3.86
Climate (1-5 scale)	0.390	2.80	0.304	2.49
Good soil quality (dummy)	0.548	2.11	0.977	4.08
Farm size (owned land in ha)	4.0×10^{-4}	3.89	3.7×10^{-4}	3.96
Education (years in school)	0.163	6.00	0.098	4.07
Adjusted R^2	0.412		0.434	

seasons. Bt is a pest-control agent; therefore, rather than affecting the yield potential of a plant, Bt can help reduce pest-related crop losses. This can be modeled in a damage control framework, as suggested by Lichtenberg and Zilberman (1986):

$$Y = F(X) \bullet G(Z), \quad (1)$$

where Y is crop output, and X is a vector of normal inputs (such as labor and fertilizer). Because these inputs influence potential yield, they are included in the normal production function, $F(X)$. Z, in contrast, denotes pest control agents (such as Bt and chemical insecticides), which are part of the damage control function, $G(Z)$. G possesses the properties of a cumulative distribution function with values between zero and one. Thus, $F(X)$ is the potential maximum yield to be obtained with zero pest damage or maximum pest control. Although different authors used this framework to estimate pesticide productivity, Huang, Hu, Rozelle, Qiao, and Pray (2002) have used it for the first time in the context of Bt technology. For our estimates, a quadratic functional form was used for F, whereas G was specified as a logistic curve. To avoid problems of endogeneity, predicted insecticide amounts were used instead of actual amounts. For specification tests and other details, reference is made to Qaim and de Janvry (2003a). The estimation results are shown in Table 3 for the 2000/01 growing season.

Labor has a positive effect on cotton output, which is somewhat reduced on highly mechanized farms. The impact of fertilizers is also positive, but not statistically significant. Only 13% of all farmers used fertilizers on their cotton plots. Unsurprisingly, use of certified seeds, irrigation, and more education also lead to higher output. Evaluated at sample means, the model predicts a potential cotton yield (i.e., zero pest damage) of 1,940 kg/ha. Average crop losses are estimated at 26%. The coefficients for insecticides and Bt in the damage control function demonstrate that both agents contribute significantly to crop protection.

Table 3. Estimated production function with damage control specification (2000/01).

	Coefficient	t-statistic
Constant	572.64	1.96
Labor (hours/ha)	9.51	2.13
Square of labor	-0.08	-2.37
Labor-machinery interaction	-3.33	-1.93
Fertilizer (kg/ha)	4.30	0.66
Square of fertilizer	-0.03	-0.48
Certified seeds (dummy)	285.59	3.66
Irrigated (dummy)	296.06	1.94
Climate (1-5 scale)	73.03	1.46
Good soil quality (dummy)	16.05	0.12
Farm size (owned land in ha)	0.07	1.23
Education (years in school)	33.23	2.62
Age (years)	6.68	1.96
Logistic damage control function		
Fixed damage effect	0.29	1.21
Insecticide, predicted (kg/ha)	0.57	4.59
Bt (dummy)	2.69	1.87
Adjusted R^2	0.51	

Based on the estimation results, Figure 1 shows percentage damage control with and without Bt, depending on the insecticide amounts used. At lower insecticide levels, effective yields are much higher with the technology. With zero pesticides (which is not uncommon,

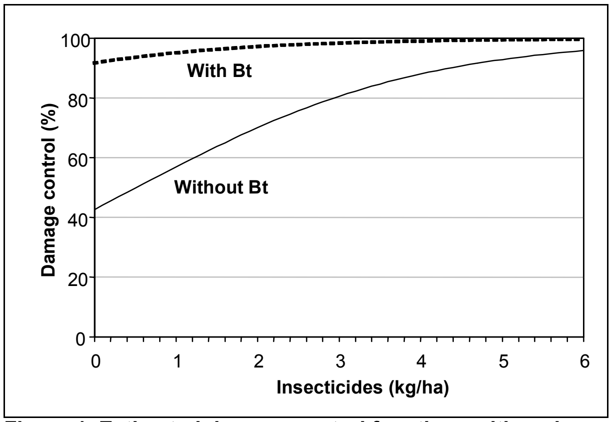

Figure 1. Estimated damage control functions with and without Bt.

especially among smallholder farmers), only about 45% of the yield potential is achieved in conventional cotton, whereas Bt could protect pest damage at a level of 90%. This difference diminishes gradually with increasing insecticide use, which is also the main reason why yield effects of Bt cotton are smaller in the United States and China. This analysis supports Qaim and Zilberman's (2003) hypothesis that yield effects will be higher in situations where crop damage is not effectively controlled by chemical pesticides. Similar results were also obtained by Shankar and Thirtle (2003) in South Africa.

Predicted Effects for Nonadopters

So far, Bt technology in Argentina has been adopted only by a small number of large-scale cotton farmers. Following national statistics (SAGPyA, 2000), farmers can be classified into two groups. The first comprises small-scale producers who own less than 90 ha of agricultural land. These are mostly resource-poor peasant farmers, who cultivate cotton with low input intensities and a low to medium degree of mechanization. The second group comprises large-scale producers with more than 90 ha of agricultural land, who are comparatively better off. With an average farm size of 730 ha, 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 ha.

To obtain a broader picture of the technology's agronomic potentials in these heterogeneous farming systems, the damage control framework was used to make predictions for current nonadopters. The results, disaggregated by farm size, are shown in Table 4. Insecticide reductions assume that farmers would adjust their application rates from currently observed levels to economically optimal levels with Bt technology (i.e., value marginal product equal to insecticide price). On average, pesticide amounts across farms could be reduced by 82%, or 1.9 l/ha. Although in relative terms insecticide reductions are similar across farm groups, in absolute terms they are bigger for the large-scale growers. Because chemical application rates are positively correlated with farm size, there is more to save on the bigger farms. It should not be surprising, however, that for the yield effect the opposite holds true: predicted yield gains are much more pronounced for smaller than for larger farms, both in absolute and relative terms.

Table 4. Predicted insecticide use and yield effects of Bt cotton on conventional plots.

	All conventional plots (n = 288)	Only large farms (n = 115)	Only small farms (n = 173)
Insecticide reduction (kg/ha)	1.9	2.6	1.4
Insecticide reduction (%)	81.7	79.6	83.1
Insecticide saving (US$/ha)	20.4	28.3	15.2
Yield gain (kg/ha)	386.8	294.6	446.8
Yield gain (%)	30.3	18.7	41.4
Yield gain (US$/ha)	71.0	54.1	82.0
Total gross benefit (US$/ha)	91.3	82.4	97.2

This is a typical situation in many developing countries—owing to financial and human capital constraints, smallholders invest less in chemical pest control, so their crop damage is relatively high. Therefore, pest-resistant transgenic crops can be associated with significant yield effects and overall economic gains in such situations. Although gross benefit of Bt technology in Argentina is predicted at $82/ha for large farms, it could be around $97/ha for small-scale cotton producers. However, Bt technology is patented in Argentina, which provides monopoly power to Monsanto. A technology premium of US$78/ha is charged, so farmers are understandably hesitant to adopt. Qaim and de Janvry (2003b) show that high seed price is the main constraint for wider technology adoption in Argentina. This is unfortunate, because at reasonable prices Bt cotton could lead to considerable productivity gains and income increases, especially among the smallholders.

Resistance Simulations

Just as susceptibility of insect populations to specific chemical pesticides decreases over time, populations

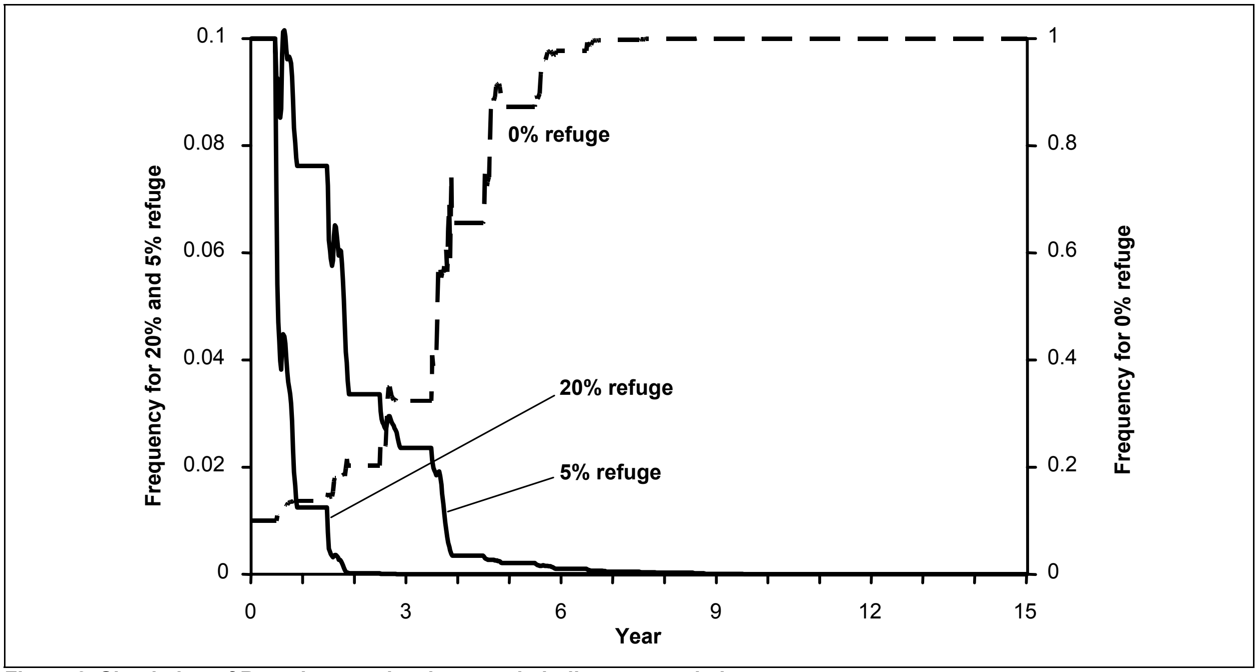

Figure 2. Simulation of Bt resistance development in bollworm population.

can also develop resistance to the Bt toxin expressed by transgenic crops. This is a serious concern with respect to the technology's economic and ecological sustainability. Before the introduction of transgenic crops, Bt had been used for a long time as a biological insecticide without reports of substantial resistance. However, the situation might be different for transgenic Bt crops, which express the toxin continuously (Gould, 1998). To reduce selection pressure for resistance, a spatial refuge strategy is implemented for Bt crops in the United States and a number of other countries, including Argentina. That this strategy can work has been shown for pink bollworm in Arizona (Carrière et al., 2003). However, effects will vary according to pest species as well as ecological and agronomic conditions in any given setting.

To simulate possible resistance buildup in target pests under Argentine conditions, physiologically based age-structured models of the cotton system were used. Developed by Gutierrez, Ponsard, and Adamczyk (2002), these models explicitly consider the interactions between plants, pests, and natural enemies on Bt fields and insect immigration from non-Bt refuge areas. Furthermore, they account for declining toxin expression in aging plants and sublethal effects in insect populations. As Bt target species, cotton bollworm, beet armyworm, and pink bollworm were included. The models were calibrated using agroecological and entomological data from Argentina (see Qaim and de Janvry, 2003a, for more details). Simulations were run for a period of 15 years. Because the initial frequency of the resistance allele in pest populations is not known, a starting value of 0.1 is used as a cautious assumption.

The results are shown in Figure 2 for cotton bollworm. The outcome is very similar for beet armyworm, whereas pink bollworm is only of minor importance in Argentina. Initially, a 20% refuge area was assumed, which is the official requirement in the country. Under this assumption, the frequency of the resistance allele declines rapidly, already reaching zero in the second year after adoption. Sufficient immigration from the refuge plots of susceptible insects, which can mate with surviving individuals on the Bt plots, leads to dilution of the resistance trait. This suggests that a breakdown of Bt technology could be prevented if farmers would comply with official refuge requirements. Full compliance is unlikely, however. Due to the high technology price, farmers have an incentive to use farm-saved seeds or to acquire seeds from unofficial sources. In such cases, effective monitoring is extremely difficult. Also, cotton farmers in Argentina are permitted to use chemical pesticides on their refuge areas—a practice which is likely to decrease migration of susceptible insects to the nearby Bt plots (cf. Hurley, Babcock, & Hellmich, 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% (not shown), resistance development is similar to the 20% scenario. Even with a 5% refuge assumption, resistance drops to zero within nine years. With zero refuge area, however, rapid resistance buildup would occur, reaching a frequency of one within 6-7 years (Figure 2). These findings emphasize that refuge areas are crucial for preventing resistance development in pest populations. However, Bt adoption rates are still low in Argentina. Thus, even if adopting farmers complied only partially with official refuge requirements, a rapid resistance buildup and associated pest outbreaks are unlikely. Furthermore, bollworm also attacks a number of other plants besides cotton, including corn, soybean, and sorghum. These other host plants are commonly grown in Argentina and could provide additional non-Bt refuges.

These findings suggest that the agronomic and ecological benefits of Bt cotton in Argentina can be maintained over the long run, even if technology adoption rates should increase in the future. Some caution is warranted with far-reaching conclusions, though, because the simulations are not able to capture all possible effects in cotton ecosystems. Cotton leafworm and tropical plant bugs, for instance, could not be considered, because physiologically based models do not exist for those species. Furthermore, a Bt-induced reduction in broad-spectrum insecticides could lead to increasing problems with secondary nontarget pests over time. More research is needed, before conclusive statements about the technology's sustainability can be made.

Conclusion

The agronomic effects of Bt cotton in Argentina have been analyzed empirically. On average, adopting farmers use 50% less insecticides on their Bt plots than they use on plots grown with conventional cotton. Almost all of these reductions occur in highly toxic chemicals, with concomitant positive effects for the environment and farmers' health. These results are largely consistent with earlier studies in other countries. But in addition to pesticide reductions, Bt cotton adopters in Argentina also achieve significantly higher yields. This has not been shown in many other countries. Due to nonexistent subsidies and human capital constraints, average pesticide application rates in Argentina are low by international standards. Accordingly, pest-related crop losses are substantial. Econometric estimates demonstrate that application rates in conventional cotton would need to be doubled in order to achieve the same output per hectare as with Bt technology. These findings emphasize that technological impacts critically depend on the underlying conditions. In general, yield effects will be higher in situations where pest pressure is severe and crop damage is not effectively controlled by chemical pesticides or other alternatives.

So far, only relatively few large-scale farmers have adopted Bt cotton in Argentina; this low adoption rate is due to a substantial price premium charged for transgenic seeds. To obtain a broader picture of technology potentials in the heterogeneous farming systems, predictions of likely impacts were made for current nonadopters. Because pesticide use is positively correlated with farm size, potential savings in chemicals are bigger for larger farms. For the yield effect, however, the opposite holds true. Many smallholders do not use insecticides at all, so they currently suffer significant crop losses. Whereas the net yield gain is predicted at 19% for average large-scale growers, for small producers the gain could be around 41%. Similarly, 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 agronomic and environmental benefits but could also entail progressive social effects.

The sustainability of the technology has been analyzed by simulating resistance development in pest populations. Scenario results demonstrate that rapid resistance buildup and associated pest outbreaks appear to be 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 contribute to the dilution of resistance. This suggests that the technological advantages can be maintained in the long run. Nonetheless, some caution is warranted with respect to far-reaching generalizations. More research is needed into the technology's complex interactions with environmental systems before conclusive statements about its sustainability can be made.

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Authors' Note

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