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Adoption of Bt Cotton and Impact Variability: Insights from India

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There is a growing body of literature about the impacts of *Bacillus thuringiensis* (Bt) cotton in developing countries. While many studies show remarkable benefits for farmers, there are also reports that question these results. Most previous studies consider impacts in deterministic terms, neglecting existing variability. Here we explain the main factors influencing the agronomic and economic outcomes. Apart from differences in pest pressure and patterns of pesticide use, germplasm effects can play an important role. Theoretical arguments are supported by empirical evidence from India. Better understanding of impact variability can help explain some of the paradoxes in the recent controversy over genetically modified crops.

Bacillus thuringiensis (Bt) cotton, which provides resistance to several bollworm species, has been commercialized in a number of countries, including the United States, Australia, China, Mexico, Argentina, South Africa, and India. Over the last few years, the technology spread rapidly among large and small farms (Food and Agriculture Organization). Several studies carried out in different developing countries show that farmers who have adopted Bt cotton experience remarkable pesticide savings and higher effective yields (Pray et al.; Morse, Bennett, and Ismael; Bennett et al. 2004b; Thirtle et al.; Traxler et al.; Qaim and de Janvry; Qaim and Matuschke). Yet there are also reports claiming genetically modified (GM) crops in general and Bt cotton in particular, are unsuitable for developing

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countries, causing negative impacts in the small farm sector (Shiva and Jafri; Genetic Resources Action International Network). Recent disputes center especially around the experience in India—the third largest cotton-producing country in the world—where the crop is mostly cultivated by smallholder farmers.

In India, Bt cotton was the first GM crop technology to enter the market. Three Bt cotton hybrids were approved in early 2002. These were MECH 12, MECH 162, and MECH 184 developed by the Maharashtra Hybrid Seed Company (Mahyco). Mahyco had backcrossed the Cry1Ac Bt gene into its breeding lines under a licensing agreement with Monsanto. In the first year of commercial adoption in India, GM hybrids were grown on about 90,000 acres, and on almost 250,000 acres in 2003/4. In 2004, a fourth Bt cotton hybrid, developed by Rasi Seeds, was commercially approved, and the official Bt area increased to an estimated 1.3 million acres, equivalent to about 7% of the total national cotton area (Mayee). In addition, there is a sizeable black market for unapproved Bt cotton seeds (Pray, Bengali, and Ramaswami).

Farmers' revealed preferences suggest that Bt cotton is associated with advantages for the majority of adopters. This substantiates analyses of field trial data collected prior to commercial technology approval (Naik; Qaim; Qaim and Zilberman). Sizeable farm-level economic gains were also reported in a survey commissioned by Mahyco and Monsanto (AC Nielsen), and in an independent evaluation of a large dataset collected by Mahyco in the state of Maharashtra over two years (Bennett et al. 2004a). Nonetheless, biotechnology critics carried out their own studies and found that the cotton farmers they had surveyed were not satisfied with their Bt experience (Sahai and Rahman; Qayum and Sakkhari). Clearly, there is a need to better understand under what conditions farmers can benefit from Bt technology.

In this article, we explain the main factors influencing the agronomic and economic effects of the technology. In a brief theoretical section, we argue that the outcome depends on the agroecological and socioeconomic conditions under which farmers operate. Since these are heterogeneous, variability in impacts has to be expected. Previous studies have not sufficiently accounted for such variability and its determinants. In the empirical part of our analysis, evidence from India supports the argumentation. We use detailed farm survey data collected in four states during the first season of official Bt cotton adoption, in order to demonstrate that the positive aggregate results mask significant regional differences. The last section of the article concludes and discusses policy implications.

Conceptual Framework

For an individual farmer, the change in profit, $\Delta\pi$, resulting from Bt cotton adoption can be decomposed as:

$$\Delta\pi = \underbrace{(p \cdot \Delta y)}_{\text{yield effect}} + \underbrace{(q \cdot \Delta x)}_{\text{pesticide effect}} - \Delta s \qquad (1)$$

where $\Delta y = y_{\mathrm{Bt}} - y_{\mathrm{conv}}$ is the difference in effective yields between Bt and conventional cotton; $\Delta x = x_{\mathrm{conv}} - x_{\mathrm{Bt}}$ is the amount of pesticide saved due to the technology; p is the cotton output price net of harvesting costs; q is the pesticide input price, including spraying costs; and $\Delta s = s_{\text{Bt}} - s_{\text{conv}}$ is the difference in seed costs between Bt and conventional cotton. The size of the Bt yield and pesticide effects depends on pest pressure and crop management techniques. Farmers who use small amounts of pesticides in conventional cotton in spite of high pest pressure, will realize a sizeable yield effect since Bt reduces previously uncontrolled crop damage (Qaim and Zilberman). Conversely, the pesticide effect will dominate in situations where farmers use higher amounts of chemical inputs. The actual size of Δx also depends on farmers' correct understanding of the substitution effect between Bt and pesticides, and therefore their ability to optimally adjust pesticide use to the new technology.[1]

The yield effect of a particular Bt cotton variety can be further decomposed as:

$$\Delta y = \underbrace{\Delta d}_{\text{Bt gene effect}} + \underbrace{\Delta v}_{\text{germplasm effect}} \tag{2}$$

where $\Delta d = d_{\text{conv}} - d_{\text{Bt}}$ is the reduction in pest damage caused by Bt technology, and $\Delta v = v_{\text{Bt}} - v_{\text{conv}}$ is the difference in yield potential between the variety that carries the Bt gene and the conventional variety grown by farmers in a particular location. In principle, Bt can be incorporated into any variety. Hence, Δv could be zero if isogenic lines with and without Bt are compared, or it could be positive if Bt is incorporated into superior germplasm. However, $\Delta v < 0$ if the Bt variety is not well adapted to local conditions, so that the Bt gene effect will be counteracted by a negative germplasm effect. Although it always holds that $\Delta d \geq 0$, suboptimal germplasm can even result in a negative aggregate yield effect, especially in situations where pest pressure is low or pesticide use is high.

Assuming constant input and output prices, the impact of adopting a new Bt cotton variety depends on (*a*) pest pressure, (*b*) pesticide amounts used in conventional cotton, (*c*) the farmer's capacity to adjust pesticide use, and (*d*) the suitability of the germplasm to local conditions. Since these factors differ from farmer to farmer and are partly associated with randomness, variability in impacts has to be expected.

Data

In order to analyze Bt cotton impacts empirically, we carried out an independent survey of adopters and nonadopters in India. Due to the large size of the country and the high degree of heterogeneity in cotton growing conditions, India is a particularly interesting example to analyze variability. In 2003, 341 cotton farmers were interviewed in four states: Maharashtra, Karnataka, Andhra Pradesh, and Tamil Nadu, which together account for more than 60% of cotton production in central and southern India.[2] Data were collected on farm and household characteristics, as well as on details of cotton production in the 2002/3 growing season. Within each state, a multistage random sampling procedure was used, resulting in a sample of farmers from ten different districts and fifty-eight villages. Bt adopters were deliberately oversampled by randomly selecting from the complete lists of technology users at the village level. This was important to have sufficient Bt observations for robust impact assessment in the first season

Table 1. Agronomic and economic effects of Bt cotton (plot observations in 2002/3)

	Bt Cotton ($n = 133$)		Conventional Cotton ($n = 301$)	
	Mean	SD	Mean	SD
Number of insecticide sprays	4.18***	3.28	6.79	3.64
Insecticide use (kg/acre)	2.07***	2.65	4.17	3.37
Yield of raw cotton (kg/acre)	659***	394	491	336
Output price (Rs./kg)	20.65	1.96	20.93	2.26
	Crop Enterprise Budgets (Rs./acre)			
Seed cost	1,573***	196	490	286
Insecticide cost	1,258***	1,469	2,128	1,748
Fertilizer cost	1,883*	1,199	1,658	1,073
Manure cost	722*	834	590	729
Labor and custom operations cost	1,721***	1,310	1,406	1,080
Harvesting cost	1,198***	1,339	847	822
Other cost	85	179	104	218
Total variable cost	8,441***	3,452	7,224	3,337
Revenue	13,735***	8,425	10,357	7,290
Net revenue	5,294***	8,117	3,133	6,774

*,**,*** Significantly different from conventional cotton at the 10%, 5%, and 1% level, respectively.
Rs. = Rupees.

of commercial adoption. Farmers in the sample are predominantly resource-poor smallholders. The average cotton area is 4.5 acres for nonadopters and 4.9 acres for adopters. Most Bt adopters in the sample also grew some conventional cotton. In these cases, input–output details were collected for both alternatives, so the number of plot observations is bigger than the number of farmers surveyed. Including conventional plot observations of Bt adopters helps reduce a possible nonrandom selection bias in impact analyses.

Empirical Results

Average Impacts

Table 1 shows average impacts of the technology across all four states. They suggest:

- *Less spraying.* In 2002/3, Bt cotton was sprayed 2.6 times less often against insect pests than conventional cotton. Spraying was not abandoned completely, because the toxin encoded by the Bt gene does not provide resistance to sucking pests, and its protection against certain bollworm species is also less than 100%.[3] Insecticide amounts on Bt plots were reduced by 50%.
- *Higher cost.* As expected, fewer sprays entail lower insecticide expenditures. Yet these savings did not fully compensate for the higher seed costs: official Bt seeds are more than triple the price of conventional hybrids. Technology adopters also

spent slightly more on other variable inputs and crop maintenance. Although Bt does not alter input requirements other than pesticides, it is a common phenomenon that farmers dedicate extra care to their crop when having invested in relatively expensive seeds. Total production costs per acre were higher with Bt than without.

- *Higher yields.* Bt cotton adopters experienced higher yields, with a mean difference of 34%.[4] Although this yield difference is bigger than in most other countries, it was smaller than observed in the previous year during multilocation field trials (Qaim). Seasonal differences are mainly due to fluctuations in pest infestation. While bollworm pressure in India was high in 2001/2, it was below average in 2002/3 (Indian Council of Agricultural Research).
- *Higher profits.* Higher average yields and associated revenue gains overcompensate the cost increases, so the impact on farmers' income was positive. On average, per acre net revenues for Bt cotton were 2,161 rupees (Rs.) (equivalent to US $45) higher than for conventional cotton.

Variations in input levels, irrigation intensities, and other farm and farmer characteristics can also lead to productivity differences, which are unrelated to Bt technology. To control for such factors, we estimated a production function where a Bt dummy is included as an explanatory variable. We chose the flexible translog model, which showed a somewhat better fit to the microlevel data than the more restrictive Cobb–Douglas specification. In addition to Bt and agricultural inputs in cotton production, we included state dummies and different farm and household characteristics that might influence the output. Table 2 shows the estimation results (model 1). Not surprisingly, all the inputs have a positive effect on cotton yield. Furthermore, the harvesting date and regional factors matter. The Bt coefficient confirms that the technology's yield effect is positive and significant. Across the four states, the net yield effect derived from this model is 27%.[5]

Impact Variability

The average impacts of Bt cotton technology across states mask the high degree of heterogeneity among farmers. India is a huge country, with cotton growers facing diverse agroecological and socioeconomic conditions. Table 3 shows differential technology impacts by state. While Bt adopters in Maharashtra, Karnataka, and Tamil Nadu realized significant net benefits in 2002/3, their colleagues in Andhra Pradesh suffered a loss in average incomes. Strikingly, most of the studies carried out by biotechnology critics placed heavy emphasis on observations from Andhra Pradesh (Shiva and Jafri; Sahai and Rahman; Qayum and Sakkhari).

Interregional differences in farmers' experience with new technologies are common (Sunding and Zilberman). Overall, cotton in Andhra Pradesh is sprayed more often than in other states (table 3). Therefore, crop losses in conventional cotton are likely to be lower, and the expected Bt yield effect is small, especially in years with only moderate bollworm pressure.

Germplasm Effects

In 2002/3, this small positive Bt gene effect in Andhra Pradesh was counteracted by a negative germplasm effect (see equation (2) above). Many of the farmers

Table 2. Estimated translog production functions for cotton in India, 2002/3

	Model 1		Model 2		Model 3	
	Coefficient	*t*-Statistic	Coefficient	*t*-Statistic	Coefficient	*t*-Statistic
Bt (dummy)	0.237***	3.10	0.348***	3.75	0.463***	4.74
Fertilizer (kg/acre)	1.969***	2.80	1.930***	2.75	1.931***	2.79
Labor (days/acre)	1.495	1.47	1.386	1.37	1.634	1.63
Insecticide (Rs./acre)[a]	1.015**	2.34	1.020**	2.36	1.057**	2.48
Square of fertilizer	−0.165**	−2.25	−0.157**	−2.14	−0.137*	−1.90
Square of labor	−0.080	−0.61	−0.081	−0.61	−0.098	−0.76
Square of insecticide	0.007	0.03	0.001	0.03	−0.004	−0.19
Fertilizer-labor interaction	0.111	0.71	0.100	0.65	0.061	0.40
Fertilizer-insecticide interaction	−0.084	−1.52	−0.086	−1.55	−0.091*	−1.67
Labor-insecticide interaction	−0.153*	−1.86	−0.129	−1.56	−0.115	−1.41
Irrigation (times/season)	0.063***	5.78	0.061***	5.58	0.062***	5.71
Sowing date (days)	0.003	1.54	0.003	1.59	0.004*	1.87
Harvesting date (days)	0.003***	2.81	0.003***	2.78	0.003***	2.81
Karnataka (dummy)	−0.250***	2.77	−0.248***	−2.75	−0.160*	−1.73
Andhra Pradesh (dummy)	−0.189**	−2.01	−0.105	−1.03	−0.060	−0.59
Tamil Nadu (dummy)	−0.510***	−2.75	−0.505***	−2.74	−0.399**	−2.16
Education (years)	0.005	0.62	0.005	0.62	0.004	0.55
Age (years)	−0.007**	−2.22	−0.007**	−2.19	−0.007**	−2.29
Bt-Andhra Pradesh interaction			−0.326**	−2.09	−0.332**	−2.15
Bunny hybrid (dummy)					0.275***	3.36
Constant	−7.633***	−2.66	−7.370**	−2.58	−8.120***	−2.87
R^2	0.355		0.362		0.380	

Note: The dependent variable is the natural logarithm of cotton yield (in kg per acre). Likewise, the inputs fertilizer, labor, and insecticide are expressed as natural logarithms. Models 2 and 3 only differ from model 1 in the inclusion of additional explanatory variables as shown. The number of plot observations is 417 in all three models.

*,**,***Coefficients are statistically significant at the 10%, 5%, and 1% level, respectively.

[a]Insecticide amounts used are measured in monetary terms, in order to account for quality differences.

Rs. = Rupees.

Table 3. Effects of Bt cotton disaggregated by state (plot observations in 2002/3)

	Maharashtra		Karnataka		Tamil Nadu		Andhra Pradesh	
	Bt	Conventional	Bt	Conventional	Bt	Conventional	Bt	Conventional
				Mean (standard deviation)				
No. of insecticide sprays	3.86***	5.69	3.52***	6.27	1.45***	5.95	6.69**	8.49
	(2.15)	(3.02)	(2.61)	(3.58)	(1.61)	(2.97)	(4.00)	(3.81)
Insecticide cost (Rs./acre)	1,072***	1,906	824***	1,612	473***	1,746	2,322	2,864
	(1,201)	(1,725)	(931)	(1,222)	(601)	(1,226)	(1,907)	(2,004)
Yield of raw cotton (kg/acre)	641***	486	780***	451	781***	546	502	518
	(306)	(222)	(522)	(427)	(347)	(234)	(327)	(358)
Output price (Rs./kg)	19.69***	20.39	20.31	21.05	22.75	22.40	20.97	21.03
	(1.28)	(1.25)	(1.78)	(3.14)	(2.20)	(3.08)	(1.74)	(1.76)
Revenue (Rs./acre)	12,751***	9,920	16,040***	9,577	17,504***	12,167	10,729	11,063
	(6,451)	(4,630)	(10,854)	(9,191)	(7,572)	(5,159)	(7,355)	(7,926)
Total variable cost (Rs./acre)	7,753**	6,717	7,734**	6,525	10,613	10,071	8,720*	7,710
	(3,030)	(3,374)	(2,473)	(2,614)	(4,674)	(4,407)	(3,517)	(3,248)
Net revenue (Rs./acre)	4,998**	3,203	8,306***	3,051	6,890***	2,096	2,008	3,353
	(6,173)	(4,517)	(3,051)	(1,396)	(7,265)	(4,931)	(8,305)	(8,120)
No. of observations	44	97	33	84	20	21	36	99

*,**,*** Significantly different from conventional cotton at the 10%, 5%, and 1% level, respectively.
Rs. = Rupees.

surveyed in Andhra Pradesh were affected by severe drought conditions to which the Bt hybrids were not optimally adapted. Although the Bt gene does not alter the cotton plant's performance under water stress, the underlying germplasm of the three GM hybrids that had been approved until 2004, is not particularly well suited for extreme drought situations.[6] Model 2 in table 2 controls for this regional disadvantage by including a Bt-Andhra Pradesh interaction term. Not surprisingly, this interaction term is negative and significant, and the calculated net Bt yield effect for the other states increases to 42%.

In general, negative germplasm effects have to be expected whenever conventional hybrids are better adapted to local biotic and abiotic stress factors than the germplasm into which the Bt gene is incorporated. In their study in Maharashtra, Bennett et al. (2004a) showed that variability can also occur within a state. This is consistent with our subsample from Maharashtra, where individual Bt adopters complained about wilting problems, which occur occasionally in certain pockets. While there are some conventional hybrids in the market with resistance to fusarium wilt and parawilt, these had not been endowed with the Bt gene until recently.

Regulatory policy can also play an important role with respect to germplasm effects. If the registration procedure of additional Bt hybrids is slow, and newer hybrids have higher yield potentials, their adoption by non-Bt users will reduce the comparative gain from Bt, until Bt versions of these newer hybrids are released. The conventional versions of the initial three Bt hybrids performed well in the mid 1990s, when Mahyco started its research on Bt cotton in India. Today, however, there are more productive hybrids available in the market. A case in point is the hybrid Bunny, which was used by a number of conventional cotton growers in our sample. Indeed, including Bunny as a dummy variable in the production function shows that it has a sizeable positive effect on cotton yield (model 3 in table 2). Simultaneously, the net Bt yield gain increases to 59% when controlling for this "Bunny effect."

Apart from disadvantages in yield due to germplasm effects, the hybrids chosen for incorporation of the Bt gene can affect cotton quality and thus market prices obtained by farmers. The most important quality criterion is the fiber staple length of a hybrid. Bunny, for instance, has an average staple length of 31.6 mm, which is similar to the Bt hybrids MECH 12 and MECH 184. MECH 162, however, has an average staple length of only 27.3 mm (Naik et al.), so that farmers who used this Bt hybrid in 2002/3, partly received lower output prices. In Maharashtra, this resulted in a statistically significant output price difference between Bt and conventional cotton (table 3). Such quality and price differences were mistakenly attributed to the Bt gene itself by some observers (e.g., Shiva and Jafri).

Black Market Seeds

The determinants of variability discussed so far relate to the officially approved Bt cotton hybrids. Yet, there are also unapproved Bt cotton seeds of varying quality. Even before 2002, Navbharat Seed Company had sold a Bt cotton hybrid (NB 151) in the state of Gujarat. In spite of its good performance, the use of this hybrid has been prohibited by the government because it was never tested and authorized. Nevertheless, unofficial sales of NB 151 by some smaller companies and seed producers continue, and also F2 generations have been traded in Gujarat and other states. Given their cheaper price, these seeds have been widely adopted, so that Bt cotton area in India might be double the officially registered total (Pray, Bengali, and Ramaswami). However, due to the lack of quality control in the black market, there have also been reports of spurious Bt cotton seeds, which resulted in unexpected crop losses. Eventually, farmers might turn back to the official market, accepting the higher price as an insurance premium for getting genuine Bt seeds.

Discussion and Conclusion

Our results from the first season of Bt cotton adoption in India show that the technology leads to significant pesticide reductions, yield gains, and income increases on average. Yet, heterogeneity among farmers causes significant variability in impacts. We have shown that agroecological conditions—such as biotic and abiotic stresses at the local level—and farmers' spraying habits are important determinants for spatial differences in technology outcomes. The same factors can also be responsible for temporal variability, as shown by Bennett et al. (2004a) and Qaim. Innovation adoption is a learning process, and farmers have to identify optimal input adjustments through experimentation and reliable external advice. Seed providers also adjust their product and support to growers. Bt technology might not be suitable for all farmers because pest pressure and access to effective alternatives vary from case to case. Those who do not benefit will abandon the technology, but the rapidly increasing demand for Bt seeds in India confirms that they are beneficial for a vast number of cotton growers. The high rate of adoption at this early stage bodes well for the technology's future, as experience and learning are likely to lead to further improvements in its performance.

The performance and future of the technology can also benefit from regulatory changes. Currently, the regulatory procedure in India requires separate approval for every single Bt cotton hybrid. Our analysis suggests that a delay in authorization of additional Bt hybrids can be associated with negative germplasm effects. Moreover, it can potentially foster a loss in agrobiodiversity, when farmers replace a large number of locally adapted cultivars with a small number of available GM hybrids. Countries that have approved a particular technology should therefore take a liberal policy with respect to registrations based on the same transformation event. While the optimal number of modified varieties is a question of marginal costs and benefits, a certain minimum number of varieties, well adapted to diverse conditions, is important to realize the full agronomic and economic potentials of GM technologies.

In 2005, thirteen additional Bt cotton hybrids were approved by the Indian authorities, including a Bt version of Bunny (Sharma). Furthermore, there are private and public efforts underway to develop Bt cotton hybrids based on new transformation events. Although this will require additional biosafety testing, it will eventually lead to increased competition in the industry. Cotton farmers will be the main beneficiaries of declining price markups for official GM seeds and growing technological diversity.

Acknowledgments

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Endnotes

[1]While Bt provides good resistance to most bollworm species, it does not control sucking pests. Farmers have to take this into account when making their spraying decisions. See the empirical part for more details.

[2]Until early 2005, no Bt cotton hybrid had been approved for northern India.

[3]While resistance of Cry1Ac to pink bollworm (*Pectinophora gossypiella*) is almost 100%, it is less than 90% for American bollworm (*Helicoverpa armigera*) and spotted bollworm (*Earias vittella*) (Gould).

[4]For the net Bt yield effect, after controlling for other factors, see the production function analysis below.

[5]We calculate the percentage difference by using the formula $\{\exp(\hat{\beta}) - 1\}100$, as suggested by Halvorsen and Palmquist for the exact interpretation of dummy variables in models with a logarithmic dependent variable.

[6]While additional Bt hybrids have been approved by now, in early 2005 the Indian authorities disallowed commercial cultivation of the three initial Bt hybrids MECH 12, MECH 162, and MECH 184 in the state of Andhra Pradesh (Sharma).

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