Economic impacts and impact dynamics of Bt (*Bacillus thuringiensis*) cotton in India

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Despite widespread adoption of genetically modified crops in many countries, heated controversies about their advantages and disadvantages continue. Especially for developing countries, there are concerns that genetically modified crops fail to benefit smallholder farmers and contribute to social and economic hardship. Many economic studies contradict this view, but most of them look at short-term impacts only, so that uncertainty about longer-term effects prevails. We address this shortcoming by analyzing economic impacts and impact dynamics of Bt cotton in India. Building on unique panel data collected between 2002 and 2008, and controlling for nonrandom selection bias in technology adoption, we show that Bt has caused a 24% increase in cotton yield per acre through reduced pest damage and a 50% gain in cotton profit among smallholders. These benefits are stable; there are even indications that they have increased over time. We further show that Bt cotton adoption has raised consumption expenditures, a common measure of household living standard, by 18% during the 2006–2008 period. We conclude that Bt cotton has created large and sustainable benefits, which contribute to positive economic and social development in India.

farm survey | small farms | agricultural biotechnology

Despite widespread adoption of genetically modified (GM) crops in many countries (1), controversies about their advantages and disadvantages continue. In the public debate, negative attitudes often seem to dominate. Civil society groups tend to emphasize potential risks of GM crops and question reports about positive agronomic and economic effects (2–5). Especially with a view to developing countries, there are widespread concerns that GM crops fail to benefit smallholder farmers and contribute to social and economic hardship (4, 5). Much of this debate focuses on Bt cotton (5–9), as this is currently the most widely used GM crop technology among smallholders. Using comprehensive data from India, we show that these concerns about negative social and economic impacts are not backed by representative empirical evidence.

Bt cotton contains genes from *Bacillus thuringiensis* that make the plant resistant to the cotton bollworm complex. This inbuilt insect resistance can lead to savings in chemical pest control and higher effective yields in farmers' fields (9). Several studies have shown that Bt cotton adoption is associated with significant benefits to farmers in various countries (10–14). In addition to productivity gains (15–19), Bt adoption entails reduced incidence of acute pesticide poisoning among smallholders (20). However, the available literature on Bt cotton impacts has four important shortcomings, which may also explain why controversies continue. First, with very few exceptions (21), most of the evidence is based on data from field trials or from the first few growing seasons after the commercial release of Bt varieties in a country. This evidence is unsatisfying because it does not allow analysis of longer-term developments. For example, resistance build-up in pest populations or growing importance of secondary pests may potentially lower Bt benefits over time (22–24). Second, most impact studies do not properly control for nonrandom selection bias (17), which may occur when more successful farmers adopt the new technology earlier or more widely (25). As these successful farmers may have higher crop yields and profits anyway, this can result in inflated benefit estimates. Third, most available studies focus on agronomic impacts of Bt, such as yield and pesticide use effects, but economic effects, such as profit changes, are not analyzed at all or only based on simplistic comparisons. Fourth, and related to the previous point, many existing studies concentrate on impacts at the plot level, without considering possible broader welfare effects for farm households.

We address these shortcomings by using comprehensive panel data collected in India in four waves between 2002 and 2008. Estimation of panel data models allows us to account for selection bias and also analyze impact dynamics. In particular, we estimate fixed-effects specifications of yield, profit, and consumption expenditure models to derive net impacts of Bt adoption on cotton yield per acre, profit per acre, and household living standard. To our knowledge, this economic impact assessment of any GM crop technology that builds on more than 2 y of panel data is unique.

Results

In India, cotton is primarily grown by smallholder farmers with farm sizes of less than 15 acres and cotton holdings of 3–4 acres on average. The first Bt cotton hybrids were commercially released in India in 2002. By 2011, 7 million farmers had adopted Bt on 26 million acres, around 90% of the total Indian cotton area (1). We carried out a survey of Indian cotton farmers in four waves between 2002 and 2008. This survey covered a total of 533 farm households in four principal cotton-producing states (see *Materials and Methods*). The sample is representative of Bt and conventional cotton farmers in central and southern India. Given that we purposively oversampled Bt adopters in the first wave, sample adoption rates differ from actual adoption rates. The share of Bt-adopting farmers in our sample was 38% in 2002. After a small decline in 2003, it increased to 46% in 2004. (In the 2004, 2006, and 2008 survey waves, we also asked farmers for their adoption of Bt hybrids in 2003, 2005, and 2007, respectively. However, further details about the cultivation experience were only asked for the respective survey years.) The adoption share jumped to 93% in 2005 and reached 99% in 2008. A similar trend is also observed for individual adoption intensities, defined as the Bt acreage relative to the total cotton acreage on a farm. Alongside a range of household characteristics, data on all cotton plots of surveyed households were recorded, leading to a total of 1,655 plot observations.

Table 1 compares selected variables between Bt and conventional cotton plots and farms (for a more detailed overview, see

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Table 1. Descriptive statistics for 1,655 plots and 533 associated households (averages for 2002–2004 and 2006–2008)

	2002–2004		2006–2008	
Plot or household information	Conventional	Bt	Conventional	Bt
Plot level information				
Seed cost (1,000 Rs/acre)	0.51 (0.26)	1.60*** (0.43)	0.47 (0.21)	0.91*** (0.32)
Pesticide cost (1,000 Rs/acre)	2.27*** (1.80)	1.43 (1.57)	1.07 (1.21)	1.07 (1.38)
Yield (kg/acre)	520.64 (315.54)	705.40*** (360.41)	588.85 (318.66)	829.03*** (341.08)
Profit (1,000 Rs/acre)	3.60 (5.80)	6.14*** (6.89)	5.31 (6.80)	10.32*** (7.73)
No. of plots	601	298	64	692
Household level information				
Land owned (acres)	13.25 (15.45)	15.07* (18.42)	11.48 (12.28)	11.61 (12.68)
Expenditures (1,000 Rs/y)	85.87 (71.01)	122.76*** (79.00)	87.90 (64.14)	90.43 (88.82)
No. of households	363	222	61	432

*, *** imply that the mean value is significantly higher than that of conventional/Bt in the same time period at the 10% and 1% level, respectively. Mean values are shown with SDs in parentheses. Household expenditures were deflated using the consumer price index. Rs, Indian Rupees. Additional variables are shown in Table S1.

Table S1). We differentiate between early (2002–2004) and late (2006–2008) adoption periods. Most previous studies on Bt cotton impacts in India concentrated on the early period; evidence for the later period is thin. Bt seed costs per acre were more than three times higher than conventional seed costs during the early period. During 2006–2008, the cost difference was lower because of government interventions in seed pricing and increasing competition in the market for Bt technology (19, 26). Pesticide costs were significantly higher on conventional plots than on Bt plots during 2002–2004, and there was no difference during 2006–2008. Widespread adoption of Bt has led to area-wide suppression of bollworm populations, so that conventional cotton farmers also substantially reduced their pesticide applications (27). Similar positive spillover effects were observed for Bt cotton in China and Bt maize in the United States (28, 29).

In terms of yield per acre, Bt strongly outperformed conventional cotton in both time periods (Table 1). This finding is not because of higher yield potentials of Bt hybrids, but because of more effective pest control and thus lower crop losses. Higher yields are also the main reason for much higher profits on Bt cotton plots. These observed differences provide interesting insights into Bt effects, but they cannot be interpreted as net impacts of the technology, because confounding factors and possible nonrandom selection bias have to be controlled for. This process requires regression analysis.

Impact on Cotton Yield. Results of panel fixed-effects specifications of a cotton yield function are shown in Table 2 (full model results with all control variables are shown in Table S2). The positive and significant coefficient of Bt in column 1 indicates that Bt has a positive net impact on cotton yield per acre. Controlling for all other factors, Bt increases cotton yield by 126 kg per acre, which is equivalent to a 24% gain over mean yields on conventional cotton plots. The Bt dummy variable captures Bt adoption in any year, whereas the additional Bt 2006–2008 dummy takes a value of one only when Bt was used in the 2006 or 2008 survey waves. In the first column, the Bt 2006–2008 coefficient is insignificant, indicating that the Bt yield effect was stable over time and did not increase or decrease in the later compared with the earlier period.

The dummies for the three survey waves in column 1 of Table 2 are all positive and significant, indicating that overall yield levels were higher in 2004, 2006, and 2008, compared with the reference year 2002. Omitting these year dummies in column 2 leads to a large positive and significant Bt 2006–2008 coefficient. These results suggest that the Bt yield gain was in a magnitude of 297 kg per acre (sum of Bt and Bt 2006–2008 coefficients) in the later period and thus more than doubled compared with 2002–2004. As Bt adoption strongly increased over time, there is a close correlation between Bt 2006–2008 and the year dummies. Hence, some of the Bt effects are captured by the year dummies in column 1. Not including year dummies, as in column 2, may overestimate the Bt yield gains, because Bt 2006–2008 may then also capture time effects that are unrelated to the technology. However, systematic changes in temperature or rainfall did not occur during the period of analysis (30, 31), and there were also

Table 2. Net impact of Bt on cotton yield and profit per acre

	Yield (kg/acre)		Profit (Rs/acre)	
Explanatory variables	1	2	3	4
Bt (dummy)	125.90*** (20.41)	116.91*** (20.68)	1,877.21** (889.16)	2,151.51** (893.33)
Bt 2006–2008 (dummy)	3.59 (43.46)	180.06*** (20.54)	−260.45 (1,144.58)	1,736.39** (803.31)
2004	125.39*** (17.68)		2,066.07*** (466.18)	
2006	297.03*** (40.53)		5,006.86*** (1,017.09)	
2008	208.61*** (43.68)		2,332.61** (1,149.50)	
R^2	0.39	0.34	0.38	0.36
Hausman test	90.47***	70.00***	42.39***	24.60**

, *, Coefficient is statistically significant at the 5% and 1% level, respectively. Coefficient estimates are shown with SEs in parentheses. Estimates are based on panel regressions with household fixed effects to control for nonrandom selection bias. The reference year is 2002. Not all explanatory variables included in the models (e.g., input quantities, prices, and other controls) are shown for brevity (full model results with all control variables are shown in Tables S2 and S3). The Hausman test results show that fixed-effects are preferred over random-effects specifications. Rs, Indian Rupees.

no other breakthrough technologies in Indian cotton production (20, 32). Nor did we find evidence of attrition bias. (Because we have an unbalanced panel, there is the possibility of attrition bias, which could emerge when farmers who obtained lower than average yields with Bt cotton in 2002–2004 dropped out of the sample in the later 2006–2008 period. This drop could potentially hide a decrease in Bt impact over time. Analyses with different subsamples that we carried out do not support this hypothesis. We re-estimated the model in column 1 of Table 2 excluding the dropout farmers. With this smaller sample, the Bt coefficient is 130.94, which is very similar to the original coefficient of 125.90, and the Bt 2006–2008 coefficient remains insignificant. Hence, we conclude that there is no attrition bias.) Therefore, Bt was probably the main factor contributing to the observed time effects.

Impact on Cotton Profit. Bt technology can influence cotton profit mainly through three channels, namely changes in yield, changes in pesticide cost, and changes in seed cost (33). To assess net profit changes per acre, we estimated fixed-effects specifications of a profit function (Table 2; full model results with all control variables are shown in Table S3). The coefficients in column 3 indicate that Bt increases profit by 1,877 Rs per acre (38 US$), equivalent to a 50% profit gain over conventional cotton. In this specification, the Bt impact per acre does not change significantly over time. However, total cotton profits per farm rose, because farmers increased their Bt adoption intensity. Combining the estimate of 1,877 Rs with the data on adoption intensity, Bt added 5,307 Rs (107 US$) to annual farm-level cotton profits during 2002–2004 and 10,524 Rs (213 US$) during 2006–2008. Nationwide, for the 26 million acres currently under Bt, this implies an annual net gain of almost 50 billion Rs (1 billion US$) in cotton profits.

Similar to the yield analysis above, the year dummies in column 3 of Table 2 are all significant. When omitting these year dummies, the Bt 2006–2008 coefficient turns positive and significant (column 4), indicating that the Bt profit gains may actually have increased substantially in the later period to 3,888 Rs (79 US$) per acre (sum of Bt and Bt 2006–2008 coefficients). This result may partly be explained by lower Bt seed prices during 2006–2008. However, as seeds only account for a relatively small share of total production costs, the more important reason for larger profits per acre are higher yield gains and thus higher sales revenues.

Impact on Household Living Standard. Cotton is often the major crop for cotton-producing households in India, so that profit gains through Bt technology are also likely to increase household living standard. A common way of measuring living standard in the development literature is to look at household consumption expenditures, because expenditure is usually a more reliable indicator than income (34). We use a fixed-effects specification of a consumption expenditure model. As the level of analysis is the household, instead of using dummy variables to capture Bt adoption, we use the households' Bt area in any year and the Bt area in 2006–2008 as variables of particular interest. The results suggest that Bt had no significant effect on consumption expenditures in the early adoption period, but it increased household living standard significantly in the later period (Table 3; full model results with all control variables are shown in Table S4). This finding is plausible. Although Bt-adopting households also increased cotton profit during 2002–2004, they did not immediately change their consumption behavior but waited until they realized that the profit gains are sustainable.

In 2006–2008, each acre of Bt increased household consumption by 2,826 Rs (57 US$) per year (Table 3). Based on this finding, we can also calculate the total living standard effect per household by multiplying with the mean Bt area of adopting farms. During 2006–2008, Bt-adopting households increased their annual consumption expenditures by 15,841 Rs (321 US$) on average. Compared with nonadopters, this finding implies a net increase of 18%, which underlines that Bt cotton has significantly raised living standards of smallholder farm households.

Table 3. Net impact of Bt on household living standard

Explanatory variables	Consumption expenditure (Rs/y)
Bt area (acres)	197.65 (1,227.07)
Bt area 2006–2008 (acres)	2,825.65** (1,196.64)
2004	19,433.01*** (4,543.11)
2006	1,257.58 (5,653.66)
2008	9,250.43 (5,937.91)
R^2	0.17
Hausman test	35.50***

, *, Coefficient is statistically significant at the 5% and 1% level, respectively. Coefficient estimates are shown with SEs in parentheses. Household expenditures were deflated using the consumer price index. Estimates are based on panel regressions with household fixed effects to control for nonrandom selection bias. The reference year is 2002. Control variables include cotton area, so that the coefficients of Bt area and Bt area 2006–2008 can be interpreted as the net effect of Bt technology (full model results with all control variables are shown in Table S4). The Hausman test result shows that fixed-effects are preferred over a random-effects specification. Rs, Indian Rupees.

Discussion

The results show that Bt cotton adoption has caused sizeable socioeconomic benefits for smallholder farm households in India. The technology has increased cotton yields and profits by 24% and 50%, respectively. These effects are similar in magnitude to the ones shown in earlier studies for India based on cross-section data (15–19, 33). The panel data used here confirm that impacts per acre of Bt cotton have been stable over time. Because of rapidly rising Bt adoption rates in India, the aggregate benefits increased tremendously. Countrywide, this technology is now used on 90% of the cotton area. On average, household living standard increased by 18% among Bt adopters. Most of these adopting households are relatively poor. Hence, Bt cotton contributes to positive economic and social development.

The stable Bt effects per acre are a conservative interpretation. Robustness checks indicate that the per acre benefits probably increased over time. This finding could be explained by the growing number of available Bt hybrids and the release of new Bt events after 2005. In 2002, only three Bt hybrids, which were developed by the Indian seed company Mahyco and contained Monsanto's Bollgard I technology (event MON 531), were approved by the national regulatory authorities. In 2004 and 2005, three other Indian seed companies, which had sublicensed the Bollgard I technology, received approval for the commercialization of several additional Bt hybrids. In 2006, the number of approved Bt hybrids increased sharply. In addition, new Bt events were deregulated by the national authorities, including Monsanto's Bollgard II technology, but also technologies developed by public research institutes. By 2011, the number of commercialized Bt varieties and hybrids containing different events had increased to over 880 (1). More Bt events and greater varietal diversity imply effectiveness against a broader spectrum of insect pest species and better adaptation to different agroecological conditions.

Our findings of large and sustainable economic and social benefits of Bt cotton do not imply that impacts may not decrease in the long run. As of now, Bt resistance development and secondary pest outbreaks do not seem to be major problems in India, but this should be further monitored. Sustainable innovation in agriculture always implies that technologies are further improved or replaced by new technologies after some time. Nonetheless, our results clearly refute the assertion that Bt technology would harm smallholder farmers because of low and eroding economic benefits. As Bt cotton is the only GM crop technology that is already widely used by smallholder farmers, these findings may add to the wider public biotechnology debate.

Materials and Methods

Survey. A panel survey of Indian cotton farmers was carried out in four waves between 2002 and 2008. A multistage random sampling procedure was used. The survey covered four states of central and southern India, namely Maharashtra, Karnataka, Andhra Pradesh, and Tamil Nadu. These four states encompass a wide range of different cotton-growing situations. A total of 10 different districts and 63 villages were surveyed. The first wave was implemented in early 2003, covering the 2002 cotton growing season. Because this was the first season where Bt cotton was officially commercialized, the number of adopters was still very low. Therefore, Bt cotton adopters were purposely oversampled by randomly selecting from complete lists of technology users at the village level (33). Follow-up waves were implemented in 2-y intervals, in early 2005 (referring to the 2004 cotton season), early 2007 (referring to the 2006 season), and early 2009 (referring to the 2008 season). The survey is representative of Bt cotton adopters and nonadopters in central and southern India, where over 60% of the total Indian cotton area is located.

To some extent, sample attrition occurred over time, as is normal in panel surveys extending over several years. Some farmers had migrated to other areas, which happened particularly in one district of Karnataka. Other farmers had stopped cotton cultivation during the period, mostly because of focusing on new cash crops, such as sugarcane. Farmers who dropped out during the period were replaced by other randomly selected farmers in the same locations. The sample size was also slightly increased over time. In total, the sample includes observations from 533 different farm households, of which 198 were included in all four survey waves. All observations were used for the regression analysis, resulting in an unbalanced panel. An unbalanced panel allows more efficient estimation than any balanced subset of it (35).

During face-to-face interviews in all four waves, farmers were asked to provide a wide array of agronomic and economic information, including input-output details on their cotton plots. Farmers who grew Bt and conventional cotton simultaneously provided details for both alternatives, so that the number of plot observations is somewhat larger than the number of farmers surveyed. The total number of cotton plot observations is 1,655 over the four waves. At the household level, data were collected about household structure, asset ownership, and living standard. Living standard is measured by household consumption expenditures (including the value of subsistence consumption), which were captured through a 30-d recall for food and other consumables, and a 12-mo recall for more durable items.

Regression Models. We want to estimate unbiased treatment effects of Bt adoption on cotton yield per acre, profit per acre, and household living standard. For this purpose, we develop and estimate three types of models where Bt is included as an explanatory variable: a cotton yield function, a cotton profit function, and a household consumption expenditure model. These models can generally be represented as:

$$y_{it} = \boldsymbol{x}_{it}\beta + v_{it}, \quad [1]$$

where

$$v_{it} = c_i + \mu_{it}, \quad [2]$$

where y is the respective outcome variable (yield per acre, profit per acre, consumption expenditure per household), subscript i is the plot or household observation, and subscript t is time (survey wave). This fixed-effects specification allows for individual heterogeneity c_i to be correlated with the vector of explanatory variables $\boldsymbol{x}_{it}$. We use fixed effects because we suspect that more progressive and efficient farmers are more likely to adopt Bt technology. The existence of such selection bias and thus the superiority of a fixed-effects over a random-effects specification is tested with a Hausman test.

Year dummies are included in the regression models to control for time fixed effects, using the first survey wave in 2002 as the reference year. For the yield and profit functions, which are estimated using plot observations, we use a Bt adoption dummy as treatment variable, which is one for a Bt plot in any particular year and zero otherwise. In addition, we include a Bt 2006–2008 dummy, which is one if Bt was used in 2006 or 2008. The Bt dummy indicates whether or not the technology has a positive net effect on cotton yield and profit, and the Bt 2006–2008 dummy reveals whether there are impact dynamics: if the Bt coefficient is positive and significant and the Bt 2006–2008 coefficient is statistically insignificant, then the technology causes benefits that do not change over time. On the other hand, a negative Bt 2006–2008 coefficient would indicate shrinking benefits, whereas a positive coefficient would reveal increasing benefits over time.

The consumption expenditure model is estimated at the household level. Some farm households have both Bt and conventional cotton. Moreover, the acreage cultivated with Bt varies. Therefore, instead of Bt dummies, we use two continuous Bt variables. The first such dummy is Bt area, which measures the number of acres cultivated with Bt on the farm, independent of the time period. The second is Bt area 2006–2008, which measures the number of Bt acres only during that later period. We control for total cotton area on the farm. Thus, the Bt estimation coefficients can be interpreted as the effects on household consumption expenditures per acre of Bt cotton. The test for impact dynamics is as explained for the yield and profit function models.

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