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Working Paper

Are the economic benefits of Bt cotton sustainable? Evidence from Indian panel data

Discussion Papers, No. 80

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***Abstract**: While several studies have shown that genetically modified Bt cotton can benefit smallholder farmers economically, the sustainability of these effects is still unclear and debated controversially between biotechnology proponents and critics. We use unique panel data of 533 cotton farmers, collected in India between 2002 and 2008, to analyze Bt impacts on cotton yield, profit, and household living standards. Results from fixed effects models show that the adoption of Bt cotton is associated with a net yield gain of 24% and a profit increase of 50%. These benefits per acre were stable over time; there are even indications that they increased. Given rising adoption rates, the aggregate benefits grew substantially. We further show that Bt cotton adoption raised consumption expenditures, our measure of household living standards, by 18% during the 2006-2008 period. We conclude that Bt cotton has created large and sustainable benefits, which contribute to economic development in India.*

***JEL classification**: I31, Q12, Q13, Q16*

***Key words:** biotechnology, Bt cotton, genetically modified crops, farm survey, household living standards, India, technology adoption*

Acknowledgements: The long-term financial support of the German Research Foundation (DFG) for compiling the panel data set is gratefully acknowledged. Furthermore, prize money received from the German Agricultural Society (DLG) was used for this research.

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Are the economic benefits of Bt cotton sustainable?

Evidence from Indian panel data

***Abstract**: While several studies have shown that genetically modified Bt cotton can benefit smallholder farmers economically, the sustainability of these effects is still unclear and debated controversially between biotechnology proponents and critics. We use unique panel data of 533 cotton farmers, collected in India between 2002 and 2008, to analyze Bt impacts on cotton yield, profit, and household living standards. Results from fixed effects models show that the adoption of Bt cotton is associated with a net yield gain of 24% and a profit increase of 50%. These benefits per acre were stable over time; there are even indications that they increased. Given rising adoption rates, the aggregate benefits grew substantially. We further show that Bt cotton adoption raised consumption expenditures, our measure of household living standards, by 18% during the 2006-2008 period. We conclude that Bt cotton has created large and sustainable benefits, which contribute to economic development in India.*

1. Introduction

Bt cotton has recently been adopted by millions of farmers in developing countries (James, 2010). Bt cotton is a genetically modified (GM) crop containing genes from *Bacillus thuringiensis* that make the plant resistant to the cotton bollworm complex. The inbuilt insect resistance can lead to savings in chemical pest control and to higher effective yields in farmers' fields (Qaim and Zilberman, 2003). This was confirmed in studies from several countries. Indeed, most peer-reviewed empirical research indicates that Bt technology is associated with significant benefits to farmers, while only very few studies reported either insignificant or negative impacts (Carpenter, 2010). Nonetheless, controversial debates about socioeconomic effects of this technology, and about impact developments over time, continue, especially with a view to the small farm sector (Glover, 2010; Stone, 2011). This is partly due to the fact that the data and research design used in previous studies do not always allow far-reaching conclusions. As Bt cotton is the first GM crop technology that is widely used by smallholder farmers, this uncertainty hampers developments in biotechnology, which could contribute to food security, poverty reduction, and sustainable growth (Huang et al., 2004; Qaim, 2010).

More to the point, the published literature on Bt cotton impacts has four important shortcomings. First, with the exception of China (e.g., Pray et al., 2002), much of the available evidence on impacts is based on trial data or on growing seasons that followed shortly after the commercial release of Bt varieties in a country. This is unsatisfying because it prevents a view on long-term developments. Pest dynamics might alter the benefits of Bt technology through resistance buildup or the growing importance of secondary pests (Tabashnik, 2008; Wang et al., 2008; Wang et al., 2009). Second, most published impact studies do not control for potential selection bias, often due to the unavailability of panel data and/or the lack of suitable instruments. A study using a two-year panel from one state in India suggests that not accounting for selection bias may result in overestimated benefits (Crost et al., 2007). Third, the econometric estimates of available studies mostly focus on agronomic impacts of Bt, such as yield and pesticide use effects, while economic effects are only analyzed with descriptive statistics. For instance, we are not aware of any study that has estimated the net effects of Bt on cotton profits. Fourth, and related to the previous point, existing studies mostly concentrate on the plot level, without considering possible broader welfare changes for farm households. Exceptions are Subramanian and Qaim (2010) and Ali and Abdulai (2010), who analyzed household income and poverty effects of Bt cotton in India and Pakistan, respectively.

All of these shortcomings are addressed in the present paper, using the example of Bt cotton in India. India is a particularly interesting case, because it is now the world's biggest producer of Bt cotton, and the crop is predominantly grown by smallholder farmers there (Karihaloo and Kumar, 2009). Moreover, many of the controversies about the social impacts of GM crops in developing countries relate to Bt cotton in India (Glover, 2010; Stone, 2011; Gruere and Sengupta, 2011). We use panel data collected in four major cotton-producing states of India between 2002 and 2008 to analyze impacts and impact developments over time. We estimate fixed effects production and profit function models, as well as a household expenditure model to assess broader impacts on living standards. To our knowledge, this is the first economic impact assessment of any GM crop technology that builds on more than two years of panel data.

The rest of this paper is structured as follows. Section 2 gives some further insights into the available literature on Bt cotton impacts, before section 3 describes the data set and the process of Bt cotton adoption in India. In section 4, the econometric models are explained, estimated, and discussed. Section 5 concludes.

2. Background

Most impact studies for Bt cotton in India suggest that the technology has reduced chemical pesticide use and increased yields and net incomes (Bennett et al., 2004; Bennett et al., 2006; Crost et al., 2007; Morse et al., 2007; Sadashivappa and Qaim, 2009), although negative effects for individual years and in certain locations were also reported (Sahai and Rahman, 2003; Qaim et al., 2006). Qaim et al. (2006) point to the possibility of negative effects of Bt varieties if the underlying germplasm is not well adapted to local agroecological conditions. Experience from other countries, including Argentina, Australia, China, Mexico, South Africa, and USA, confirms that Bt cotton has pesticide-reducing and yield-increasing effects on average (Qaim, 2009; Carpenter, 2010).

Wider social effects were analyzed by Ali and Abdulai (2010) and by Subramanian and Qaim (2010), who concluded that Bt cotton can also contribute to poverty reduction and employment generation in the small farm sector. Studies carried out in China and South Africa looked at health benefits associated with lower pesticide use, demonstrating that Bt technology can reduce the incidence of acute pesticide poisoning among smallholder farmers (Hossain et al., 2004; Huang et al., 2003; Bennett et al., 2003). However, a clear weakness in the available literature is that most studies are based on cross-section data, which do not allow the analysis of impact developments over time. Thus, it is still unclear how sustainable the benefits of Bt cotton are.

Shrinking benefits, which could also turn into losses over time, are of special concern, because this could potentially entail social hardship for smallholder farmers. There are particularly two factors that might contribute to benefit erosion. First, there may be Bt resistance development in pest populations, which would undermine the technology's effectiveness (Tabashnik, 2008). Second, the importance of secondary pests, such as mirids, mealybugs, and other sucking pest species, may increase over time (Wang et al., 2008; Wang et al., 2009). The reason is that Bt is very specific to the bollworm complex, but does not control other insect species. When chemical pesticide use is reduced through Bt adoption, sucking pests may thrive, which could again increase pesticide application after a while.

However, there may also be factors that lead to increasing Bt benefits over time, such as further technological improvements. For instance, while the first generation of Bt varieties only contained one Bt gene (Bollgard I), a second generation contains two different Bt genes (Bollgard II), thus increasing the effectiveness of pest control. Likewise, use of better germplasm for the incorporation of the Bt genes may have a positive effect. In India, the number of different Bt varieties, which are suitable for diverse agroecological conditions, increased substantially over time, as we will further explain below. Moreover, input and output prices may change, such as Bt seed prices that were reduced in India over time. While seed prices do not affect the technology's agronomic performance, they can certainly influence the economic benefits to farmers.

Another effect that may occur over time is an overall reduction of bollworm pressure. Widespread use of Bt technology may suppress bollworm infestation levels regionally, such that non-Bt adopters may also be able to reduce pesticide applications and increase effective yields. This was observed for Bt cotton in China (Wu et al., 2008) and for Bt maize in the USA (Hutchinson et al., 2010). For India, Sadashivappa and Qaim (2009) observed that both Bt adopters and non-adopters had reduced their pesticide use over time, which also points at positive spillovers. Such spillovers would not affect the absolute performance of Bt cotton varieties, but they would affect the relative performance vis-a-vis non-Bt varieties.

We address the question of impact dynamics by using comprehensive panel data that were collected in four waves between 2002, the first year of Bt cotton commercialization in India, and 2008. Panel techniques also allow us to properly account for possible selection bias, which was rarely done in previous impact studies. A selection bias may occur because the Bt technology was not assigned randomly. Farmers choose themselves whether or not to adopt, and often more progressive and less risk-averse farmers are those that adopt a new technology earlier or more widely (Barrett et al., 2004; Dercon and Christiaensen, 2010). These progressive farmers may have above average yields and higher profits even without the new technology, which can result in inflated benefit estimates. Panel models with farmer fixed effects reduce the resulting bias by controlling for unobserved heterogeneity. Crost et al. (2007) used two-year data from one state in India and compared a pooled data model with a fixed effects specification to show that yield gains of Bt cotton may be overestimated substantially when not controlling for farmer heterogeneity.

3. Data and Bt cotton adoption in India

3.1 Panel 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. The first wave was implemented in early 2003, covering the 2002 cotton growing season. Since this was the first season where Bt cotton was officially commercialized, the number of adopters was still very low. Therefore, Bt cotton adopters were purposively oversampled. Follow-up waves were implemented in two-year 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). Further details of the sampling procedure are provided in Qaim et al. (2006) and Subramanian and Qaim (2010). The survey is representative of Bt cotton adopters and non-adopters 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. Others 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, we have observations from 533 different farm households, of which 198 were included in all four survey waves. We decided to use the entire data for our econometric analysis, which results in an unbalanced panel. Baltagi and Song (2006) showed that an unbalanced panel allows more efficient estimation than any balanced subset of it.

During the personal interviews, 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 1655 over the four waves. At the household level, data were collected about household structure, asset ownership, and living standards. Living standards are measured by household consumption expenditures, which were captured though a 30-day recall for food and other consumables, and a 12-month recall for more durable items.

Descriptive statistics of the variables used in the regression analysis are shown in Table 1, separated by Bt and conventional plots and farmers. The Table also disaggregates by time period, clubbing the first two (2002-2004) and the last two (2006-2008) survey waves. A further disaggregation by all four waves is not useful for the descriptive statistics, because the number of conventional cotton plot observations became extremely small in 2008, due to almost complete Bt adoption (also see next subsection).

[Table 1]

As can be seen from Table 1, average farm sizes are relatively small with a cotton holding of around 6 acres. Mean annual household consumption expenditures are in a magnitude of 90,000 Indian Rupees (Rs.). Dividing by the average household size, this results in a per capita expenditure of around 14,000 Rs., which is equivalent to 305 US$ using the official exchange rate from early 2011. Comparing the plot level data, significantly higher cotton yields and profits per acre were achieved on Bt plots than on conventional plots, and the differences increased from the earlier to the later period. This suggests that Bt adoption brings about sizeable benefits for Indian cotton farmers, which will be further analyzed below.

3.2 Bt adoption in India

Bt cotton was officially commercialized in India in 2002. In the first year, around 90,000 acres were planted with Bt hybrids (Qaim et al., 2006). In subsequent, years the area under Bt increased substantially and reached 23 million acres in 2010 – almost 90% of the total Indian cotton area (James, 2010). Also the number of Bt cotton varieties increased considerably over time (Table 2). 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.

[Table 2]

In 2006, the number of approved Bt hybrids increased further. 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. These were also backcrossed into hybrids from several local seed companies. In 2008, India's Central Institute for Cotton Research released the first open pollinated Bt variety based on an event developed by the Agricultural University in Dharwad. By December 2008, around 280 different Bt cotton varieties were available in India; by August 2009, this number had further increased to over 600 (Karihaloo and Kumar, 2009). This increase in the number of Bt varieties is positive for farmers, as greater varietal diversity implies better adaptation of Bt seeds to different agroecological conditions. This may have contributed to rising Bt adoption rates and benefits.

There were also changes in input and output prices that may have affected the speed of adoption (see Figure 1). Bt seed prices were in a magnitude of 1500-1600 Rs. per packet (of 450 g) until 2005. But in 2006 government authorities introduced an official Bt seed price cap at 750 Rs. per packet (Sadashivappa and Qaim, 2009), whereas the price of conventional cotton seeds remained relatively stable. On the output side, the Indian government increased the minimum support price for cotton by 30-50% in 2008 (Cotton Incorporated, 2009). While this refers to cotton output in general, regardless of the production technology, it may have been an additional incentive to adopt Bt because of the higher expected yields with this technology.

[Figure 1]

We now examine Bt adoption patterns in our sample. Because of the oversampling of adopters in 2002, adoption rates are not representative for India, but some of the general patterns are still noteworthy and also consistent with actual population adoption rates (James, 2010). The share of adopting farmers in our sample was 38% in 2002. After a small decline in 2003, it increased to 46% in 2004.[1] The adoption share increased to 93% in 2005

[1] 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.

and reached 99% in 2008. A similar trend is also observed for the adoption intensities, which are shown in Figure 2. Adoption intensity is defined here as Bt acreage relative to total cotton acreage on a farm.

[Figure 2]

Strikingly, the most significant increase in adoption rates and adoption intensity occurred in 2005, before the government had introduced the price caps on Bt seeds and before minimum support prices for cotton output were increased. This suggests that farmers were also realizing significant benefits from Bt adoption without the government price interventions, which is consistent with the descriptive statistics in Table 1. A more important driver behind the adoption takeoff was probably the approval of additional Bt varieties. In 2005, the number of Bt varieties increased from 4 to 20, and the new releases included Bt variants of the most popular conventional cotton varieties at that time. The total number of Bt varieties used by farmers in our sample increased from 3 in 2002 to 38 in 2006 and 48 in 2008. The most widely used variety in a given year was never the most widely used two years later. Also on individual farms, the number of Bt varieties used increased. The percentage of Bt adopters who used only one Bt variety dropped from 94% in 2002 to 37% in 2008. In 2008, 32% of adopters used two Bt varieties, 15% used three, and 15% used four or more Bt varieties. This is similar to the distribution of conventional variety use at the beginning of the Bt adoption process. These observed patterns allow three inferences: First, farmers value Bt technology. Second, farmers value varietal diversity. Third, the approval of new Bt varieties has catered to both of these preferences.

4. Econometric analysis

We want to estimate unbiased treatment effects of Bt adoption on cotton yield, profit, and household welfare. For this purpose, we develop and estimate three types of models where Bt is included as an explanatory variable: (1) a cotton production function, (2) a cotton profit function, and (3) a household expenditure function. These econometric models can generally be represented as follows:

$$y_{it} = \boldsymbol{x}_{it}\boldsymbol{\beta} + v_{it}$$

where

$$v_{it} = c_i + \mu_{it}$$

This fixed effects specification allows for the 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 will be tested with a Hausman test.

Year dummies will be included to control for time fixed effects, using the first survey wave in 2002 as the reference year. For the production and profit functions, which are estimated using plot level 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 either 2006 and/or 2008. Thus we implicitly divide the sample into two time periods, before and after 2005. We chose to draw the line in 2005 as the empirical record on Bt cotton impacts in India becomes very thin thereafter. While the Bt dummy indicates whether or not the technology has a positive net effect on cotton yields and profits, 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 delivers benefits that do not change considerably over time. On the other hand, a negative Bt 2006-2008 coefficient would indicate shrinking benefits, whereas a positive coefficient would reveal increasing benefits.

The expenditure model is estimated at the household level. Some farm households have both Bt and non-Bt cotton. Moreover, the acreage cultivated with Bt varies. Therefore, instead of Bt dummies, we use two continuous Bt variables. The first 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. Thus, the treatment coefficients can be interpreted as the effects on household expenditure per acre of Bt cotton. The test for impact dynamics is as explained above.

4.1 Bt impact on yields

For our production function estimates, we use cotton yield measured in kg per acre as dependent variable. In addition to the Bt dummies described above, we include use of inputs, such as fertilizer, pesticide, irrigation, and labor. Moreover, we include additional control variables, such as sowing and harvesting date and farmer characteristics that were shown to be relevant in previous production function estimates for cotton in India (Bennett et al., 2006; Qaim et al., 2006). As functional form, we chose a quadratic specification based on empirical goodness of fit criteria. The estimation results are shown in Table 3.

Column (1) shows results of a simple pooled data model. As expected, Bt has a positive and significant effect on yield. Likewise, irrigation and labor input have significantly positive effects, whereas the coefficients of fertilizer and pesticide are positive but insignificant. The state dummies show that cotton yields are lower in Tamil Nadu than they are in the other three states surveyed, and the year dummies show that yields were significantly higher in 2004, 2006, and 2008 than they were in 2002.

[Table 3]

However, the pooled data model does not account for unobserved farmer heterogeneity that may be correlated with Bt adoption. Column (2) in Table 3 shows the results from the fixed effects production function model, where all time-invariant variables are excluded. Again, the coefficient of the Bt dummy is positive and significant, but it is somewhat smaller than in the pooled model. This indicates that there is a selection bias in the pooled model that the fixed effects model controls for. The Hausman test result, which is also shown in Table 3, confirms that the fixed effects model is the preferred specification. Comparison of the Bt coefficient in columns (1) and (2) suggests that the bias in the pooled model is 24%. This is much smaller than the bias found by Crost et al. (2007). However, Crost et al. (2007) only had data from one state in India and from the first two Bt cotton growing seasons 2002 and 2003. It is reasonable that we find a lower selection bias, because we cover a larger geographical area and a longer time period during which more and more farmers have adopted Bt cotton.

The unbiased fixed effects Bt coefficient in column (2) implies that Bt increases effective cotton yield by 126 kg per acre on average. In relative terms, this implies a net yield gain of 24%. Since Bt technology does not increase the actual yield potential of cotton, the higher yields are the result of reduced crop losses due to the cotton bollworm complex.[2] The Bt 2006-2008 coefficient is not significant in column (2), indicating that the Bt yield effects were stable over the entire time period.

In column (3) of Table 3 we use a fixed effects specification where we exclude the year dummies. While most of the coefficients are similar to those in column (2), the Bt 2006-2008 coefficient suddenly becomes large and highly significant, suggesting that the Bt yield gains increased substantially over time. But why was this result not observed in column (2)? The answer is that Bt adoption is very closely correlated with time, with almost complete adoption among sample farmers in the last survey wave. Thus, it is likely that some of the Bt effects are captured by the year dummies, which were all positive and highly significant in column (2). In other words, including time fixed effects may lead to an underestimation of Bt yield gains over time.

On the other hand, not including year dummies may overestimate the gains, because the Bt 2006-2008 dummy may then also capture time effects that are unrelated to the technology itself. What could possibly drive productivity gains over time? Steady progress in breeding and agronomics usually entails gradual yield improvements, but alone this can hardly explain the large time effects observed. Nor do we find other factors beyond Bt adoption that could

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[2] This was modeled more explicitly by Qaim and Zilberman (2003), building on cross-section data and a damage control specification.

plausibly explain the large yield gains over time. Systematic changes in temperature or rainfall did not occur during the period of analysis, and there were also no other breakthrough technologies in Indian cotton production. Hence, Bt was probably the main factor contributing to the observed time effects. As explained above, rising Bt effects could be explained by the growing number of available Bt varieties and the release of new Bt events after 2005. On the other hand, phenomena that could potentially contribute to decreasing technological effects over time, such as Bt resistance development and/or secondary pest outbreaks, do not yet seem to be major problems in India.

Another reason why Bt yield effects over time may be underestimated with time fixed effects is the expected overall suppression of bollworms as a result of widespread Bt adoption. As discussed above, this would benefit Bt adopters and non-adopters alike, so that the effect would be captured by the year dummies, when they are included. Analyzing such positive technological spillovers more accurately would require spatially explicit data on Bt adoption at the village level, in order to show that time effects are stronger in locations with particularly rapid and high technology uptake. Unfortunately, such data are not available. Therefore, while there are clear indications of increasing Bt yield effects, we cannot prove them with absolute certainty.

What we did prove so far is that the Bt yield gains did not decrease over time. However, since we have an unbalanced sample, there is still 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 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 (2) of Table 3 with time fixed effects but excluding the dropout farmers. With this smaller sample, the Bt coefficient is 130.94, which is very similar to the original results, while the Bt 2006-2008 coefficient remains insignificant. Hence, we conclude that there is no attrition bias of that sort.

Finally, we combine the estimated per acre Bt coefficient from column (2) in Table 3 with the adoption intensity data discussed in section 3 to assess the impact of the technology on cotton production at the farm level. The average adoption intensity of Bt adopters was 46% in 2002-2004, and 98% in 2006-2008 (Figure 1). In absolute terms, the average Bt area of adopting households doubled from 2.8 to 5.6 acres. Hence, on average Bt technology raised total cotton production of adopting farmers by 356 kg and 706 kg during 2002-2004 and 2006-2008, respectively.

4.2 Bt impact on profits

Bt technology can influence cotton profits mainly through three channels, namely changes in yields, changes in pesticide costs, and changes in seed costs. To assess the net profit effects, we estimate a profit function with cotton profit measured in Rs. per acre as dependent variable. Following production theory, we use the same quadratic specification as for the production function, but include input and output prices instead of quantities as explanatory variables, next to the Bt treatment variables and other factors that may affect profit. The estimation results are shown in Table 4.

Again, we start with a pooled data model in column (1), which suggests that Bt has a positive and significant effect on cotton profits. The Bt 2006-2008 coefficient is also large and positive but statistically insignificant. Other factors that influence profit positively are irrigation, a later harvesting date, and output prices, which is as expected. In contrast, fertilizer price has a negative effect. Results also show that there are significant differences in profits between the four states. Farmers in Andhra Pradesh and Tamil Nadu realize lower average profits than their colleagues in Maharashtra, while farmers in Karnataka have higher profits.

[Table 4]

Column (2) of Table 4 shows results from a fixed effects specification, which is preferred due to unobserved heterogeneity, as indicated by the Hausman test result. Strikingly, compared to the pooled data model, the Bt coefficient is now even somewhat larger. Holding other factors constant, Bt adoption increases cotton profit by 1,877 Rs. (40 US$), which implies a 50% increase over the average profit in conventional cotton. The insignificance of the Bt 2006-2008 coefficient indicates that this effect was stable over time.

As for the production function, we also estimate a profit function without year dummies, results of which are shown in column (3) of Table 4. The Bt coefficient is now somewhat larger than before, but more importantly the Bt 2006-2008 coefficient is now also positive and significant, suggesting that Bt profit effects may have increased over time. Again, this could be explained by the growing number of Bt varieties and the release of additional Bt events after 2005, which may increase the yield gains and also the pesticide reductions. As was explained in section 3, there were also considerable changes in cotton output prices and Bt seed prices as a result of government market interventions. While such price changes affect cotton profits in general, they do not affect the estimated net Bt profit effects in our models, because we control for input and output prices. Remarkably, Bt seed prices do not show a significant effect in any of the models in Table 4, suggesting that the government price caps did not influence profits in a major way.

We also tested for possible attrition bias by re-estimating the model in column (2) of Table 4, but excluding the dropout farmers. As was the case in the production function estimate, there is not big change in the Bt coefficient, while the Bt 2006-2008 coefficient remains insignificant. We conclude that the net effect of Bt adoption on cotton profits was stable at 40 US$ per acre. Extrapolating to the farm level by combining this estimate with the data on adoption intensity, Bt added 5,307 Rs. (116 US$) to annual farm level cotton profits during 2002-2004 and 10,524 Rs. (229 US$) during 2006-2008.

4.3 Bt impact on household living standards

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 incomes and living standards. However, due to possible resource reallocation within the household, which may also affect the incomes derived from other economic activities, it would be too simplistic to assume that the household income effects are equal to the profit gains in cotton. Therefore, we construct an econometric model to explain household living standards, including Bt area and Bt area 2006-2008 as treatment variables, as explained above. Instead of household income, we use consumption expenditure as dependent variable, as this is considered a more reliable indicator of household living standards. For the estimations, a linear functional form is assumed. Results are shown in Table 5.

Column (1) shows results from a pooled data model. The Bt coefficient suggests that each acre of Bt cotton increases household expenditure by around 2,600 Rs. per year. We control for the total cotton area, so that this can be interpreted as the adoption impact. Furthermore, since consumption needs depend on the number and age of family members, we control for household size using adult equivalents (AE). Age and education of the household head influence consumption expenditures positively, as could be expected. There are also significant differences in living standards between the states, with households in Andhra Pradesh and Tamil Nadu being richer on average than households in Maharashtra and Karnataka.

[Table 5]

However, the Hausman test result shown in column (2) of Table 5 indicates that the pooled data model suffers from selection bias due to unobserved heterogeneity. In the fixed effects model, the Bt area coefficient is insignificant, but the Bt area 2006-2008 coefficient is positive, large, and significant. This suggests that Bt adoption did not significantly increase household living standards in the earlier period, but it did so in the later period. This is plausible given that we measure living standards with consumption expenditures.

Households that increase their income through the adoption of a new technology may not change their consumption behavior immediately, but they do so after a while when they realize that the income gains are sustainable.

In 2006-2008, each acre of Bt cotton increased household expenditures by 2,826 Rs. on average, which is equivalent to 62 US$. This is even somewhat larger than the 40 US$ gain in per acre profit through Bt adoption discussed above, which may partly be due to measurement error. However, there is also another plausible explanation, namely that the profit gain is underestimated in the specification with time fixed effects. This is supported by the fact that the year dummies for 2006 and 2008 are not significant in the household expenditure model, while they were significant and positive in the profit model. Using the profit function results without year dummies (see column (3) of Table 4), and adding up the Bt and Bt 2006-2008 coefficients results in a profit gain of 3,888 Rs. per acre, which is equivalent to 85 US$.

The results in Table 5 tell us the impact on household expenditure of converting a single acre of conventional cotton to Bt cotton. Based on this, we can also calculate the total effect of Bt cotton on living standards among adopting households, by multiplying the Bt area 2006-2008 coefficient (but not the overall Bt area coefficient due to its insignificance) with the mean Bt area of adopters During the 2006-2008 period, adopting households increased their annual consumption expenditures by 15,841 Rs. on average, or 345 US$. Compared to non-adopters, this implies a net increase in household expenditures by 18%. These results clearly underline that Bt cotton has significantly increased living standards of smallholder farm households in India.

5. Conclusions

We have analyzed the impacts of Bt technology on cotton yields, profits, and household living standards in India, using much more comprehensive data than previous studies. Our panel data covers four states of India, where surveys were implemented in four waves between 2002 and 2008. These unique panel data have also enabled us to analyze impact developments over time. Moreover, using econometric models with household fixed effects we have controlled for selection bias, which was rarely done in previous research on Bt cotton and other GM crops.

The results show that Bt adoption has positive and significant net impacts. The technology has increased per acre cotton yields and profits by 24% and 50%, respectively. These effects have been stable over time, suggesting that potential problems of Bt resistance development or secondary pest outbreaks have not yet occurred in India at a significant scale. Robustness checks indicate that the benefits in terms of yields and profits may even have increased over time. This could be explained by additional Bt events that were released after 2005 and a growing number of different Bt varieties, adjusted to diverse agroecological conditions. The overall benefits increased in any case, because of the rising Bt cotton adoption rates in India. Countrywide, this technology is now used on almost 90% of the cotton area.

To assess Bt adoption impacts on living standards, we have estimated household level models of consumption expenditures. Results show that Bt did not change consumption behavior during 2002-2004 (in spite of the gains in profit), but it did increase consumption significantly in 2006-2008. This is plausible: households with profit gains from a new technology do not change their consumption behavior immediately, but wait for a while until they know that the profit gains are sustainable. In 2006-2008, each acre of Bt cotton increased household consumption expenditures by 62 US$. Extrapolating to the average Bt cotton area per adopting farm household, the increase in expenditure is 345 US$. This implies an 18% average improvement in living standards. Extrapolating to the total Indian Bt cotton area in 2010, which was 23 million acres, the aggregate annual gain in living standards is equivalent to 1.43 billion US$. These are large benefits that spur economic development in the small farm sector and beyond. Subramanian and Qaim (2010) showed that there are additional indirect gains of sizeable magnitude also for other rural sectors and landless households through labor market effects and production and consumption linkages.

Our findings of large and sustainable economic benefits of Bt cotton do not imply that impacts may not change in the long run. This should be further observed and analyzed. Sustainable innovation in agriculture always implies that technologies are further improved or replaced by new innovations after some time. But our results clearly refute the concern that Bt technology would harm smallholder farmers due to low and/or eroding economic benefits. As Bt cotton is the only GM crop technology that is already widely used by smallholder farmers, these findings also add to the wider public biotech debate.

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Figure 1: Cotton seed and output prices in the sample

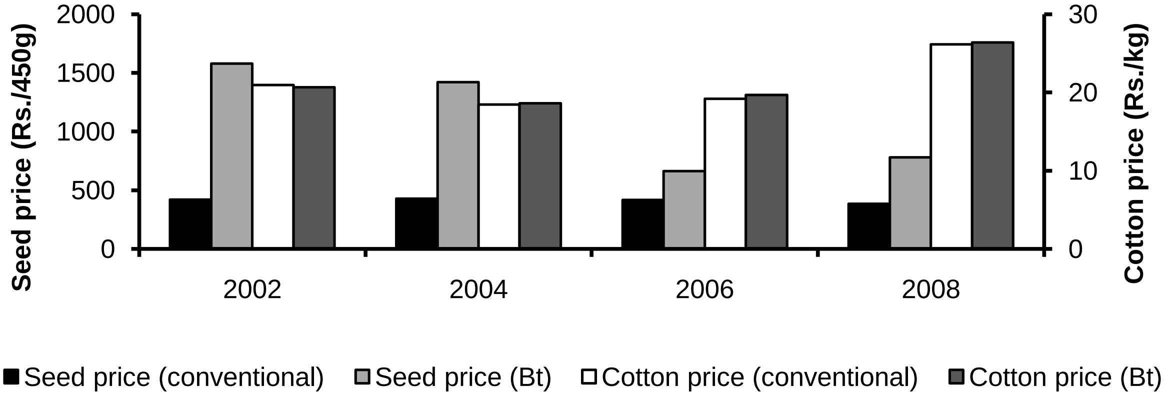

Figure 2: Bt cotton adoption and adoption intensity in the sample

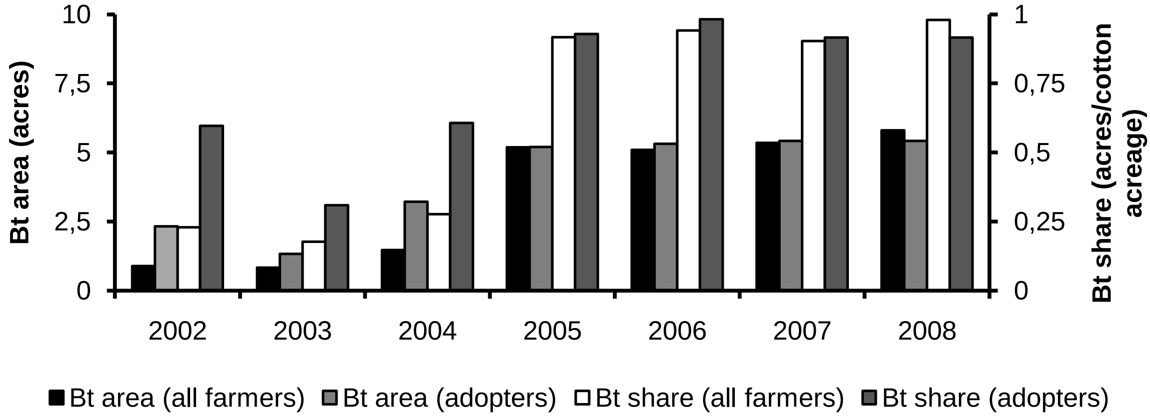

Table 1
Descriptive statistics for 1655 plots and 533 associated households (averages for 2002-2004 and 2006-2008)

	2002-2004		2006-2008	
	Conventional	Bt	Conventional	Bt
Plot level information				
Seed cost (Rs./acre)	508.57 (264.53)	1,601.39*** (428.54)	471.97 (205.47)	906.52*** (316.18)
Seed rate (g/acre)	659.82*** (552.39)	490.72 (114.23)	646.64*** (474.33)	570.75 (160.93)
Irrigation (share of plots)	0.46 (0.50)	0.58*** (0.49)	0.48 (0.50)	0.59* (0.49)
Fertilizer (t/acre)	0.23 (0.15)	0.26*** (0.16)	0.20 (0.10)	0.25*** (0.15)
Pesticide (1,000 Rs./acre)	2.27*** (1.80)	1.43 (1.57)	1.07 (1.21)	1.07 (1.38)
Labor (days/acre)	70.72 (32.30)	83.23*** (40.81)	63.12 (35.74)	69.75 (44.67)
Yield (kg/acre)	520.64 (315.54)	705.40*** (360.41)	588.85 (318.66)	829.03*** (341.08)
Cotton price (Rs./kg)	19.67 (3.06)	19.52 (2.69)	20.07 (4.87)	23.31*** (4.05)
Revenue (Rs./acre)	10,217.06 (6,358.94)	13,793.54*** (7,321.94)	12,409.93 (7,478.19)	19,348.32*** (8,416.34)
Total cost (Rs./acre)	6,621.19 (3,071.32)	7,651.07*** (2,938.14)	7,101.95 (3,342.52)	9,029.41*** (5,117.47)
Profit (Rs./acre)	3,595.87 (5,802.60)	6,142.45*** (6,889.74)	5,307.98 (6,801.66)	10,318.90*** (7,727.07)
Number of plots	601	298	64	692
Household level information				
Age of farmer (years)	44.24 (12.49)	44.43 (12.47)	48.14** (12.52)	45.18 (12.67)
Education of farmer (years)	7.29 (4.97)	8.04** (4.81)	4.73 (5.08)	7.32*** (5.15)
Land owned (acres)	13.25 (15.45)	15.07* (18.42)	11.48 (12.28)	11.61 (12.68)
Cotton area (acres)	6.99 (37.12)	6.20 (6.73)	4.42 (4.51)	5.79** (4.60)
Household size (head)	6.46 (3.46)	6.75 (3.80)	6.59 (3.38)	6.28 (4.07)
Household expenditures (Rs./year)	85,867.39 (71,006.22)	122,762.00*** (79,001.87)	87,903.07 (64,142.21)	90,425.77 (88,823.94)
Number of households	363	222	61	432

*, **, *** implies that the mean value is significantly bigger than that of conventional/Bt in the same time period at the 10%, 5%, and 1% level, respectively.
Notes: Mean values are shown with standard deviations in parentheses. Household expenditures were deflated using the consumer price index.
Rs. means Indian Rupees.

Table 2
Number of Bt cotton variety approvals and suppliers, by event (2002-2008)

Event (source)	Year approved	Number of variety approvals (suppliers)						
		2002	2003	2004	2005	2006	2007	2008
MON 531 (Monsanto, Bollgard I)	2002	3 (1)		1 (1)	16 (4)	24 (11)	56 (22)	43 (13)
MON 15985 (Monsanto, Bollgard II)	2006					7 (3)	13 (6)	73 (19)
Event 1 (IIT, Kharangpur)	2006					8 (5)	4 (2)	7 (1)
GFM Cry1A (Chinese Academy of Sciences)	2006					3 (1)	3 (3)	17 (6)
Dharwad Event (UAS, Dharwad)	2008							1 (1)
Cumulated number of approved varieties (suppliers)		3 (1)	3 (1)	4 (2)	20 (4)	62 (15)	138 (27)	281 (37)

Source: compiled from Karihaloo and Kumar (2009) and Indian GMO Research Information System
Note: Only original approvals are included, that is, renewals of approvals were not counted.

Table 3
Estimated coefficients of the quadratic production function

	Pooled data model	Fixed effects models	
	(1)	(2)	(3)
Inputs			
Bt	156.46*** (21.85)	125.90*** (20.41)	116.91*** (20.68)
Bt 2006-2008	31.62 (44.79)	3.59 (43.46)	180.06*** (20.54)
Seed rate (g/acre)	0.54** (0.02)	-0.004 (0.03)	-0.01 (0.03)
Sow date (days)	0.23 (0.40)	-0.85** (0.42)	-0.86** (0.44)
Harvest date (days)	1.16*** (0.27)	1.03*** (0.29)	-0.08 (0.25)
Irrigation (yes/no)	139.75*** (15.80)	97.26*** (19.35)	83.00*** (0.00)
Fertilizer (t/acre)	70.61 (135.43)	1.29 (144.01)	-29.08 (149.13)
Square of fertilizer	844.08** (351.59)	558.55 (358.62)	646.46* (371.64)
Pesticide (1,000 Rs./acre)	20.62 (13.17)	1.72 (14.24)	-8.91 (13.58)
Square of pesticide	-1.85 (2.91)	-1.86 (2.94)	-1.52 (3.03)
Labor (days/acre)	4.44*** (0.55)	5.11*** (0.69)	4.83*** (0.72)
Square of labor	-0.01*** (0.003)	-0.02*** (0.01)	-0.01** (0.01)
Fertilizer-pesticide interaction	-72.08*** (27.31)	-35.28 (27.95)	-38.85 (28.97)
Fertilizer-labor interaction	-1.77 (1.22)	-2.91** (1.35)	-3.23** (1.39)
Pesticide-labor interaction	0.14 (0.13)	0.17 (0.14)	0.29** (0.14)
Household characteristics			
Age (years)	-2.34*** (0.65)		
Education (years)	-0.29 (1.55)		
Cotton experience (years)	0.62 (0.91)		
Karnataka [a]	-9.89 (20.64)		
Andhra Pradesh [a]	19.43 (20.87)		
Tamil Nadu [a]	-193.54*** (40.79)		
2004 [b]	103.94*** (19.91)	125.39*** (17.68)	
2006 [b]	235.41*** (41.42)	297.03*** (40.53)	
2008 [b]	128.01*** (44.64)	208.61*** (43.68)	
Constant	-130.12 (82.19)	-104.19 (83.07)	287.23*** (69.10)
Number of observations	1648	1648	1648
R^2	0.38	0.39	0.34
Hausman test		90.47***	70.00***

*, **, *** Coefficient is statistically significant at the 10%, 5%, and 1% level, respectively.
Notes: The dependent variable is yield in kg per acre. Coefficient estimates are shown with standard errors in parentheses.
[a] The base state is Maharashtra. [b] The base year is 2002.

Table 4
Estimated coefficients of the quadratic profit function

	Pooled data model	Fixed effects models	
	(1)	(2)	(3)
Inputs			
Bt	1,595.67* (847.63)	1,877.21** (889.16)	2,151.51** (893.33)
Bt 2006-2008	1,485.88 (1,087.64)	-260.45 (1,144.58)	1,736.39** (803.31)
Seed rate (g/acre)	0.72 (0.47)	0.09 (0.63)	-0.07 (0.63)
Sow date (days)	-4.56 (8.47)	-18.37* (9.59)	-19.92** (9.72)
Harvest date (days)	14.26** (5.73)	13.72** (6.73)	-2.36 (6.15)
Irrigation (yes/no)	2,922.27*** (318.20)	2,087.24*** (439.54)	2,027.25*** (442.23)
Seed price (Rs./450g)	0.71 (0.70)	0.16 (0.76)	-0.35 (0.76)
Cotton price (Rs./kg)	812.81*** (64.91)	814.17*** (71.21)	615.53*** (53.88)
Fertilizer price (Rs./kg)	-286.88*** (90.49)	-361.04*** (98.40)	-340.12*** (99.74)
Square of fertilizer price	6.37*** (1.98)	8.39*** (2.21)	7.58*** (2.24)
Pesticide price (Rs./liter)	0.60 (0.43)	0.05 (0.48)	0.53 (0.47)
Square of pesticide price	0.0001 (0.0001)	0.0002* (0.0001)	0.0001 (0.0001)
Wage rate (Rs./hour)	138.38 (136.08)	-74.12 (152.33)	230.42 (145.12)
Square of wage rate	-10.50* (6.00)	-3.27 (9.37)	-23.84*** (8.84)
Fertilizer-pesticide price interaction	-0.10*** (0.02)	-0.09*** (0.02)	-0.09*** (0.02)
Fertilizer-labor price interaction	18.45 (13.78)	3.20 (15.66)	7.45 (15.83)
Pesticide-labor price interaction	-0.01 (0.03)	0.02 (0.04)	-0.00004 (0.04)
Variable cost			
Household characteristics			
Age	-45.37*** (13.71)		
Education (years)	5.43 (32.59)		
Cotton experience (years)	2.12 (19.25)		
Karnataka [a]	997.04** (428.77)		
Andhra Pradesh [a]	-757.56* (412.86)		
Tamil Nadu [a]	-2,331.92*** (825.00)		
2004 [b]	1,454.26*** (464.90)	2,066.07*** (466.18)	
2006 [b]	2,093.82** (933.78)	5,006.86*** (1,017.09)	
2008 [b]	-1,389.82 (1,064.79)	2,332.61** (1,149.50)	
Constant	-15,530.24*** (2,276.21)	-14,554.41*** (2,268.62)	-6,492.66*** (1,676.44)
Number of observations	1648	1648	1648
R^2	0.35	0.38	0.36
Hausman test		42.39***	24.60**

*, **, *** Coefficient is statistically significant at the 10%, 5%, and 1% level, respectively.
Notes: The dependent variable is profit in Rs. per acre. Coefficient estimates are shown with standard errors in parentheses.
[a] The base state is Maharashtra. [b] The base year is 2002.

Table 5
Estimated coefficients of the household expenditure function

	Pooled data model	Fixed effects model
	(1)	(2)
Bt area (acres)	2,636.22*** (925.83)	197.65 (1,227.07)
Bt area 2006-2008 (acres)	428.85 (973.06)	2,825.65** (1,196.64)
Cotton area (acres)	104.81 (69.19)	41.55 (74.10)
Cultivated area (acres)	1,374.32*** (147.68)	1,123.82*** (229.72)
Household size (AE)	13,735,91*** (807.15)	9,255.51*** (1,259.57)
Age	564.98*** (134.82)	
Education (years)	1,832.08*** (344.70)	
Karnataka [a]	-2,048.50 (4,211.89)	
Andhra Pradesh [a]	35,430.50*** (4,283.91)	
Tamil Nadu [a]	39,745.87*** (7,346.99)	
2004 [b]	14,234.28*** (4,556.09)	19,433.01*** (4,543.11)
2006 [b]	-406.97 (5,179.06)	1,257.58 (5,653.66)
2008 [b]	3,957.18 (5,237.25)	9,250.43 (5,937.91)
Constant	-58,234.18*** (8,787.57)	15,250.02** (6,663.66)
Number of observations	1431	1431
R^2	0.43	0.17
Hausman test		35.50***

*, **, *** Coefficient is statistically significant at the 10%, 5%, and 1% level, respectively.
Notes: The dependent variable is household expenditure in Rs. per year. Coefficient estimates are shown with standard errors in parentheses. AE means adult equivalent. The modified OECD scale is used: the first adult is weighed by a factor of one, each additional adult (child under 14) is weighed by 0.5 (0.3).
[a] The base state is Maharashtra. [b] The base year is 2002.