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Analysis

Impact of Bt cotton on pesticide poisoning in smallholder agriculture: A panel data analysis

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ABSTRACT

While substantial research on the productivity and profit effects of Bt cotton has been carried out recently, the economic evaluation of positive and negative externalities has received much less attention. Here, we focus on farmer health impacts resulting from Bt-related changes in chemical pesticide use. Previous studies have documented that Bt cotton has reduced the problem of pesticide poisoning in developing countries, but they have failed to account for unobserved heterogeneity between technology adopters and non-adopters. We use unique panel survey data from India to estimate unbiased effects and their developments over time. Bt cotton has reduced pesticide applications by 50%, with the largest reductions of 70% occurring in the most toxic types of chemicals. Results of fixed-effects Poisson models confirm that Bt has notably reduced the incidence of acute pesticide poisoning among cotton growers. These effects have become more pronounced with increasing technology adoption rates. Bt cotton now helps to avoid several million cases of pesticide poisoning in India every year, which also entails sizeable health cost savings.

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1. Introduction

Bt cotton is a genetically modified (GM) crop that contains genes from the soil bacterium *Bacillus thuringiensis*. These Bt genes make the plant resistant to certain insect pests, especially the cotton bollworm and related species, which are very damaging in many cotton-growing regions of the world and are responsible for intense chemical pesticide applications (Zehr, 2010). The inbuilt resistance in Bt cotton could potentially reduce both pest damage and the use of chemical pesticides. Bt cotton was developed by the US company Monsanto and first commercialized in the mid-1990s. Since then, this technology has been widely adopted in different developed and developing countries (James, 2010). Empirical evidence from various countries confirms that Bt cotton has allowed remarkable pesticide savings (Ali and Abdulai, 2010; Bennett et al., 2005; Falck-Zepeda et al., 2000; Morse et al., 2004; Pray et al., 2002; Qaim and de Janvry, 2005; Qaim et al., 2006; Traxler and Godoy-Avila, 2004). This is beneficial for farmers from an economic perspective, but lower pesticide use can also entail important environmental and health advantages (Travisi and Nijkamp, 2008; Travisi et al., 2006; Zilberman et al., 1991).

However, there are also studies that point at negative environmental externalities of Bt cotton, including unintended effects on non-target organisms and other ecosystem disruptions, which could undermine the technology's sustainability (Andow and Hilbeck, 2004; Gutierrez et al., 2006; Lu et al., 2010; Pemsl et al., 2008). There are also concerns about negative social consequences, especially for smallholder farmers in developing countries (Glover, 2010; Stone, 2011). Hence, Bt cotton is a central part of the broader public controversy about the potentials and risks of GM crops and appropriate regulatory approaches (Krishna and Qaim, 2007; Kvakkestad and Vatn, 2011; Séralini et al., 2007; Soleri et al., 2008). More research is needed to better understand impacts and impact dynamics under different conditions, including indirect effects and externalities.

While potential positive and negative externalities of GM crops are generally acknowledged, surprisingly little attempt has been made to quantify them from an economic perspective (Qaim, 2009). This article focuses on one potential positive externality of Bt cotton, namely the farmer health benefits that may result from pesticide savings. Especially in the small farm sector of developing countries, where highly toxic pesticides are usually applied manually with little or no protective clothing, acute pesticide poisonings are commonplace and can involve high social costs (Jeyaratnam, 1990; Soares and Porto, 2009). This is particularly true in cotton, because of the high amounts of pesticides commonly used in this crop (Maumbe and Swinton, 2003).

A few studies have documented that Bt cotton adoption has reduced pesticide-induced health risks. For instance, using farm survey data and descriptive statistics, Pray et al. (2002) and Huang et al. (2003) showed that Bt cotton adopters in China suffered less often from pesticide poisoning than non-adopters. Bennett et al. (2003) used a similar approach in South Africa, where they also found fewer cases of pesticide poisoning among Bt cotton adopters. However, only comparing Bt and

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non-Bt farmers without controlling for other factors does not allow conclusive statements about the net effects of Bt technology. Hossain et al. (2004) went further and estimated an econometric model, confirming the positive health effects of Bt cotton in China. But they did not control for unobserved heterogeneity between Bt adopters and non-adopters, which can lead to non-random selection bias in impact assessment. Moreover, their econometric analysis is based on cross-sectional survey data, so that potential impact dynamics could not be evaluated. Such dynamics may be important for two reasons. First, the effectiveness of Bt technology may potentially change over time, due to possible resistance development in pest populations or other factors (Frisvold and Reeves, 2008). Second, technology adoption is a learning process, so that farmers' perceptions and behavior may also change, which is particularly true during the early stages of technological diffusion (Marra et al., 2003).

This article contributes to the literature by controlling for non-random selection bias and analyzing impacts of Bt cotton on pesticide poisoning over time. In particular, we use unique panel data from India, which we collected in four rounds between 2002 and 2008, and estimate two-way fixed-effects models of pesticide use and the incidence of acute poisoning. India is a particularly interesting example, because it is now the world's biggest producer of Bt cotton and the crop is predominantly grown by smallholder farmers (Choudhary and Gaur, 2010). Moreover, many of the controversies about the social impacts of GM crops in developing countries relate to Bt cotton in India (Glover, 2010; Gruere and Sengupta, 2011; Stone, 2011; Subramanian and Qaim, 2010).

The remainder of this article is organized as follows: the next section provides a brief background on Bt cotton in India and describes the data collection procedure and the modeling approach to evaluate the health impact of Bt cotton adoption. Section 3 presents descriptive analyses before discussing the estimation results on impact and impact dynamics. The last section concludes.

2. Material and methods

2.1. Background on Bt cotton in India

Bt cotton was commercially approved in India for the first time in 2002. Monsanto had collaborated with the Indian seed company Mahyco, in order to adjust the technology to Indian conditions and incorporate it in local cotton varieties. Later, it was also sublicensed to a number of other Indian seed companies (Choudhary and Gaur, 2010; Sadashivappa and Qaim, 2009). Sold under the brand name Bollgard I, Bt cotton contains the Cry1Ac gene that provides resistance against American bollworm (*Helicoverpa armigera*), spotted bollworm (*Earias vittella*), and pink bollworm (*Pectinophora gossypiella*). In 2006, Bollgard II technology with stacked Cry1Ac and Cry2Ab Bt genes and a wider spectrum of target pests was also approved and has become increasingly popular since then. India is now the worlds' biggest producer of Bt cotton, with an estimated area of 23.2 million acres under this technology in 2010 – almost 90% of the total national cotton area (James, 2010). Several studies have examined agronomic, economic, and social effects of Bt cotton in India. Most of them demonstrate sizeable benefits for smallholder farmers and other rural households (Bennett et al., 2005; Choudhary and Gaur, 2010; Crost et al., 2007; Qaim et al., 2006; Sadashivappa and Qaim, 2009; Subramanian and Qaim, 2010), although there are also some studies that discuss possible negative social implications (Glover, 2010; Stone, 2011).[1] There is little work available that has looked into environmental and health externalities of Bt cotton in India.

2.2. The survey data

In order to analyze the health impact of Bt cotton adoption, we carried out a panel survey of Indian cotton farmers in four rounds between 2002 and 2008. We used a multistage sampling procedure. At first, four states were purposely selected, namely Maharashtra, Karnataka, Andhra Pradesh, and Tamil Nadu. These four states cover a wide range of different cotton-growing situations, and they produce 60% of all cotton in central and southern India (Cotton Association of India, 2008). In 2002, Bt cotton was only approved for central and southern India, so that we did not include northern states. In northern India, Bt cotton was commercialized in later years.

In the four states, we randomly selected 10 cotton-growing districts and 58 villages, using a combination of census data and agricultural production statistics. Within each village, we randomly selected farm households from complete lists of cotton producers that were provided by the village heads. In total, 341 farmers were sampled in 2002. As the number of Bt adopters was very low in the first year of commercial technology approval, we stratified by adopters and non-adopters and deliberately over-sampled adopters. This was important to have sufficient observations in each group for reliable comparisons within that first year. Thus, technology adoption rates for 2002 are not representative, but the subsamples of Bt adopters and non-adopters are representative for cotton producers in central and southern India (Qaim et al., 2006; Subramanian and Qaim, 2010). Comparison with secondary data on Bt cotton diffusion (Choudhary and Gaur, 2010; James, 2010) shows that adoption rates in our sample converged with actual state-wise adoption rates in later years. Farmers in the sample are predominantly resource-poor smallholders with average farm sizes of less than 10 acres.

The first-round survey interviews took place in early 2003, shortly after the cotton harvest for the 2002 season was completed. Using a specially-designed structured questionnaire, sample farmers were asked to provide a wide array of agronomic and socioeconomic information, including input-output details on their cotton plots. Particular emphasis was placed on capturing details on pesticide use in a disaggregated way. Farmers who grew Bt and non-Bt cotton simultaneously, provided details for both alternatives, so that the number of plot observations is somewhat larger than the number of farmers surveyed. In addition, farmers were asked about acute health problems that they had faced in connection with pesticide sprays in cotton during the last growing season. In particular, they were asked about the frequency and type of pesticide-related poisonings, such as skin and eye irritation, breathing problems, nausea, faintness, and other symptoms.[2] Moreover, those farmers that suffered from poisoning symptoms reported the health costs associated with each case, including treatment costs, travel costs to see a physician, and the opportunity cost of time for lost labor days. It should be noted that our approach only captures acute poisoning symptoms. Chronic diseases that may result from long-term and repeated exposure to pesticides (Pingali et al., 1994) are not considered, which may lead to an underestimation of the overall health costs of pesticide use.

The same survey was repeated at 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). In these follow-up rounds, the same questionnaire with only very slight adjustments was used for the interviews. To our knowledge, this is the only longer-term panel survey of Bt cotton farmers in a developing country.

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[1] There are also reports by biotech critics that Bt cotton ruins smallholder farmers in India. However, such reports do not build on representative data. Gruere and Sengupta (2011) showed that the occasional claim of a link between Bt cotton adoption and farmer suicides cannot be substantiated.

[2] The concrete symptoms asked for in the questionnaire were skin irritation, eye irritation, nausea, stomach pain, diarrhea, breathlessness, coughing, other respiratory problems, fever, general weakness, sleeplessness, and other symptoms to be specified. The same types of symptoms were also covered in previous studies related to pesticide poisoning (e.g., Huang et al., 2003; Krishna and Qaim, 2008; Maumbe and Swinton, 2003).

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To some extent, sample attrition occurred in subsequent rounds, as is normal in panel surveys extending over several years. There are mainly two reasons for the fact that some farmers from the first round could not be included in subsequent rounds. First, several farmers had stopped cotton cultivation during the period, mostly because of focusing on new cash crops. This primarily happened in two districts of Karnataka and Tamil Nadu, where irrigation projects were started and new cash crops promoted. In particular, the establishment of sugar mills in the vicinity provided price incentives for farmers to switch from cotton to sugarcane in the irrigated areas. Second, a few farmers who grew cotton on temporarily leased-in land had migrated to other areas. This occurred especially in one district in Karnataka, where migrant farming is commonplace. Since for robust impact assessment with fixed-effects models a balanced panel is preferred, we dropped observations with missing data for individual years and only kept farmers in the sample with complete information for all four survey rounds. Thus, we remain with a sample of 198 farm observations in each round, or 792 observations over all four rounds. Comparing important socioeconomic variables of this smaller sample with the full sample suggests that the procedure of balancing the panel did not lead to any systematic bias.

2.3. Econometric models

The main purpose of our analysis is to find out whether Bt technology adoption has a significant influence on the frequency of acute pesticide poisoning related to sprays in the cotton crop. As mentioned above, cases of poisoning considered include negative health effects such as skin and eye irritation, breathing problems, nausea, faintness, and other acute symptoms. Since Bt is expected to reduce chemical insecticide use, we hypothesize a lower frequency of acute poisoning among Bt adopters. This is first analyzed with descriptive statistics, before identifying net treatment effects through estimation of econometric models.

In our main modeling approach, we use the farmers' self reported frequency of acute pesticide poisoning per cotton-growing season as dependent variable. Since this is a count variable, a Poisson distribution is assumed. The Poisson panel regression is given by $\mathrm{Pr}ob(Y_{it}=y_{it}|x_{it})=e^{-\lambda_{it}}\lambda_{it}^{y_{it}}/y_{it}!$, where y_{it} is the number of acute pesticide poisoning incidences that varies across individual farmers i and over time t. The Poisson distribution is assumed to have conditional mean λ_{it}, which depends on a vector of exogenous variables. The most common specification of λ_{it} used in the literature is a log-linear model, which can be expressed as (Cameron and Trivedi, 1998):

$$In\lambda_{it} = \beta x_{it} + \gamma z_i + \alpha_i + \mu_t \tag{1}$$

where x_{it} and z_i are vectors of time-variant and time-invariant exogenous variables, with β and γ as the respective vectors of coefficients to be estimated. α_i and μ_t represent unobserved individual and time-specific effects, respectively.

To test whether Bt technology has an influence on the frequency of poisoning, we include different Bt adoption variables as part of the vector x_{it}. Especially during the early years of Bt adoption, many farmers were partial adopters, so that in a first specification we use two dummies – one for complete and the other for partial adopters. However, since partial adoption can only be measured very imprecisely through a dummy, we use the number of acres under Bt cotton in additional specifications, while controlling for the total cotton area per farm. This also allows us to derive the net average impact on pesticide poisoning per acre of Bt, which can be used to extrapolate the India-wide impact by multiplying with the total acreage under Bt cotton technology. To capture developments over time, we differentiate between Bt acreage in two time periods, namely 2002–04 and 2006–08. Furthermore, we include year dummies for the 2004, 2006, and 2008 survey rounds, using 2002 as the reference.

Other time-variant variables that we include are the farmer's age, which is a proxy for experience. Other studies showed that experience may reduce the incidence of poisoning (Asfaw et al., 2010; Maumbe and Swinton, 2003), because experienced farmers are often more aware of pesticide-related risks, which may result in more careful handling. Furthermore, we use a variable that measures the monthly expenditures on smoking as a proxy for the farmers' health awareness and health status. Smoking habits were shown to be relevant in previous studies in explaining cases of acute pesticide poisoning (e.g., Krishna and Qaim, 2008). A gender dummy for the person who sprayed is not included, because in India pesticides are almost exclusively sprayed by men. But we use a dummy that captures whether spraying operations are carried out by farmers themselves (including other members of the farm family) or by hired laborers. When employing hired laborers for spraying, farmers' reported cases of poisoning are expected to be lower.[3]

The only time-invariant variable that we include is the farmer's education, measured in years of formal schooling, which is expected to have a reducing effect on the incidence of poisoning (Hossain et al., 2004). Other authors have used participation in special training programs for pest control to capture relevant knowledge more precisely (Maumbe and Swinton, 2003), but since such training programs do hardly exist in India, this is not relevant in our context.

Eq. (1) can be estimated with a random-effects panel estimator. However, if an unobserved individual-specific effect is correlated with the incidence of pesticide poisoning as well as with one or more of the explanatory variables; the estimates of the associated parameter will be biased. In our context, Bt adoption is likely to be an endogenous regressor that partly depends on unobserved variables. In that case, the estimated Bt treatment effect would suffer from systematic selection bias. This can be overcome by using a fixed-effects (FE) estimator. Including year dummies leads to a two-way FE model. FE models have recently been used to control for selection bias in different contexts (e.g., Crost et al., 2007; Jorgenson and Birkholz, 2010).

When estimating the Poisson model in Eq. (1) with FE, the α_i are unobserved individual specific effects that are perfectly collinear with z_i. One way to resolve this issue is to estimate a conventional Poisson regression with maximum likelihood, including dummy variables for all individuals (less one). Another possibility is to eliminate α_i by conditioning on the total count $\sum_t y_{it}$ for each individual, which requires fully parametric assumptions as proposed by Andersen (1970). These two estimation methods – unconditional maximization of the likelihood and conditional likelihood – always yield identical estimates for the β coefficients and associated covariance matrices (Cameron and Trivedi, 1998). We use the conditional maximum likelihood method for our estimates.

In addition to the Poisson model to explain the incidence of pesticide poisoning, we also estimate a linear pesticide use model in order to analyze the Bt adoption effect on pesticide quantity as follows:

$$q_{it} = c + \sigma x_{it} + \varphi p_{it} + \eta_i + \rho_t + \upsilon_{it} \tag{2}$$

where q_{it} is pesticide quantity applied by farmer i in year t, measured in terms of kilograms of formulated chemical used on the farm's total cotton acreage, x_{it} includes the same set of time-variant variables as

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[3] Even though we had asked survey respondents to report all cases of pesticide poisoning, it is likely that cases that occurred among farmers themselves or family members were reported more accurately than those that occurred among hired laborers. In the multi-location panel survey it was impossible to verify the information obtained with all hired laborers employed for spraying by sample farmers.

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Table 1
Descriptive statistics.

Variables	Bt		Non-Bt	
	Mean	Stand. dev.	Mean	Stand. dev.
	Plot level information (n = 864)			
Pesticide quantity (kg/acre)	1.28***	1.61	3.54	3.34
Hazard category I (kg/acre)	0.49***	0.86	1.57	2.24
Hazard category II (kg/acre)	0.74***	1.20	1.85	2.24
Hazard category III (kg/acre)	0.02	0.10	0.02	0.16
Hazard category IV (kg/acre)	0.04*	0.16	0.10	0.69
Number of pesticide sprays per acre	1.52***	1.99	2.22	3.15
Pesticide cost (Rs/acre)	1059.23***	1323.67	2038.77	1767.26
	Farm level information (n = 792)			
Number of acute pesticide poisonings during last cotton season	0.19***	0.68	1.60	1.48
Age (years)	47.93***	12.59	43.46	12.65
Education (years)	8.28	4.58	7.92	4.73
Total cotton area (acres)	5.95	5.35	5.70	5.47
Self spray dummy	0.38***	-	0.78	-
Monthly expenditures on smoking (Rs)	250.58***	1833.52	889.39	2780.58

***, ** and * indicate that the mean values between Bt and non-Bt observations are significantly different at 1%, 5%, and 10%, respectively.
Notes: *t*-tests are used for continuous and chi-square tests for categorical variables to identify differences in mean values. Plot level information is based on 864 observations, out of which 538 are Bt and 326 non-Bt plots. Farm level information is based on 792 observations, out of which 407 are Bt and 385 non-Bt farms.

explained above, and p_{it} is pesticide price, measured in Indian Rupees (Rs) per kg. p_{it} is calculated as the weighted average price of the different products used on a particular farm in a given year. Since the demand for pesticides is expected to be price responsive, including p_{it} as a regressor is a common approach in pesticide use models (Hossain et al., 2004; Huang et al., 2002; Qaim and de Janvry, 2005). σ and φ are coefficients to be estimated, and c, η_i, ρ_t, and υ_{it} are intercept, unobserved individual-specific effects, unobserved time-specific effects, and random error term, respectively. As Bt is an endogenous variable, we use an FE estimator to obtain unbiased treatment effects.

3. Results and discussion

3.1. Descriptive analysis

Descriptive statistics for the variables of interest are presented in Table 1, differentiated by Bt and non-Bt cotton. In this table, the data are pooled for all four survey rounds. The upper part of the table shows plot level details per acre of cotton. As mentioned above, because some farmers had both Bt and non-Bt plots, especially during the early stages of the technology diffusion process, the number of plot observations is larger than the number of farmers surveyed. Comparison reveals that farmers use significantly lower pesticide quantities on Bt than on non-Bt plots. This is further analyzed in Fig. 1, which illustrates that lower pesticide quantities on Bt plots are not only observed on an average but along the entire variable distribution. A Kolmogorov-Smirnov test confirms that the two distribution functions are significantly different with $p<0.01$. These results suggest that the technology is effective in reducing bollworm populations, so that the need for chemical pest control diminishes on Bt cotton plots.

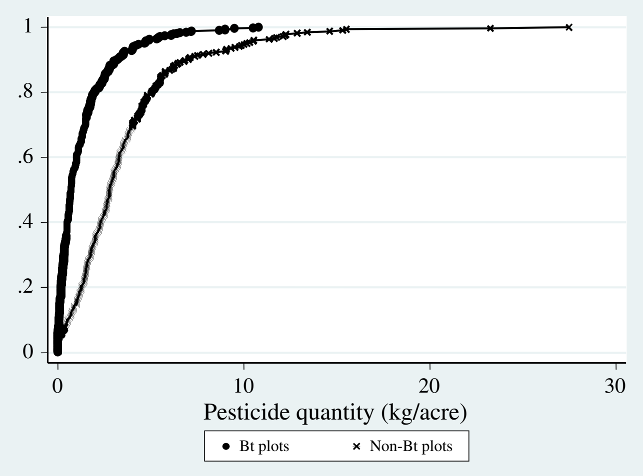

Fig. 1. Cumulative distribution of pesticide quantity used on Bt and non-Bt cotton plots.

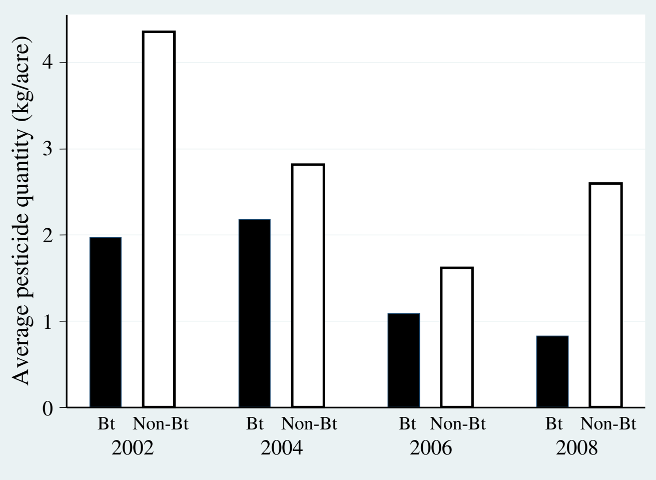

Fig. 2. Average pesticide quantity used on Bt and non-Bt cotton plots.

Fig. 2 further disaggregates the pesticide use data by growing season. In all four seasons, lower quantities of pesticides were used on Bt than on non-Bt plots. It is also interesting to observe that chemical pesticide use declined over time, which holds true for both Bt and non-Bt plots. This is probably due to area-wide suppression of bollworms as a result of the widespread adoption of Bt cotton technology, which benefits both Bt adopters and non-adopters (Sadashivappa and Qaim, 2009). The same effect was also observed for Bt crops in China and the USA (Hutchinson et al., 2010; Wu et al., 2008). Declining pesticide use also suggests that Bt resistance development has not yet become an issue of practical relevance in India.[4] Variations in the differences in pesticide use between Bt and non-Bt plots over time can partly be explained by seasonal variations in sucking pests, such as mirids, mealy bugs, aphids, and jassids, which are not controlled by the Bt toxins.

In Table 1, pesticide quantities are further subdivided into four groups according to the recently revised World Health Organization (WHO) criteria for acute toxicity hazard (WHO, 2010). On Bt plots, significantly lower quantities of hazard category I (extremely hazardous) and II (moderately hazardous) pesticides are used. No difference between Bt and non-Bt plots is observed for hazard category III (slightly hazardous) pesticides, and the difference for hazard category IV (unlikely to present acute hazard) pesticides is relatively small. This pattern suggests that the largest Bt-related reductions occur in the most toxic pesticides, which is consistent with previous studies in India and elsewhere (Qaim and de Janvry, 2005; Qaim and Zilberman, 2003). Table 1 also shows significantly fewer sprays and lower pesticide costs on Bt than on non-Bt plots.

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[4] It should be noted that Monsanto reported in a press release in 2009 that they had detected lower susceptibility of pink bollworm to Bollgard I in four districts of Gujarat. However, this was not reported outside these four districts. No resistance to Bollgard II has yet been detected in India.

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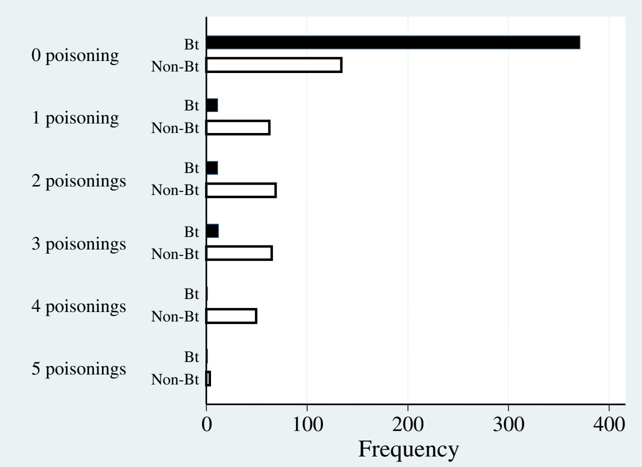

Fig. 3. Frequency of the incidence of acute pesticide poisoning among Bt and non-Bt farmers ($\chi^2 = 274.78^{***}$).

Table 2
Random and fixed-effects Poisson regression models for acute pesticide poisoning incidences.

Variables	(1) Random effects	(2) Random effects	(3) Fixed effects	(4) Fixed effects
Pesticide quantity (kg)	0.008***	-	-	-
	(0.002)	-	-	-
Complete Bt adoption dummy	-	−1.796***	−1.209***	−0.813***
	-	(0.133)	(0.183)	(0.203)
Partial Bt adoption dummy	-	0.084	0.230*	0.277**
	-	(0.100)	(0.136)	(0.137)
Age (years)	−0.021***	−0.008*	−0.234***	-
	(0.005)	(0.005)	(0.034)	-
Education (years)	−0.004	0.003	-	-
	(0.013)	(0.012)	-	-
Self spray dummy	1.336***	0.798***	1.064***	0.994***
	(0.116)	(0.124)	(0.171)	(0.173)
Monthly expenditures on smoking (Rs)	0.0001***	0.00003**	−0.00001	0.00001
	(0.00001)	(0.00001)	(0.00002)	(0.00002)
2004 dummy	-	-	-	−0.180**
	-	-	-	(0.0896)
2006 dummy	-	-	-	−1.399***
				(0.195)
2008 dummy	-	-	-	−1.835***
	-	-	-	(0.309)
Constant	−0.267	0.080	-	-
	(0.313)	(0.291)	-	-
Number of observations	791	791	679	679
Log likelihood	−985.74	−860.51	−381.82	−369.74
Wald χ^2	234.52	348.57	323.35	308.74
Prob > χ^2	0.00	0.00	0.00	0.00

***, ** and * indicate significance at 1%, 5%, and 10%, respectively.
Note: Coefficient estimates are shown with standard errors in parentheses.

In the lower part of Table 1, differentiation is made between Bt and non-Bt farms, because not all variables of interest can be expressed at the plot level. Of particular interest here is the number of acute pesticide poisoning incidences. On average, only 0.19 poisoning cases per cotton season were reported by Bt farmers, as compared to 1.60 cases by non-Bt farmers. This difference is highly significant. Fig. 3 shows that the majority of Bt farmers reported no poisoning incidences, whereas non-Bt farmers have a significantly higher frequency for each count of pesticide poisonings. On average, each case of poisoning entails a health cost of 264 Rs (5.7 US$), including 172 Rs for medical treatment and travel costs, and 92 Rs for lost labor time due to sickness.

The remaining variables in Table 1 show that Bt farmers are older on average than non-Bt farmers, but there are no significant differences in terms of educational levels and total cotton area. The share of Bt farmers who spray pesticides themselves is lower than the share of non-Bt farmers. Bt farmers also spend significantly less on smoking.

3.2. Econometric analysis

3.2.1. General impacts of Bt cotton

In order to study the determinants of acute pesticide poisoning incidences more carefully, we use the panel data to estimate different econometric models, as elaborated in Section 2.3. Since the incidence of poisoning is expected to be correlated with the intensity of chemical pesticide use, we start with a simple random-effects Poisson model, using pesticide quantity next to other explanatory variables, but excluding Bt. As the number of poisoning incidences in cotton is measured per farm and not per plot, the pesticide quantity variable also refers to the total cotton acreage on the farm. Results of this model are shown in column (1) of Table 2. Indeed, pesticide quantity used has a positive and highly significant impact on the incidence of farmer pesticide poisoning.

Other significant variables in this model include the farmer's age, the self spray dummy, and monthly expenditures on smoking. Age has a negative effect, implying that older farmers suffer fewer problems of pesticide poisoning. As mentioned, this can probably be explained through more experience in farming and pest control (Asfaw et al., 2010). The positive effect of the self spray dummy is also not surprising. All other things equal, the coefficient indicates that farmers who spray pesticides themselves reported 1.3 poisoning cases more per season than farmers who employ hired laborers for spraying. Monthly expenditures on smoking are positively correlated with the poisoning incidence. Smokers are generally less health-conscious than non-smokers, so that the effect is as expected. In addition, heavy smokers are also likely to smoke during spraying operations, which increases the risk of inhaling toxic pesticide dust. These effects are in line with findings by Krishna and Qaim (2008).

Since the descriptive analysis has shown that Bt adoption is associated with lower pesticide use, in a second model we replace the pesticide quantity variable with two Bt adoption dummies, one for farmers who completely adopted Bt on their total cotton area and the other for partial Bt adopters. Results are shown in column (2) of Table 2. On average, complete adopters experience 1.8 fewer cases of pesticide poisoning per season than non-adopters. This is a large effect, which corroborates our expectation of significant positive Bt health impacts. On the other hand, the effect of partial adoption is insignificant. Partial adoption was observed especially in the early years of technological diffusion, when Bt areas were still relatively small on many farms.

Next we test whether there is correlation of unobserved variables with any regressor in our model, which could lead to a systematic bias. As Crost et al. (2007) argued, Bt adoption in particular may be influenced by unobserved variables, which can cause selectivity problems in the Bt coefficient estimates. A Hausman test is employed to test the null hypothesis of zero correlation. The resulting test statistic of 59.04 is highly significant with $p<0.01$, implying that the null hypothesis has to be rejected. Hence, we conclude that the FE specification is more appropriate for our data. Column (3) in Table 2 shows the estimation results with a FE specification, where education as the only time-invariant variable is dropped. The coefficient of the complete Bt adoption dummy remains negative and highly significant, but, with 1.2 fewer cases of poisoning, it is smaller in absolute terms than it was in column (2). The difference suggests that non-random selection problems led to an upward bias in the absolute coefficient value in column (2), which is now controlled for in column (3). Against this background, we continue our econometric analyses using FE estimators.

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Table 3
Fixed-effects Poisson regression models for acute pesticide poisoning incidences.

Variables	(1)	(2)	(3)
Bt cotton area (acres)	-0.045^{*}	-	-
	(0.026)	-	-
Bt cotton area in 2002–04 (acres)	-	0.021	0.042
	-	(0.039)	(0.041)
Bt cotton area in 2006–08 (acres)	-	-0.104^{**}	-0.388^{***}
		(0.041)	(0.036)
Total cotton area (acres)	0.008	0.008	0.007
	(0.015)	(0.015)	(0.015)
Self spray dummy	0.995^{***}	1.034^{***}	1.294^{***}
	(0.170)	(0.173)	(0.169)
Monthly expenditures on smoking (Rs)	−0.000002	0.000003	0.00003^{**}
	(0.00002)	(0.00002)	(0.00002)
2004 dummy	-0.218^{**}	-0.230^{**}	-
	(0.091)	(0.092)	-
2006 dummy	-1.730^{***}	-1.409^{***}	-
	(0.189)	(0.229)	-
2008 dummy	-2.444^{***}	-2.091^{***}	-
	(0.277)	(0.314)	
Number of observations	679	679	679
Log likelihood	−382.10	−379.01	−409.95
Wald χ^2	308.19	298.62	234.92
Prob > χ^2	0.00	0.00	0.00

***, ** and * indicate significance at 1%, 5% and 10%, respectively.
Note: Coefficient estimates are shown with standard errors in parentheses.

In column (4) of Table 2, we estimate the two-way FE specification, including year dummies for the survey rounds. Since these dummies are highly collinear with the age variable, we dropped age. This is suitable, because in the FE model age measures nothing else but a time effect: the age of each individual farmer simply increases by one every year. The estimation results show that time seems to be an important component, as all three year dummies are highly significant. The negative signs of the dummy coefficients indicate that the incidence of pesticide poisoning has decreased over time. All other things equal, 1.8 fewer cases of poisoning per farm occurred in 2008 than in 2002.

As can also be seen, the negative effect of complete Bt adoption decreases, while the positive effect of partial adoption increases somewhat in comparison to column (3). This is related to the close correlation between adoption and the time dummies: the number of complete adopters increased substantially over time, whereas the number of partial adopters decreased. Such dynamics are further analyzed in the following subsection.

3.2.2. Impact dynamics

So far, we only differentiated between complete and partial Bt adoption, without accounting for the actual area under the technology. Moreover, we implicitly assumed that Bt impact on pesticide poisoning would be constant over the time period considered. We now take a closer look at these aspects through supplementary model specifications. Instead of technology adoption dummies, we employ continuous variables of the Bt cotton area on a farm, measured in acres. We also control for total cotton area, so that the Bt coefficients can be interpreted as the net impact on pesticide poisoning of switching from one acre of non-Bt to one acre of Bt cotton.

We start by using only one Bt area variable. Results are shown in column (1) of Table 3. As expected, the estimated coefficient is negative and significant, but relatively small. Each acre of Bt cotton decreases the incidence of pesticide poisoning by 0.045. In order to analyze whether the effect has changed over time, we use two Bt area variables in column (2), one for the earlier period covering 2002–04, and the second for the later period covering 2006–08. As can be seen, the Bt effect is not significant for 2002–04, but it is negative and highly significant for 2006–08. It is also much higher in absolute magnitude than the combined effect for the whole period that was shown in column (1).

The insignificance of Bt area in the earlier period may be due to the fact that adoption rates were still relatively low: only 9% and 14% of our sample farmers had completely adopted Bt in 2002 and 2004, respectively. The early adopters were likely more knowledgeable farmers who may have suffered less from pesticide poisoning anyway. Indeed, also for the early adoption years, mean value

Table 4
Fixed-effects linear regression models for pesticide use.

Variables	(1)	(2)	(3)	(4)
	Total pesticide quantity	Hazard category I quantity	Hazard category II quantity	Hazard category III + IV quantity
Bt cotton area in 2002–04 (acres)	-1.113^{***}	-0.562^{*}	-0.491^{*}	−0.061
	(0.420)	(0.301)	(0.272)	(0.050)
Bt cotton area in 2006–08 (acres)	-1.793^{***}	-1.076^{***}	-0.662^{***}	-0.057^{**}
	(0.232)	(0.166)	(0.151)	(0.028)
Total cotton area (acres)	2.998^{***}	1.669^{***}	1.249^{***}	0.080^{***}
	(0.211)	(0.151)	(0.137)	(0.025)
Self spray dummy	3.773^{**}	1.788	1.690^{*}	0.306
	(1.557)	(1.114)	(1.010)	(0.186)
Monthly expenditures on smoking (Rs)	−0.0002	−0.00003	−0.0002	0.00002
	(0.0003)	(0.0002)	(0.0002)	(0.00003)
Pesticide price (Rs/kg)	-0.004^{***}	-0.003^{***}	-0.001^{**}	0.0001
	(0.001)	(0.001)	(0.0004)	(0.0001)
2004 dummy	-4.951^{***}	−0.979	-3.954^{***}	−0.006
	(1.703)	(1.219)	(1.105)	(0.204)
2006 dummy	-3.534^{*}	0.428	-3.875^{***}	−0.065
	(2.070)	(1.481)	(1.342)	(0.248)
2008 dummy	−3.015	0.754	-3.803^{**}	0.054
	(2.303)	(1.648)	(1.493)	(0.275)
Constant	4.316^{**}	0.320	4.028^{***}	−0.0318
	(2.033)	(1.455)	(1.318)	(0.243)
Observations	791	791	791	791
R-squared	0.376	0.263	0.215	0.035
F(9, 584)	39.15	23.21	17.80	2.36
Prob > F	0.00	0.00	0.00	0.01

***, ** and * indicate significance at 1%, 5%, and 10%, respectively.
Note: Coefficient estimates are shown with standard errors in parentheses.

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comparisons show fewer cases of poisoning among Bt adopters than among non-adopters, but these effects are not attributable to the new technology, as the fixed-effects specification correctly reveals. Farmer learning effects may also partly explain why the Bt effect became more visible and significant only after 2006.

Learning in our context is particularly related to the appropriate adjustment of chemical pesticide use after Bt adoption. In the early years, information flows about Bt were imperfect. Also, some of the farmers initially did not fully trust the technology's efficacy in controlling bollworms, so that chemical pesticides were not always reduced to the extent that they could have been (Qaim et al., 2006). Thus, increasing experience with the technology led to further pesticide reductions. This is supported by the analysis in Fig. 2, which showed that pesticide use on Bt plots was lower in 2006 and 2008 than it was in 2002 and 2004. The same is confirmed in Table 4, which shows pesticide use models as explained in Section 2.3 (Eq. 2).

Column (1) of Table (4) shows a model where total pesticide quantity used on the cotton acreage is the dependent variable. While in 2002–04, each acre of Bt cotton reduced chemical pesticide use by 1.1 kg, this effect increased to 1.8 kg by 2006–08. Compared to mean per-acre pesticide use in non-Bt cotton, this means a reduction of about 30% in 2002–04 and of 50% in 2006–08.

Besides, changes in the Bt effect on poisoning may be related to the types of pesticides saved through Bt adoption. As is known, pesticides can differ widely in terms of their toxicity for human health and the environment. To analyze this, we disaggregated total pesticide quantity using the WHO hazard categories (see Section 3.1). For each hazard category, we re-estimated the pesticide use model, with results shown in columns (2) to (4) of Table 4. Indeed, notable differences in the Bt effects can be observed. As already suggested by the descriptive statistics, the largest part of the overall pesticide reductions through Bt adoption occurs in the most toxic hazard category I pesticides, and this effect almost doubled between 2002–04 and 2006–08 (column 2). The effect of Bt in the later period of almost −1.1 kg per acre is equivalent to a 70% reduction, as compared to mean quantities of category I pesticides on non-Bt plots. Most of the other reductions occur in hazard category II pesticides, also with an increasing effect over time (column 3). Column (4) shows that the technology's impact on the use of category III and IV pesticides is relatively small.[5]

3.2.3. Spillovers and extrapolation

A striking feature in columns (1) and (3) of Table 4, and also in columns (1) and (2) of Table 3, are the large negative and significant coefficients of the year dummies. They suggest that both pesticide use and the number of pesticide poisonings decreased over time, even beyond the effect of Bt adoption. This is also consistent with the descriptive analysis in Fig. 2, which revealed a decreasing trend in pesticide use not only on Bt plots, but also on non-Bt plots. In this connection, area-wide suppression of bollworms as a result of the widespread adoption of Bt cotton was mentioned as a likely reason. In fact there are no plausible other reasons that could explain the phenomenon of the large negative year dummy coefficients. In principle, climatic factors, which we do not control for in our models, could influence pest infestation levels, but there are no indications of a sudden and systematic change in local climate after 2002. Nor did a broad-based introduction of alternative pest control strategies or integrated pest management programs occur in India during that period. In fact, in the surveyed regions conventional cotton has been grown for long, and pesticide use has shown an increasing rather than a decreasing trend in recent decades.

If the only systematic change that occurred in cotton production in India during the period observed is really the widespread adoption of Bt technology, then the year dummies would capture some of this, and the Bt treatment effects would be underestimated. In other words, there would be spillovers that we do not properly model. To be more concrete, widespread and continued use of Bt cotton suppresses bollworm populations more broadly, including on non-Bt cotton grown in the vicinity. Hutchinson et al. (2010) recently showed for Bt maize in the US that this type of spillover can be sizeable. Proving it in our modeling approach 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.

We conclude, however, that the Bt impact on the incidence of pesticide poisoning derived with the two-way FE specification is probably a conservative estimate. In order to demonstrate this, we re-estimated the model shown in column (2) of Table 3, but this time excluding the year dummies. These additional results are shown in column (3) of Table 3. Indeed, the coefficient for Bt area in 2006–08 increases substantially in absolute terms from 0.104 in column (2) to 0.388 in column (3). We use these two values after 2006 as lower and upper-bound estimates for some extrapolations. Each acre of Bt cotton decreases the incidence of acute pesticide poisoning by 0.104-0.388. Multiplying by the total area under the technology in India, which was 23.2 million acres in 2010, suggests that Bt cotton reduces the number of pesticide poisonings by 2.4-9.0 million cases every year.[6] Above we reported that each case of poisoning causes health costs in a magnitude of 264 Rs. Hence, Bt cotton helps to save health costs of 0.6-2.4 billion Rs (14–51 million US$) per year.

4. Conclusions

This article contributes to the assessment and quantification of health externalities associated with Bt cotton technology. In particular, we have analyzed the impact of Bt cotton on pesticide poisoning among smallholder farmers in India. A few previous studies carried out in developing countries have documented that Bt has reduced pesticide-induced acute poisoning incidences among cotton growers, but they have failed to account for unobserved heterogeneity between adopters and non-adopters of this technology. This may be an important source of bias in previous estimates. Here, we have improved upon previous approaches by using unique panel survey data and controlling for non-random selection bias through the estimation of fixed-effects econometric models. Furthermore, the panel, which consists of four rounds of data collected between 2002 and 2008, has allowed us to analyze impact developments over time.

The results demonstrate that Bt cotton has notably reduced the incidence of pesticide poisoning among smallholder farmers in India. While no significant effects were observed in the early years of adoption, clear reductions have occurred since 2006. Thus, the positive health effects have increased with increasing technology adoption rates. Extrapolating the estimation results to India as a whole, Bt cotton now helps to avoid at least 2.4 million cases of pesticide poisoning every year, which is equivalent to a health cost saving of 14 million US$. These are lower-bound estimates of the health benefits, because they neglect the positive spillovers that Bt cotton entails. Alternative estimates suggest that Bt cotton may avoid up to 9 million poisoning incidences per year, which translates into a

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[5] Very few chemical insecticides used in Indian cotton production fall into the lower hazard categories III and IV. Hence, even in non-Bt cotton only very small quantities of these less hazardous pesticides are used on average (see Table 1).

[6] While our survey data only cover cotton-growing states in central and southern India, results from other studies suggest that the Bt effects may be similar also in northern India (Choudhary and Gaur, 2010).

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health cost saving of 51 million US$. In any case, the positive health externalities are sizeable.

The main reason for these health benefits of Bt technology is that the inbuilt resistance against major insect pests allows high cotton yields with much lower levels of chemical insecticides. As smallholder farmers spray pesticides manually, usually with insufficient protective clothing, lower pesticide use means lower exposure to toxic chemicals. Pesticide use models, which we also estimated with fixed-effects specifications, show that Bt cotton has reduced pesticide use by 50%, with savings increasing over time. Strikingly, the largest reductions of 70% occur in the most toxic pesticides belonging to hazard category I. While not further evaluated here, this also entails advantages for the environment.

Bt technology may not be the only option to reduce chemical pesticide use in cotton production. In some regions, pesticides are overused, entailing a disruption of beneficial insects and increasing pest levels (Gutierrez et al., 2006; Pemsl et al., 2008). In such cases, pesticide reductions would be possible without a loss in productivity. More careful pest scouting and biological control measures – such as promoted in integrated pest management (IPM) programs – could also help to cut down chemical pesticide use. However, IPM is labor and knowledge intensive, so that it is not widely adopted in smallholder agriculture (Lee, 2005). This is different for Bt cotton in India. In any case, IPM and Bt technology are highly complementary approaches (Romeis et al., 2008), so that pursuing one should not be seen as a substitute for the other.

However, the public debate about GM crops in general, and Bt cotton in particular, is often primarily focused on health and environmental risks. Our results suggest that positive health and environmental externalities should also be considered, because they can be substantial. More research is needed to assess and quantify the different types of GM crop externalities and their developments over time.

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