Pesticide Reduction Sustainability of Bt Technology in India

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Abstract

The primary focus of the study is the changes that occurred in the pesticide-use structure of cotton production sector of India, owing to the diffusion of *Bacillus thuringiensis* (Bt) technology. Studies from different countries show that transgenic Bt crops can reduce chemical pesticide use with positive economic, environmental, and health effects. However, most of these studies build on cross-section survey data, so that longer term effects are uncertain. Bt resistance and secondary pest outbreaks may potentially reduce or eliminate the benefits over time, especially in developing countries where refuge strategies are often not implemented. Here, data from a unique panel survey of cotton farmers, conducted in India between 2002 and 2008, show that the Bt pesticide reducing effect has been sustainable. In spite of an increase in pesticide sprays against secondary pests, total pesticide use has decreased significantly over time. Bt has also reduced pesticide applications by non-Bt farmers. These results mitigate the concern that Bt technology would soon become obsolete in small farmer environments. The survey data on actual pesticide use in farmers' fields complement previous entomological research.

1. Introduction

Transgenic crops that contain Cry genes from *Bacillus thuringiensis* (Bt) were commercialized in many countries and widely adopted by farmers over the last 15 years. Several studies showed that Bt crops, which provide resistance to some lepidopteran and coleopteran insect pest species, have helped reduce chemical pesticide use and increase effective yield (Huang et al., 2005; Qaim and de Janvry, 2005; Wossink and Denaux, 2006; Krishna and Qaim, 2007; Carpenter, 2010). Next to Bt maize, Bt cotton is currently the most widely grown Bt crop (James, 2009). The largest Bt cotton areas are found in India and China, where the technology is mainly used to control the American bollworm (*Helicoverpa armigera*) and to a lesser extent spotted bollworm (*Earias vittella*), pink bollworm (*Pectinophora gossypiella*), and related species (Pemsl and Waibel, 2007; Wu et al., 2008; Qaim, 2009). In both countries, the cotton sector is heavily dominated by smallholder farmers, who benefit from Bt technology adoption in terms of higher incomes and lower occupational health hazards associated with pesticide sprays (Huang et al., 2002, Hossain et al., 2004; Qaim et al., 2009). In India and Pakistan, it was also shown that Bt cotton contributes to poverty reduction and broader rural development (Qaim and Subramanian, 2010; Ali and Abdulai, 2010).

However, there is still uncertainty with respect to the sustainability of these effects. In particular, there are two factors that could undermine the effectiveness of Bt technology over time. First, there could be Bt resistance development in target pest populations (Bates et al., 2005; Tabashnik et al., 2009). Second, while primary pests are controlled through Bt, the lower use of chemical pesticides may entail the outbreak of secondary pests, especially mirids, mealybugs, and other sucking pest species, which are not Bt target pests (Nagrare et al., 2009; Lu et al., 2010). Both factors could potentially lead to chemical pesticide use increasing again after a certain time of reduction. The probability of this happening may be higher in the small farm sector of developing countries, where implementation of Bt refuge strategies and careful monitoring are more difficult. However, beyond such undesirable effects, there are also possible positive spill-overs: widespread use of Bt technology may suppress bollworm infestation levels regionally, such that non-Bt adopters may also be able to reduce their pesticide applications (Carrière et al., 2003; Wu et al., 2008; Hutchinson et al., 2010).

Such aspects were analyzed in the recent literature, mostly through long-term field observations of pest populations in different environments (Carrière et al., 2003; Bates et al., 2005; Marvier et al., 2007; Wu et al., 2008; Tabashnik et al., 2009; Nagrare et al., 2009; Lu et al., 2010). While this is very important to understand ecological interactions, there is hardly any research that has analyzed what this actually means for farmers' pesticide use over time. One exception is China, where farm survey data collected over several years were used to analyze pesticide use trends in cotton (Wang et al., 2008; Wang et al., 2009). However, those surveys were not constructed as a panel, which is a drawback when the focus is on evaluating technological impact dynamics.

In this paper, we address this research gap and analyze pesticide use trends in the Indian cotton sector, building on a unique panel survey of farmers. India is a particularly interesting example, because the country is currently the biggest producer of Bt cotton and the crop is mostly grown by smallholder farmers. Bollgard I technology, containing the Cry1Ac gene, was officially commercialized in India in 2002. In 2006, Bollgard II technology, containing stacked Cry1Ac and Cry2Ab genes, was also approved. These technologies were developed by Monsanto in cooperation with the Indian seed company Mahyco. By 2009, over five million Indian farmers had adopted Bt cotton on 20.8 million acres (8.4 million ha) – almost 90% of the country's total cotton area (James, 2009).

2. Materials and methods

2.1. Data

The survey data from cotton farmers in India were collected in four rounds between 2002 and 2008. The sample covers farmers in four different states, namely Maharashtra, Karnataka, Andhra Pradesh, and Tamil Nadu; it is representative of cotton farmers in central and southern India. These states were sampled purposely to cover a wide variety of different cotton growing situations; they produce 60% of all cotton production in central and southern India (Cotton Association of India, 2008). Central and southern India were also the only regions for which Bt cotton was commercially approved in 2002. Approval for northern India was only given in later years.

In 2002, 10 districts and 58 villages in the four states were randomly selected. Within the villages, at total of 341 cotton farmers were randomly sampled. Bt adopters were deliberately over-sampled by randomly selecting from complete lists of technology users at the village level. This was important to have sufficient Bt observations for robust impact assessment in the first season of commercial adoption. A structured questionnaire was prepared and administered through face-to-face interviews. The interviews were conducted in local languages by a small team of enumerators, who were selected, trained, and monitored by the authors. The actual interviews took place in early 2003, shortly after the cotton harvest for the 2002 season was completed. Sample farmers were asked to provide a wide array of agronomic and socioeconomic information, including input-output details on their cotton plots. Farmers who grew Bt and non-Bt cotton simultaneously, provided details for both options, so that the number of plot observations is somewhat larger than the number of farmers surveyed (Table 1). Farmers in the sample are predominantly resource-poor smallholders. The average cotton area in 2002 was 4.5 acres for non-adopters of Bt and 4.9 acres for adopters (Qaim et al., 2006).

The survey was repeated 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). In these follow-up rounds, the same questionnaire with only very slight adjustments was used for the interviews. The sample size was slightly increased (Table 1) to account for sample attrition. The share of original farmers (those interviewed during the first survey round) was 89%, 69%, and 67% in the second, third, and fourth round, respectively. To our knowledge, this is the only longer-term panel survey of Bt cotton farmers in a developing country.

2.2. Statistical analysis

We first compare mean values of pesticide use, cotton yield, and profit per acre between Bt and non-Bt plots, in order to see whether there are significant differences and how these differences evolved over time. By 2008, most sample farmers had fully adopted Bt technology, so that the number of non-Bt observations became very small (Table 1). Therefore, for the purpose of these mean value comparisons, we club observations from two consecutive rounds, respectively, resulting in data for two periods, namely 2002-04 and 2006-08. This approach also helps smooth seasonal variations in cotton production, which can be large in the semi-arid regions. Pesticide use is measured in terms of quantity of active ingredient (a.i.) per acre. In addition to total pesticide use, we differentiate between products sprayed against different target pests. Farmers either use insecticides against bollworms, or against sucking pests, or they use broad-spectrum chemicals against both types of pests. Disaggregating into these three categories is of interest, because Bt technology controls bollworms while it is not effective against sucking pests. Beyond physical quantities, we also analyze total pesticide costs incurred by farmers. The reason is that there is a wide variety of pesticides on the market, which partly differ considerably in terms of formula concentrations and prices.

Pesticide use by farmers can also be determined by factors other than Bt technology adoption, so that simple comparison of mean values between Bt and non-Bt plots may potentially be misleading. Other important factors may include agronomic differences, such as irrigation intensity and crop cycle duration, or socioeconomic differences, such as farmers' education and living standard. In order to identify net effects of Bt technology, we estimate pesticide use models, using panel regression techniques and including Bt as an explanatory variable next to a number of other covariates. Two dummy variables represent Bt adoption: $Bt^{2002\text{-}04}$, which takes a value of one if Bt was adopted on a particular plot in the 2002-04 period, and $Bt^{2006\text{-}08}$, which takes a value of one if Bt was adopted in 2006-08. To capture time effects properly, an additional non-$Bt^{2006\text{-}08}$ dummy is introduced to the model, such that non-$Bt^{2002\text{-}04}$ is the reference against which all other technology alternatives are compared.

We estimate two separate models, one with pesticide quantity and the other with pesticide cost as dependent variable. As some farmers did not use any pesticides in individual years, the distribution of these dependent variables is censored at zero, so that the ordinary least squares method fails to provide unbiased estimates (Greene, 2008). Therefore, we use a random-effects Tobit model specification. Furthermore, to test whether Bt technology has an effect on the probability of spraying against secondary pests, we use a random-effects Probit model.

3. Results and discussion

3.1. Mean value comparisons

Table 2 shows that cotton yields and profits were significantly higher on Bt than on non-Bt plots, which is consistent with previous research in India (Qaim and Zilberman, 2003; Bennett et al., 2005; Crost et al., 2007; Karihaloo and Kumar, 2009). These benefits of Bt technology increased remarkably over time, which can largely be explained by three factors. First, the number of commercialized Bt varieties well adapted to different conditions grew. While only four Bt varieties had been approved until 2004, around 300 were commercially available by 2008 (James, 2009). Second, Bt seeds became cheaper for farmers due to government price interventions starting in 2006 (Krishna and Qaim, 2008). Third, in addition to Bollgard I technology, since 2006 Bollgard II technology with a wider spectrum of lepidopteran and coleopteran target pests has been commercialized and adopted in India.

Looking at pesticide use, in 2002-04 the quantity of active ingredient applied on Bt plots was 37% lower than on non-Bt plots; this difference increased to 50% by 2006-08, again using non-Bt plots in 2002-04 as the reference (Table 2). Hence, rather than diminishing, pesticide reductions through Bt further increased over time, suggesting that Bt resistance development or secondary pest outbreaks are no major issues yet.

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 (Monsanto, 2009). However, this was not reported outside these four districts. Even though our survey revealed that farmers do not always maintain non-Bt cotton refuge areas, which are actually mandatory in India, there are several other crops grown on the same farms that are also host plants for bollworms. Examples include maize, sorghum, pulses, and several vegetable species (Matthews and Tunstall, 1994; Qaim and de Janvry, 2005). It appears that cultivation of these other crops also contributes to diluting Bt resistance development in smallholder environments. No resistance to Bollgard II has yet been detected. In general, resistance development is delayed when two or more Bt genes are incorporated into the plant (Zhao et al., 2003).

Strikingly, Table 2 shows that pesticide quantities were also much lower on non-Bt plots in 2006-08 as compared to 2002-04. As there were no major differences between the two periods in terms of average rainfall or temperature, other explanatory factors have to be sought. The most obvious one would be positive spill-overs of widespread Bt adoption, which may suppress bollworms also on adjacent non-Bt plots. Yet, there is another potential explanation for decreasing pesticide use on non-Bt plots, which is related to farmer self-selection into the group of Bt adopters. If all farmers that suffer from high bollworm pressure decide to adopt Bt, then the non-Bt plots observed in 2006-08 would mainly belong to farmers with low pest pressure conditions, who have always sprayed less. However, when only focusing on those farmers who had not adopted Bt by 2006, it becomes clear that they actually did reduce their pesticide use over time (Fig. 1), while Bt adoption in their neighborhoods increased. We conclude that Bt causes positive spill-overs and contributes to pesticide reductions also on non-Bt plots. This is similar to what has been reported by entomologists in China and the USA (Carrière et al., 2003; Wu et al., 2008; Hutchinson et al., 2010).

Table 2 shows that for pesticide costs the patterns are almost the same as for pesticide quantity; hence, our findings about pesticide use trends are hardly affected by the way of measurement. In the lower part of Table 2, pesticide use patterns are disaggregated by target pests. Unsurprisingly, the share of farmers spraying specifically against bollworms is significantly lower among Bt adopters than among non-adopters. Likewise, quantities and costs of pesticides used specifically against bollworms are lower among Bt farmers. And, the reducing effect increased over time – another clear indication that resistance development is not yet an issue of practical relevance. For broad-spectrum pesticides, the picture looks similar.

However, a different trend can be observed for chemicals used against sucking pests, which are not controlled through Bt toxins. There was no significant difference between Bt and non-Bt plots in 2002-04, but in 2006-08 sprays against sucking pests decreased on non-Bt plots, while they increased on Bt plots. The latter indicates that secondary pests became more important through Bt adoption and concomitant chemical pesticide reductions, which is consistent with Bt farmers' own perceptions (Fig. 2). Nonetheless, so far the pesticide reducing effect of Bt is stronger than the increasing effect through secondary pests. It should also be stressed that broad-spectrum pesticides and those used specifically against bollworms are often much more toxic for the environment and human health than specific pesticides against sucking pests (Qaim and Zilberman, 2003; Hossain et al., 2004; Qaim and de Janvry, 2005).

3.2 Regression results

Table 3 illustrates the results of the panel regressions described in section 2.2. Models (1) and (2) show the estimation results with plot level pesticide quantity and cost as dependent variables. The coefficient estimates confirm that Bt reduces pesticide use significantly, and this effect increased over time. The net Bt impact in 2006-08 was a reduction of 1.3 kg of pesticide a.i. per acre – or 27 million kg for the 20.8 million acres currently under Bt cotton in India. Relative to what has been sprayed without Bt in 2002-04 (see Table 2), the net reduction is 53% and 57% in pesticide quantity and cost, respectively. The positive spill-over is captured by the non-$Bt^{2006\text{-}08}$ coefficient, which is also highly significant in models (1) and (2).

To analyze the effects of Bt technology adoption on pesticide use to control secondary pests, we employ a somewhat different approach. Above we saw that the quantity of pesticide used against sucking pests had increased on Bt plots in 2006-08. This may be due to either more Bt farmers specifically spraying against sucking pests or higher dosages used per spray. Table 4 shows that, among those farmers who sprayed against sucking pests, differences in dosages between Bt and non-Bt plots were not statistically significant. Thus, we conclude that Bt adoption mainly determines whether or not a farmer sprays specifically against sucking pests, which can be captured in a Probit model. However, the decision to use pesticides against sucking pests may potentially be correlated with decision to use broad-spectrum pesticides. We tested this option by estimating a bivariate probit model for both types of pesticides. As the error term correlation was insignificant, the simple Probit, shown as model (3) in Table 3, was used. The results demonstrate that Bt had no significant effect in 2002-04, but in 2006-08 it increased the probability of sucking pest sprays by 0.51. This is further evidence that secondary pests became more important on Bt plots, while this is not the case on non-Bt plots.

4. Conclusion

This is the first study that has analyzed the advantages of transgenic Bt cotton over time, using a panel survey of farmers covering a period of six years. The results show that Bt cotton adoption has led to large and sustainable pesticide reductions and yield gains in India. While the importance of secondary pests has increased, this has not thwarted the overall benefits. On the contrary, the magnitude of pesticide reductions increased over time. Bt has also reduced pesticide applications by non-Bt farmers, because widespread adoption has contributed to area-wide suppression of bollworm populations. Further research analyzing potential long-term effects is necessary, but the results mitigate the concern that Bt technology would soon become obsolete in small farmer settings. Hence, the economic, social, environmental, and health benefits associated with Bt cotton technology continue. The survey data presented here on farmers' actual pesticide use, as well as yields and profits, over time are an important complement to previous entomological research.

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Table 1. Number of farms and plots sampled in the four survey rounds

Year	No. of farmers sampled	New farmers over previous round	No. of plot observations	No. of observations from	
				Bt plots	Non-Bt plots
2002	341	--	434	133	301
2004	362	58	464	165	299
2006	342	71	369	315	54
2008	380	63	383	375	8

Table 2. Comparison of yield, profit, and chemical pesticide use on Bt and non-Bt cotton plots

	Non-Bt$^{2002\text{-}04}$	**Bt$^{2002\text{-}04}$**	**Non-Bt$^{2006\text{-}08}$**	**Bt$^{2006\text{-}08}$**
Number of observations	600	298	62	690
Yield (100 kg /acre)	5.21	7.05	6.08	8.31
	(3.16)	(3.60)	(3.05)	(3.39)
% difference over non-Bt$^{2002\text{-}04}$	--	35.43**	16.70*	59.63**
Profit ('000 Rs/acre)	2.63	5.08	4.53	9.15
	(6.18)	(7.15)	(7.02)	(7.92)
% difference over non-Bt$^{2002\text{-}04}$	--	92.78**	72.15*	247.24**
Pesticide use (kg a.i./acre)	2.46	1.55	1.19	1.24
	(1.45)	(1.27)	(1.28)	(1.08)
% difference over non-Bt$^{2002\text{-}04}$	--	-36.99**	-51.63**	-49.59**
Pesticide cost ('000 Rs/acre)	2.26	1.42	1.05	1.07
	(1.78)	(1.55)	(1.21)	(1.38)
% difference over non-Bt$^{2002\text{-}04}$	--	-37.06**	-53.43**	-52.93**
Share of farmers using				
Pesticides against bollworms	0.91	0.71**	0.68**	0.46**
Pesticides against sucking pests	0.66	0.65	0.48**	0.80**
Broad-spectrum pesticides	0.85	0.71**	0.58**	0.55**
Any pesticides	0.97	0.94*	0.81**	0.94**
Pesticide quantity (kg a.i./acre)				
Pesticides against bollworms	0.92	0.45	0.40	0.24
	(0.65)	(0.49)	(0.43)	(0.37)
% difference over non-Bt$^{2002\text{-}04}$	--	-50.65**	-56.39**	-74.26**
Pesticides against sucking pests	0.43	0.37	0.26	0.50
	(0.55)	(0.44)	(0.36)	(0.55)
% difference over non-Bt$^{2002\text{-}04}$	--	-13.55	-38.28*	17.31*
Broad-spectrum pesticides	1.12	0.73	0.53	0.51
	(1.04)	(0.90)	(0.91)	(0.70)
% difference over non-Bt$^{2002\text{-}04}$	--	-34.64**	-53.02**	-54.97**
Pesticide costs ('000 Rs/acre)				
Pesticides against bollworms	1.11	0.59	0.50	0.28
	(1.03)	(0.85)	(0.66)	(0.67)
% difference over non-Bt$^{2002\text{-}04}$	--	-46.91**	-54.84**	-74.33*
Pesticides against sucking pests	0.31	0.29	0.17	0.45**
	(0.51)	(0.48)	(0.41)	(0.77)
% difference over non-Bt$^{2002\text{-}04}$	--	-6.76	-44.33*	46.33**
Broad-spectrum pesticides	0.85	0.55	0.38	0.33
	(1.04)	(0.86)	(0.60)	(0.60)
% difference over non-Bt$^{2002\text{-}04}$	--	-35.18**	-54.90**	-60.94**

Sample mean values are shown with standard deviations in parentheses; a.i. means active ingredients; Rs means Indian Rupees; *, ** means that the difference over the corresponding non-Bt$^{2002\text{-}04}$ value is statistically significant at the 0.05 and 0.01 level, respectively.

Table 3. Determinants of pesticide use among cotton farmers

	Random-effects Tobit models				Random-effects Probit model	
	Model (1) Pesticide quantity (kg a.i./acre)		Model (2) Pesticide cost ('000 Rs/acre)		Model (3) Use of pesticides against SP (dummy)	
	Marginal effect	*p*-value	Marginal effect	*p*-value	Marginal effect	*p*-value
Technology adoption status						
$Bt^{2002\text{-}04}$ (dummy)	-0.926	0.00	-0.842	0.00	0.002	0.99
$Bt^{2006\text{-}08}$ (dummy)	-1.310	0.00	-1.290	0.00	0.514	0.00
Non-$Bt^{2006\text{-}08}$ (dummy)	-1.352	0.00	-1.401	0.00	-0.310	0.11
Plot level controls						
Crop duration (no. of days)	3.E-04	0.76	-9.E-05	0.93	0.003	0.03
Irrigation (no. of times)	0.075	0.00	0.078	0.00	-0.005	0.69
Farm/household level controls						
Farms size (acres)	4.E-04	0.89	0.001	0.83	-0.006	0.08
Farmer education (years)	-0.028	0.00	-0.033	0.00	0.019	0.05
Farmer age (years)	-0.007	0.02	-0.008	0.02	-0.006	0.08
Household members (no.)	0.004	0.67	0.017	0.16	0.030	0.02
Food expenditure share (%)	-0.005	0.01	-0.006	0.02	-0.001	0.82
State controls						
Maharashtra (dummy)	1.479	0.00	1.129	0.00	0.712	0.00
Karnataka (dummy)	1.352	0.00	1.077	0.00	0.266	0.20
Andhra Pradesh (dummy)	1.996	0.00	2.398	0.00	0.493	0.02
Intercept	1.480	0.00	1.427	0.00		
Model statistics						
Number of observations	1650		1650		1650	
Log likelihood	-2540.03		-2819.27		-911.99	
Wald $\chi^2(13)$	668.04		513.30		100.10	
Prob > χ^2	0.00		0.00		0.00	

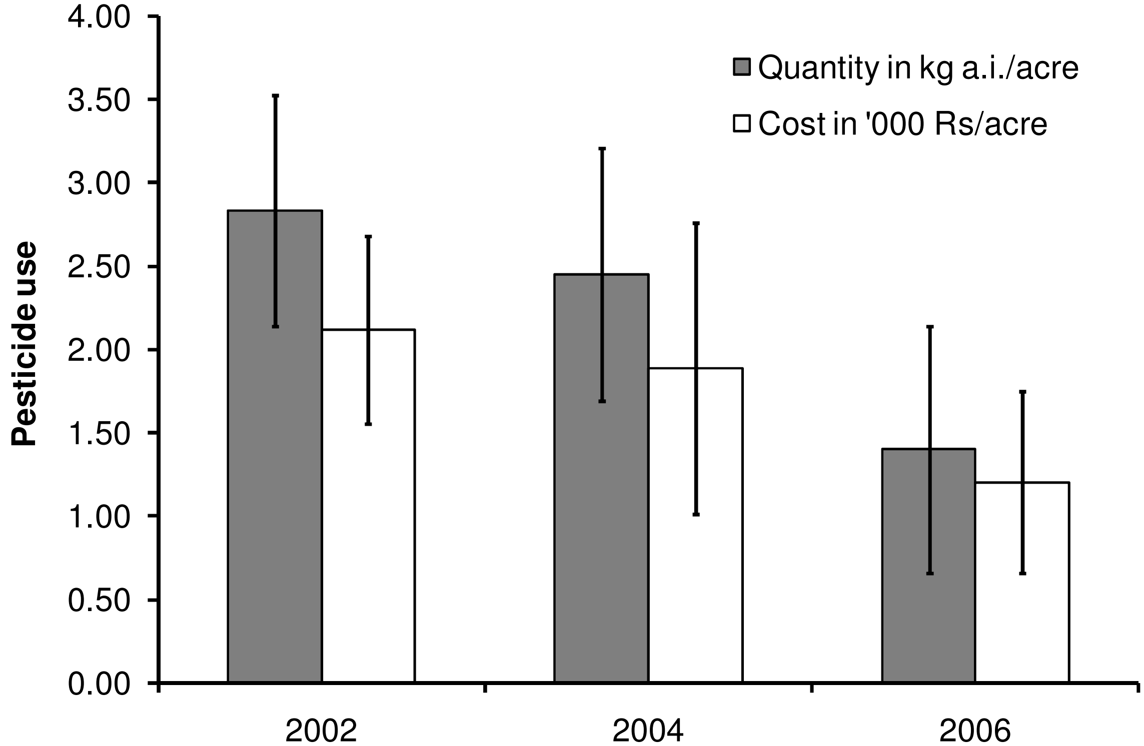
Estimates are based on panel regressions; a.i. means active ingredients; Rs means Indian Rupees; SP means sucking pests.

Table 4. Pesticide quantities used against sucking pests by farmers that specifically sprayed against sucking pests

	Non-$Bt^{2002\text{-}04}$	Non-$Bt^{2006\text{-}08}$	$Bt^{2006\text{-}08}$
Number of observations	393	30	549
Pesticide quantity (kg a.i./acre)	0.652	0.544	0.629
	(0.559)	(0.342)	(0.552)

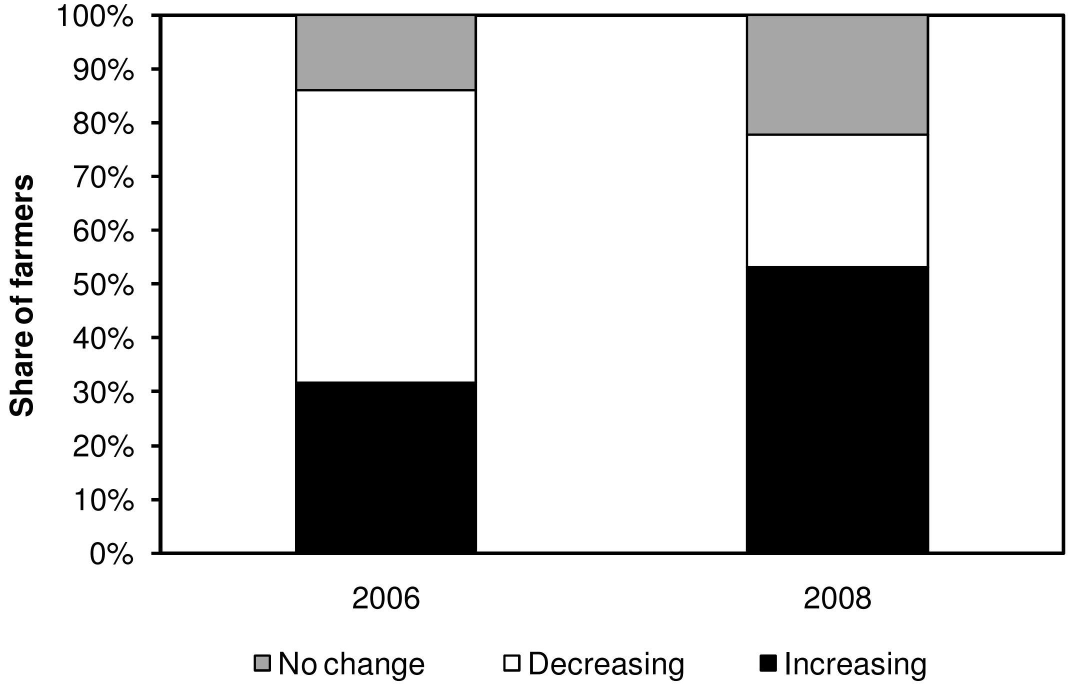
Sample mean values are shown with standard deviations in parentheses; a.i. means active ingredient. The differences between all mean values shown are not statistically significant ($p > 0.05$).

Figure 1. Pesticide use history of sample farmers who had not adopted Bt by 2006



The number of observations in each year is 38. Mean values are shown with error bars representing standard deviations. Significant differences ($p \leq 0.05$) exist between pesticide use (both quantity and cost) in 2006 and both previous rounds. Differences between 2002 and 2004 are not statistically significant. a.i. means active ingredients; Rs means Indian Rupees.

Figure 2. Farmers' perceptions about change in sucking pest pressure through Bt adoption



Only Bt adopters are included. The share of farmers who perceived an increase in secondary pest pressure was significantly higher ($p < 0.01$) in 2008 than in 2006. A significant majority ($p < 0.05$) perceived secondary pest pressure as decreasing through Bt adoption in 2006 and as increasing in 2008. The same question was not asked in the survey rounds in 2002 and 2004.