RTG 1666 GlobalFood

Transformation of Global Agri-Food Systems:
Trends, Driving Forces, and Implications for Developing Countries

Georg-August-University of Göttingen

GlobalFood Discussion Papers

No. 41

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August 2014

RTG 1666 GlobalFood · Heinrich Düker Weg 12 · 37073 Göttingen · Germany
www.uni-goettingen.de/globalfood

ISSN (2192-3248)

Bt Cotton and Ecosystem Impacts of Pesticide Reductions

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Abstract

This paper examines the ecosystem impacts of transgenic Bt cotton technology resulting from reduced chemical pesticide use. Employing unique panel data from smallholder farmers in central and southern India, negative environmental and health effects of pesticide use are quantified with the environmental impact quotient (EIQ), with and without Bt technology. An environmentally-sensitive production function is estimated, treating the environmental risk of pesticide toxicity as an undesirable output in the production process. Negative externalities are significantly lower in Bt than in conventional cotton. The reduction in EIQ through Bt adoption has increased from 39% during 2002-2004 to 68% during 2006-2008. Bt adoption also contributes to higher environmental efficiency. We find that environmental efficiency is influenced by the quality of Bt technology; high-quality Bt seeds are associated with higher environmental efficiency than lower-quality seeds.

Key words: Bt cotton, Directional distance function, Environmental impact quotient, India, Pesticide externality.

JEL Classification: D62; O44; Q12; Q16.

Acknowledgement: This study was financially supported by the German Research Foundation (DFG).

1. Introduction

The potential impacts of transgenic crops on farmer welfare and the environment are widely discussed. While the economic impacts of transgenic crops are rather well-documented (Smale et al., 2009; Qaim, 2010), their impacts on agro-ecosystems remain less clear. Possibly due to limited empirical evidence, concerns that this technology could cause negative environmental effects and jeopardize the health of consumers commonly dominate reports in the popular media. Frequently cited potential negative impacts of transgenic crops include biodiversity risks of introducing invasive species into ecosystems, negative effects for beneficial and other non-target organisms, and indirect effects on species that depend on the pests controlled by transgenic crops for survival (Wolfenbarger and Phifer, 2000). Barrows et al. (2014) observe that the public arguments against the application of transgenic crops have hardly changed over the last 20 years, and that possible environmental benefits are commonly overlooked. One possible environmental benefit relates to reductions in the use of chemical pesticides. While impacts of transgenic crop adoption on pesticide quantity have been studied, changes in pesticide toxicology levels and their environmental and health effects have hardly been analysed. We address this research gap using the example of transgenic Bt cotton technology in India. Given that the application of chemical pesticides causes considerable negative externalities in developing countries (van der Werf, 1996), this is an important direction. But obviously there may be other environmental effects of transgenic crops that we do not address in this study.

Transgenic pest resistance technology with *Bacillus thuringiensis* (Bt) genes was developed to reduce farmers' dependence on chemical pesticides for managing Lepidopteran and certain Coleopteran pests. Bt cotton and Bt maize are currently among the most widely used transgenic crop technologies worldwide (James, 2013). While conventional cotton and maize are often sprayed heavily to control insect pests, the proportion of pesticide active ingredients (a.i.) actually reaching the target pests is relatively low. Accordingly, negative environmental externalities are commonplace (Pimentel, 1995). At the same time, pest control remains partial, especially in developing countries (Qaim and Zilberman, 2003). Bt technology adoption can make insect pest control more effective while reducing the need to spray toxic chemical pesticides.

Transgenic Bt cotton has been adopted in a number of cotton-producing countries in North and South America, Africa, and Asia. In India, this technology was first commercialized in 2002. Since then, Bt cotton has been adopted by several million smallholder farmers and is currently cultivated on more than 90% of the Indian cotton area (James, 2013). Using four rounds of panel data collected between 2002 and 2008, we capture the early Bt diffusion phase with relatively low adoption rates, as well as the later phase with much higher technology adoption. The data provide a quasi-experimental setting for the evaluation of Bt technology impacts under changing conditions.

The changes in pesticide use in India through Bt cotton adoption were studied by Krishna and Qaim (2012) and Kouser and Qaim (2011). However, the eco-toxicological dimensions of these shifts in pesticide use remain unstudied. This also holds true for other countries where Bt technology is used. Bennett et. al. (2004), Hossain et al. (2004), Wossink and Denaux (2006), Morse et al. (2006), and Kouser and Qaim (2013b; 2013a) have all analysed specific aspects, such as impacts of Bt cotton adoption on farmer pesticide poisoning, but none of these studies has looked at eco-toxicological effects from a broader perspective. The common approach to evaluate pesticide effects of transgenic technology adoption is to quantify changes in the quantity of pesticides or a.i. used. However, pesticide quantity is only a crude proxy of environmental and health impacts, because pesticides differ widely in terms of their eco-toxicological effects. The type and nature of pesticides used in Bt and conventional cotton are often not the same. To account for this issue, we calculate the environmental impact quotient (EIQ) associated with pesticide use in Bt and conventional cotton. In a recent study, Abedullah et al. (2014) also used the EIQ to estimate impacts of Bt cotton adoption on environmental efficiency in Pakistan. They used EIQ as an input in a production function model. However, Färe and Grosskopf (2003; 2004) pointed out that the approach of considering environmental risk as one of the production inputs is not fully consistent with physical laws and the standard axioms of production theory. We use a different approach and treat the environmental risk of pesticide externalities as an undesirable output in a directional distance function model.

In short, this paper contributes to the literature in two ways. First, by using unique farm level panel data, the impact of transgenic cotton on environmental risks of chemical pesticide use is calculated from a broad eco-toxicological perspective. Second, by using an improved estimation method, we addresses some of the shortcomings in the existing literature on evaluating the environmental efficiency of transgenic cotton production.

2. Materials and Methods

The objectives of this study are twofold. First, we assess the ecosystem impacts of Bt cotton adoption in India, accounting for the change in pesticide toxicological levels at the farm level. We hypothesize that Bt cotton reduces the negative ecosystem impacts and further analyse whether this effect varies over time. Second, we estimate and compare the environmental efficiency of Bt and conventional cotton production, hypothesizing that Bt adoption leads to higher environmental efficiency. Since chemical pesticides cause undesirable effects on human health and the environment, we carry out the efficiency analysis by treating the negative externalities as an undesirable output, alongside the desirable output (cotton) in the production process. Thus, we explicitly consider the trade-off between desirable cotton yield and undesirable environmental risk.

2.1 Data

We use data from a panel survey of Indian cotton farmers, which was carried out in four rounds between 2002 and 2008. In a multistage sampling framework, four states in central and southern India were purposively selected, namely Maharashtra, Karnataka, Andhra Pradesh, and Tamil Nadu. From these states, 10 cotton-growing districts and 58 villages were randomly selected. In total, 341 cotton farmers were sampled in 2002. Details of the household survey are described by Kathage and Qaim (2012) and Krishna and Qaim (2012). For analysing possible changes of impacts over time, we divide the period between 2002 and 2008 into two phases; the early phase (2002-2004) when the process of Bt diffusion started, and the later phase (2006-2008) when the majority of the farmers had adopted the new technology.

2.2 Estimation of EIQ

The environmental impact analysis compares patterns of pesticide use in transgenic and conventional cotton and the resulting undesirable effects on human health and the environment. These effects are quantified with the EIQ, a comprehensive and consistent measure to assess pesticide risks in agricultural production systems (Maud et al., 2001; Kleter et al., 2007). EIQ involves three main components: risk to farm workers, risk to consumers, and risk to the ecosystem. Ten health and environmental factors that cause concern to farm workers, consumers, and the environment are commonly identified, rating persistence, toxicity, and exposure measures on a scale from 1 to 5, with 1 being the lowest toxicity or potential to harm and 5 being the highest (Kovach et al., 1992; Brimner et al., 2005). In the calculations, this information is reduced to a single indicator value, EIQ, for each pesticide a.i.as follows (Kovach et al., 1992):

$$EIQ = \frac{1}{3}\left\{C\,[(DT*5)+(DT*P)] + \left[\left(C*\frac{(S+P)}{2}*SY\right)+L\right] + \left[(F*R)+\left(D*\frac{(S+P)}{2}*3\right)+(Z*P*3)+(B*P*5)\right]\right\} \tag{1}$$

where, C is chronic toxicity, DT is dermal toxicity, SY is systemicity, F is fish toxicity, L is leaching potential, R is surface loss potential, D is bird toxicity, S is soil half-life, Z is bee toxicity, B is beneficial arthropod toxicity, and P is plant surface half-life.

Our study focuses only on the pesticide risk on farm workers and the ecosystem, because consumer toxicity is not relevant for a non-food crop such as cotton. To compare impacts of pesticides in Bt and conventional cotton at field level, EIQ field use rating is calculated, which is the product of EIQ per unit of a.i. and the actual quantity of pesticides applied. The total seasonal environmental impact of each production system is calculated by summing up the EIQ field use ratings for each pesticide spray over the entire cropping season.

In a next step, we use the calculated EIQ values as dependent variable in panel regression models to analyse factors that influence pesticide environmental and health impacts. In these plot-level regressions, Bt adoption is used as one explanatory variable, next to a set of other covariates, including farm and household characteristics and regional control variables. Bt adoption is captured through two dummy variables, Bt2002–2004, which takes a value of one if Bt was adopted in the 2002–2004 phase, and Bt2006–2008, which takes a value of one if Bt was adopted in 2006–2008. Additionally, a non-Bt2006–2008 dummy is used to capture the time effect, leaving non-Bt2002–2004 as the reference. We estimate both random effects (RE) and fixed effects (FE) models. The RE model can also produce estimates for time-invariant factors, but it may potentially lead to biased estimates for endogenous variables such as Bt adoption (Baltagi, 2008; Imbens and Wooldridge, 2009; Krishna and Qaim, 2012). This bias is tested and controlled for in the FE specifications.

2.3 Estimation of environmental efficiency

Agriculture involves the joint production of desirable (good) and undesirable (bad) outputs. One example of undesirable outputs are negative externalities of chemical pesticides In India, cotton had been one of the most chemical-intensive crops during the 1990s, before the introduction of transgenic Bt technology (Krishna et al., 2003). The undesirable externalities are represented by the EIQ values. The joint production of good and bad outputs can be expressed in terms of feasible output sets $P(x), x \in \Re_{+}^{K}$ (Ball et al., 2001):

$$P(x) = \left[(y_g, y_b) \middle| \left(x, y_g, y_b\right) \in T\right] \qquad (2)$$

where $T = [(x, y_g, y_b) | \, x \text{ can produce } (y_g, y_b)]$ represents the technology, $y_g \in \Re_{+}^{1}$ denotes desirable cotton output, $y_b \in \Re_{+}^{1}$ is undesirable EIQ output, and $x \in \Re_{+}^{K}$ represents *K* inputs.

We use environmental efficiency models to account for the joint production of cotton yield and pesticide EIQ and delineate a sustainable production process that considers both household welfare and environmental quality. Two approaches are used here to analyse the environmental efficiency of Bt technology. First, we use a directional distance function (DDF) approach, specifying the direction of desired production by considering the cost of the environmental risk. That is, simultaneously, the good output is maximised and the undesirable output is minimised in the production process. Second, we use an environmental production function (EPF), which seeks to maximise desirable output without directly crediting the reduction of undesirable output.

The desired direction of the environmental-economic DDF is the maximum expansion of cotton yield in the d^g direction with the largest feasible proportional contraction in inputs and EIQ in $-d^x$and $-d^b$ directions, respectively. Formally, the DDF is defined as:

$$\vec{D}_T(x, y_g, y_b; d) = sup[\delta : (y_g + \delta d^g, y_b - \delta d^b) \in P(x - \delta d^x)] \quad (3)$$

where $d = (d^x, d^g, -d^b)$. Under properties of null-jointness, jointly weak disposability, and strong disposability of desirable output, the value δ measures the environmentally sensitive productive technical inefficiency (Färe and Grosskopf, 2004; Färe et al., 2004). If we assume $d^b = 0$ and $d^g = 1$, the environmental DDF described in Eq. (3) becomes the environmental production function (Färe et al., 2007).

We illustrate the DDF approach using Fig. 1, in which the production process consisting of one desirable and one undesirable output is depicted and the input vector is held at a constant level. As stated in Eq. (3), the objective of the environmental DDF is to expand the production in desired direction (d^g) while contracting the bad output to the minimum possible level (d^b direction). Let the production feasibility set (P^G) be OSLMN under the assumption of strong disposability, and OWLMN under the assumption of weak disposability. Consider farm

A which is under-producing y_g and over-producing y_b. The objective of the DDF model is to move A to f$_w$ $(y_b - \delta' d^b, y_g + \delta' d^g)$ under the weak disposability assumption and to f$_s$ $(y_b - \delta^* d^b, y_g + \delta^* d^g)$ under the strong disposability assumption, in order to make the farm efficient. To operationalize the DDF model, we adopt the activity analysis for decision-making unit (farm) $i = 1,\dots, N$, producing one desirable and one undesirable output and using *k* = 1,...,K inputs, with the assumption of jointly weakly disposable outputs and constant returns to scale as follows (Färe and Grosskopf, 2004; Färe et al., 2007; Macpherson et al., 2010):

$$\vec{\mathbf{D}}\left(x_{i^*}, y_g^{i^*}, y_b^{i^*}; d\right) = \max \delta_{i^*}$$

$$\text{s.t.} \qquad \sum_{i=1}^{N} z_i y_g^i \geq y_g^{i^*} + \delta_{i^*} d^g$$

$$\sum_{i=1}^{N} z_i y_b^i = y_b^{i^*} - \delta_{i^*} d^b$$

$$\sum_{i=1}^{N} z_i x_{ik} \leq x_{i^*k} \quad k = 1, \dots . K$$

$$z_i \geq 0 \qquad i = 1, \dots\dots, N \qquad (4)$$

where z is the intensity variable. The second constraint explains that the undesirable output is weakly disposable. This can easily be modified to incorporate strong disposability by changing the equality constraint. The expansion factor δ measures the distance from the observed performance of the farm to the production frontier at the boundary of the feasible production set in the desired direction, *d*. Alternatively, if δ_i is equal to zero, farm *i* lies on the production possibility frontier. Here, δ does not require any functional form specification but is sensitive to measurement units and magnitude of the variable. This sensitivity can cause serious problems, as inconsistency is common across agri-environmental variables (Macpherson et al., 2010). To manage this sensitivity, we transform the variables to:

$$y_g^* = \frac{y_g}{y_g^{max}};\ y_b^* = \frac{y_b}{y_b^{max}};\ \text{and}\ x_k^* = \frac{x_k}{x_k^{max}}\ \forall k \qquad (5)$$

Under this transformation, δ is similar to an elasticity measure (Picazo-Tadeo et al., 2005) and is equivalent to the maximum increase (decrease) in desirable outputs (inputs and undesirable outputs) as a percentage of the maximum observation for each variable in the dataset (Macpherson et al., 2010).

2.4 Estimating the meta technology ratio (MTR)

Let $\vec{D}_k(x, y_g, y_b; d)$ be the output oriented distance function for the group frontier representing the group benchmark technology $\mathrm{P^k}$ $\left(\mathrm{P^k} = \{\mathrm{P^{Bt}}, \mathrm{P^{NonBt}}\}\right)$ and $\vec{D}_G(x, y_g, y_b; d)$ be the distance function of the meta-frontier representing global technology, $\mathrm{P^G}$. Then, the meta technology ratio, MTR (technology gap ratio), is defined as:

$$MTR^k(x, y_g, y_b; d) = \frac{\vec{D}_G(x, y_g, y_b; d)}{\vec{D}_k(x, y_g, y_b; d)} \qquad (6)$$

This can be illustrated using Fig. 1 for farm A cultivating Bt cotton. The distance $\mathrm{Af_1}$ represents the relative position of the farm with reference to the group frontier (Bt frontier), and $\mathrm{Af_w}$ is the distance from the global frontier. Thus, $MTR^{Bt}(x, y_g, y_b; d) = \frac{\vec{D}_G(x, y_g, y_b; d)}{\vec{D}_{Bt}(x, y_g, y_b; d)} = \frac{Af_1}{Af_w}$.

3. Results and discussion

3.1. Descriptive statistics

Pest-resistant transgenic crops were introduced as a potential technology option that combines higher yields with environmentally friendly agronomic practices (Phipps and Beever, 2000). The left-hand part of Table 1 shows pesticide quantity and pesticide cost per hectare (ha) of Bt and conventional cotton, disaggregating pesticides by World Health Organization (WHO) toxicity classes.[1] Across all toxicity classes, we observe lower pesticide use in Bt than in conventional cotton. Overall, pesticide use in conventional cotton was more than double the use in Bt cotton. Lower pesticide use with Bt cotton was also observed in other countries where this technology is used (e.g, Qaim and de Janvry, 2005; Lu et al., 2012; Krishna and Qaim, 2012). However, an unexpected pattern is observed with respect to the use of uncategorized chemicals: while the quantity of a.i. used is comparable across technologies, the cost is twice as high in conventional cotton. This is because certain highly priced pesticides, like Spinosad (broad-spectrum insecticide) and Indocarb (effective against bollworms), which fall into this category, are used more frequently in conventional cotton.

A breakdown of pesticide use by survey round is provided in Figure S1 (Supplementary Material). Interesting to observe is that there has been a reduction across all toxicity classes over time for both Bt and conventional cotton. In Bt cotton, pesticide use was already low in 2002, but a further reduction of highly toxic pesticides occurred between 2004 and 2006. This coincides with more widespread adoption of Bt cotton and the introduction of a larger number of Bt varieties that are better adapted to diverse agro-climatic conditions (Krishna et al., 2014).

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[1] Class Ia stands for extremely toxic; class III refers to the least toxic products. Chemicals that are either unlikely to be hazardous or have not yet been classified are captured under “others”.

Also in 2006, Bt cotton varieties containing two Bt genes (*cry1Ac* and *cry2Ab*) that together provide more effective resistance to a broader spectrum of insect pests were commercially released. The wide adoption of Bt varieties in the later period contributed to area-wide suppression of Bt target pests, so that even non-adopters of the technology were able to reduce their chemical pesticide use.

3.2. Environmental impacts of Bt adoption

The use of chemical pesticides causes negative health and environmental externalities, but these externalities are not necessarily proportional to pesticide quantity, as products vary in terms of their eco-toxicological impacts. The WHO toxicity classes are a better indicator of toxicity, but they only provide a partial picture, because they concentrate on human health impacts and less on environmental effects. As explained above, we calculate the EIQ to assess health and environmental effects from a broader perspective. The right-hand part of Table 1 compares pesticide EIQ for Bt and conventional cotton (see Figure S2 of the Supplementary Material for a breakdown by survey round). We compare EIQ field use rating (field) as an aggregate measure, as well as EIQ for farm workers (worker/human) and the ecology (ecological) as separate categories. The field use rating shows significant differences between Bt and conventional cotton, especially for the higher WHO toxicity classes. Pesticide use in Bt cotton has much lower negative health and environmental impacts.

The disaggregation reveals that the difference is larger for ecological than for human health dimensions (Table 1), which is consistent with findings by Kleter et al. (2007). In spite of significant differences between Bt and conventional cotton, it should be noted that the EIQ values for both technologies are associated with high variability. This variability is due to differing cultivation practices across the geographic regions with varying agro-climatic and socio-economic conditions. This issue is addressed below as part of the regression analysis.

Estimation results of the panel regressions with EIQ and its components (ecological and farm worker) as dependent variables are shown in Table 2. While the RE and FE specifications show similar results, the Hausman test reveals systematic differences, so that the FE results are preferred for the interpretation of Bt impacts in particular. Bt adoption has led to a significant decrease in negative health and environmental impacts of pesticide use, and this beneficial effect has increased over time. The net impact of Bt adoption is equivalent to a 39% decrease in EIQ field use rating during 2002-2004, and to a 68% decrease during 2006-2008. The separate models for ecological and farm worker EIQ show similar results. The negative and significant effect of non-Bt during 2006–2008 can be explained through the area-wide suppression of Bt target pests through widespread Bt adoption, as was already mentioned above.

Most of the other control variables have the expected signs. Irrigation and more rainfall are associated with higher EIQ (Table 2), as moist conditions lead to higher insect pest pressure and more frequent pesticide applications. The household food expenditure share, which we use as a proxy for living standard, does not have a significant effect, suggesting that richer and poorer cotton-growing households produce with similar environmental impacts, once other factors are controlled for. However, the RE specifications show that better educated farmers produce with lower negative health and environmental impacts, probably due to their higher awareness of the toxic effects of chemical pesticides. Finally the state dummies point at significant regional differences. Cotton production in Maharashtra, Andhra-Pradesh, and

Karnataka is associated with more negative externalities than cotton production in Tamil Nadu, which is the reference state in these model specifications.

3.3. Environmental efficiency of cotton production

As argued above, cotton production generates both desirable and undesirable outputs. Summary statistics for both types of output are shown in Table 3, alongside the input variables used in the production frontier models. The pooled sample shows a significantly higher average yield and a lower EIQ for Bt cotton. Positive yield effects of Bt cotton were also reported in other studies for India (Subramanian and Qaim, 2010; Kathage and Qaim, 2012) and other developing countries (Pray et al., 2002; Thirtle et al., 2003; Qaim, 2009; Ali and Abdulai, 2010; Kouser and Qaim, 2013a). The yield difference is consistent across all four survey rounds. In contrast, the EIQ differences between Bt and conventional cotton vary over time, which is due to the fact that both Bt and non-Bt adopters could reduce their pesticide applications since 2006.

The estimation results of the environmental-economic efficiency models are shown in Table 4. While the results of the DDF and EPF models are broadly similar, we consider the DDF model with weak disposability of the undesirable output as most appropriate (model 1). We used the meta-frontier concept as the boundary of an unrestricted technology set. This frontier envelops both types of technologies (Hayami and Ruttan, 1970; Beltrán-Esteve et al., 2014). A global frontier is also constructed by enveloping all the available technology sets over the entire period of the study. As shown in Table 4, this global frontier reveals a significantly higher efficiency for Bt technology. With an average efficiency score of 66%, Bt farmers are 10 percentage points more efficient than non-Bt farmers. However, the efficiency scores are relatively low in general, pointing at high heterogeneity and ample scope to improve the environmental-economic performance. While Bt technology helps to reduce negative health and environmental externalities, many Bt adopters still over-use chemical pesticides. The interpretation is similar when comparing Bt and non-Bt plots in each survey year with respect to the individual group frontiers. Furthermore, it can be seen that the differences in efficiency scores between Bt and non-Bt have decreased over time: the difference was 11 percentage points in 2002; it decreased to 7 percentage points in 2006 (in 2008, the number of non-Bt plot observations was too small for a meaningful comparison).

Fig. 2 establishes the differential impact of environmentally hazardous pesticide use on the efficiency of Bt and non-Bt cotton production. On average, pesticide use has a positive influence on efficiency for non-Bt cotton, particularly at lower and higher levels (less so in the medium range of pesticide use), whereas it has a clear negative influence on efficiency for Bt cotton.

The meta-technology ratios (MTR), which measure how close Bt and non-Bt production are to the global technology frontier (Battese et al., 2004; O'Donnell et al., 2008), are also shown in Table 4. Overall, the MTR does not differ much between the two technologies in the DDF models, but the MTR is higher for Bt when the cost of disposing the pesticide environmental risk is not taken into account in the EPF models. In model (1), both Bt and non-Bt production exhibit a technology gap of about 15% with respect to the global technology frontier. However, we observe an interesting development over time. While the MTR for Bt cotton production increased after 2002, the same trend is not observed in non-Bt cotton production. These trends suggest that Bt cotton production is more promising in both technological and environmental dimensions.

3.4. Technology quality and efficiency

The results of the environmental-economic efficiency and MTR analyses showed high heterogeneity even among the Bt adopters. Several studies pointed at significant variability in Bt impacts due to differences in farm, household, and contextual characteristics (Gouse et al., 2005; Qaim and de Janvry, 2005; Qaim et al., 2006; Morse et al., 2007; Kouser and Qaim, 2011). Another possible factor is the varying quality of the transgenic technology itself, which has rarely been analysed (Gouse et al., 2005; Useche et al., 2009). In India, different types of Bt seeds were sold in different phases of the diffusion process. Between 2002 and 2004, only a few Bt varieties were officially approved and sold by a small number of seed companies at relatively high prices. In addition, illegal Bt seeds of varying quality were sold in the market, usually at lower prices. We use the Bt seed price as an indicator of technology quality. The left-hand panel of Fig. 3 shows a clear positive relationship between the Bt seed price and efficiency in Bt cotton production in the 2002-2004 period.

In 2006, the market for Bt seeds changed considerably (Sadashivappa and Qaim, 2009; Krishna and Qaim, 2012). First, many additional Bt varieties were officially approved and sold by a much larger number of seed companies. Many of the new Bt varieties also contained the improved transgenic technology with two different Bt genes. Second, regional governments in some of the states intervened in the market by setting maximum retail prices for the sale of Bt seeds. In some districts, local governments even subsidized the Bt seed price to make the technology more accessible to farmers. At the same time, the first publicly developed Bt seeds were commercialized. The right-hand panel of Fig. 3 shows that the relationship between Bt seed prices paid by farmers and efficiency of Bt cotton production changed in the 2006-2008 period, following a U-shape. Very low seed prices are associated with high mean efficiency scores. These seem to be the observations of farmers who used high-quality Bt seeds but only had to pay a low price, because they benefited from subsidies and low maximum retail levels imposed by the state governments.

Medium-priced seeds were associated with low efficiency scores in 2006-2008. These were probably seeds of dubious quality obtained from various sources. In some regions, due to the government price intervention, the demand for Bt seeds was higher than the supply in the formal market, so that different forms of black-market sales emerged. Beyond a certain Bt seed price level, a positive relationship with production efficiency is observed. We conclude that technology quality also played an important role for efficiency in 2006-2008.

5. Conclusion

Controversies around transgenic technologies arise and persist primarily in the absence of credible empirical evidence on the impacts (Sturgis et al., 2005; Marvier et al., 2007). In this paper, we have provided empirical evidence on the impact of Bt cotton on pesticide-induced environmental and health risks in India. Based on the results, the following conclusions can be drawn.

First, cotton farmers who adopted Bt technology moved toward more eco-friendly pesticides. Bt adoption has decreased the use of chemical pesticides in general, but particularly of those pesticides that are highly hazardous for the environment and human health. Thus, Bt technology contributes to a greener production process. At the same time, yields with Bt cotton are consistently higher than that with conventional varieties.

Second, a higher level of environmental efficiency is achievable with Bt technology. Nevertheless, we also observed considerable heterogeneity, which can partly be attributed to differences in technology quality. Lower-quality Bt seeds are associated with low efficiency, while higher-quality Bt seeds are associated with higher efficiency. This points at the importance of transparent and competitive seed markets to foster sustainable agricultural growth.

Finally, even though Bt adoption has resulted in significant efficiency gains, the overall environmental-economic production still shows ample scope for further improvement. The mean environmental-economic efficiency score of Bt cotton cultivation is only 66% with a 15% technology gap. Varying technology quality can explain some of this gap, but several other factors are likely to play a role, too. This requires further investigation. In any case, transgenic seeds should be considered as one element of a broader agricultural development strategy, not as a magic technology that could substitute for other important elements such as improved agronomy, education, markets, or agricultural policy.

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Tables & Figures

Table 1: Pesticide use and EIQ across Bt and non-Bt plots

WHO Toxicity class	Quantity [kg a.i./ha]		Cost [Rs/ha]		EIQ					
					Field		Worker/human		Ecological	
	Bt	Non-Bt	Bt	Non-Bt	Bt	Non-Bt	Bt	Non-Bt	Bt	Non-Bt
Ia	4.E-03***	0.01	10.31	15.21	0.46***	1.38	0.603**	1.178	0.704***	2.659
	(0.04)	(0.08)	(80.37)	(81.35)	(3.79)	(8.63)	(5.114)	(6.823)	(6.070)	(17.639)
Ib	0.11***	0.36	246.57***	668.37	22.13***	54.98	31.724***	73.321	27.059***	75.706
	(0.25)	(0.52)	(491.99)	(962.54)	(59.85)	(70.94)	(91.742)	(99.949)	(70.998)	(100.697)
II	0.12***	0.38	1500.19	1629.89	13.30***	38.87	5.846***	18.451	28.875***	77.793
	(0.21)	(0.46)	(2171.92)	(2531.90)	(27.09)	(46.62)	(18.967)	(22.588)	(54.629)	(89.506)
III	0.06***	0.11	84.12***	136.69	3.40***	6.33	2.046***	3.760	6.462***	12.115
	(0.24)	(0.48)	(267.30)	(534.13)	(12.55)	(26.02)	(7.561)	(15.647)	(23.789)	(49.442)
Others	0.15***	0.19	5717.97***	10542.23	4.23*	5.67	1.951**	2.823	9.827***	13.425
	(0.36)	(0.21)	(8776.53)	(15179.59)	(11.05)	(14.47)	(7.296)	(10.762)	(26.089)	(35.896)
Overall	0.45***	1.06	7559.16***	12992.40	43.52***	107.22	42.169***	99.533	72.928***	181.698
	(0.65)	(1.07)	(9455.54)	(16086.59)	(73.34)	(106.45)	(96.647)	(114.656)	(108.592)	(175.118)

Mean values are shown with standard deviations in parentheses. The number of observations is 988 for Bt and 662 for non-Bt plots. *,**,***: the difference between Bt and non-Bt plots is statistically significant at 0.1, 0.05, and 0.01 levels, respectively.

Table 2. Determinants of EIQ

	EIQ (field)		EIQ (ecology)		EIQ (worker)	
	Model (1) RE	Model (2) FE	Model (3) RE	Model (4) FE	Model (5) RE	Model (6) FE
Technology adoption status						
Bt2002-04 (dummy)	-48.311***	-41.340***	-84.516***	-75.444***	-39.477***	-30.513***
	(6.029)	(6.701)	(9.481)	(10.485)	(7.230)	(8.229)
Bt2006-08 (dummy)	-76.531***	-73.325***	-124.765***	-124.768***	-72.475***	-69.742***
	(4.881)	(5.591)	(7.676)	(8.748)	(5.854)	(6.866)
Non-Bt2006-08 (dummy)	-66.649***	-72.579***	-111.559***	-125.665***	-56.796***	-65.282***
	(11.292)	(13.290)	(17.756)	(20.794)	(13.538)	(16.319)
Production variables						
Crop duration (days)	-0.020	0.061	0.061	0.167	-0.103	0.026
	(0.063)	(0.078)	(0.099)	(0.123)	(0.076)	(0.096)
Plot size (ha)	0.226	1.091	0.500	2.504*	-0.166	0.376
	(0.652)	(0.949)	(1.024)	(1.485)	(0.781)	(1.166)
Irrigation (no. of times)	5.172***	3.741***	7.667***	5.291***	5.370***	4.504***
	(0.633)	(0.987)	(0.995)	(1.544)	(0.758)	(1.212)
Rainfall (centimetres)	0.229***	0.282***	0.572***	0.529***	0.130***	0.226***
	(0.056)	(0.085)	(0.088)	(0.133)	(0.067)	(0.104)
Household characteristics						
Farmer education (years)	-1.766***		-2.974***		-1.794***	
	(0.461)		(0.724)		(0.552)	
Farmer age (years)	-0.180		-0.377		-0.131	
	(0.180)		(0.282)		(0.215)	
Household members (no.)	-0.041		-0.123		0.280	
	(0.598)		(0.940)		(0.716)	
Food expenditure share (%)	-0.134	-0.160	-0.272	-0.228	-0.124	-0.273
	(0.141)	(0.191)	(0.222)	(0.298)	(0.169)	(0.234)
State controls						
Maharashtra (dummy)	29.514***		42.165***		43.136***	
	(10.802)		(16.967)		(12.919)	
Andhra Pradesh (dummy)	33.542***		38.893**		54.159***	
	(10.884)		(17.097)		(13.018)	
Karnataka (dummy)	47.493***		57.857***		66.791***	
	(10.449)		(16.415)		(12.499)	
Intercept	68.132***	55.480***	91.019***	72.240**	71.216***	68.940***
	(20.890)	(22.612)	(32.829)	(35.380)	(25.012)	(27.767)
Model statistics						
LR/Wald χ^2 [14]	413.83***		470.39***		266.89***	
F value [8,1109]		32.1***		39.15***		18.73***
Hausman test χ^2 [8]		14.90*		14.66*		15.34**

Notes: Estimates are based on unbalanced panel regressions with 1650 observations and 533 groups. Numbers in parentheses are standard errors. EIQ, environmental impact quotient; RE, random effects, FE, fixed effects.

*,**,***: Statistically significant at 0.1, 0.05, and 0.01 levels, respectively.

Table 3: Summary statistics of production inputs and outputs in the frontier models

	2002		2004		2006		2008		All	
Variable	**Bt**	**Non-Bt**	**Bt**	**Non-Bt**	**Bt**	**Non-Bt**	**Bt**	**Non-Bt**	**Bt**	**Non-Bt**
	(n=133)	(n=301)	(n=165)	(n=299)	(n=315)	(n=54)	(n=375)	(n=8)	(n=988)	(n=662)
Outputs										
Yield	6.59^{***}	4.91	$7.43^{**,++}$	5.51^{++}	$8.47^{***,+++}$	6.12	8.18	5.81	7.93^{***}	5.29
	(3.94)	(3.36)	(3.28)	(2.92)	(3.51)	(3.21)	(3.28)	(1.78)	(3.50)	(3.16)
EIQ	58.95^{***}	126.42	71.51^{**}	100.13^{+++}	42.17^{+++}	51.69^{+++}	26.88^{+++}	24.76	43.52^{***}	107.22
	(72.09)	(103.90)	(132.67)	(111.43)	(56.11)	(60.15)	(35.91)	(43.33)	(73.34)	(106.45)
Inputs										
Duration	223.52	224.92	209.98^{+++}	213.23^{+++}	197.35^{+++}	196.83^{+++}	238.80^{+++}	238.13	218.72	217.51
	(36.14)	(30.56)	(30.26)	(28.17)	(33.64)	(33.59)	(31.31)	(39.11)	(37.06)	(31.01)
Irrigation	3.74^{***}	2.29	2.41^{+++}	1.81	2.10	2.17	2.24	1.88	2.43^{**}	2.06
	(4.81)	(3.78)	(4.29)	(3.63)	(2.53)	(2.91)	(3.39)	(3.48)	(3.58)	(3.64)
Plot size	2.51^{***}	3.51	2.87	3.25	3.49^{+}	3.01	3.24	2.56	3.16	3.34
	(4.34)	(3.02)	(3.18)	(3.23)	(4.11)	(3.44)	(2.79)	(1.88)	(3.55)	(3.14)
Seed	0.45^{***}	0.67	$0.52^{***,+++}$	0.65	0.56^{+++}	0.56^{++}	0.58^{++}	1.20	0.55^{***}	0.66
	(0.06)	(0.60)	(0.13)	(0.50)	(0.10)	(0.22)	(0.20)	(1.11)	(0.15)	(0.55)
Fertilizer	2.74^{***}	2.39	2.78^{*}	2.47	$2.46^{**,++}$	2.01^{++}	2.41	2.75	2.53^{*}	2.40
	(1.66)	(1.49)	(1.58)	(1.64)	(1.58)	(1.09)	(1.53)	(1.91)	(1.58)	(1.54)
Pesticide	2.07^{***}	4.17	$2.03^{***,+}$	3.09^{+++}	1.22^{+++}	1.55^{+++}	0.89^{+++}	1.19	1.34^{***}	3.43
	(2.65)	(3.37)	(2.66)	(2.60)	(1.41)	(1.52)	(0.98)	(2.42)	(1.83)	(3.02)
Labour	81.98^{***}	71.00	$84.24^{***,++}$	70.59	89.18	100.12^{+++}	78.44^{+++}	75.90	83.31^{***}	73.25
	(42.03)	(31.46)	(39.89)	(33.10)	(53.91)	(53.84)	(49.02)	(35.95)	(48.54)	(35.41)

*,**,*** : Difference between Bt and non-Bt plots in the same year is significant at 0.1, 0.05, and 0.01 levels, respectively; $^{+,++,+++}$: Difference with the same technology in the previous period is significant at 0.1, 0.05, and 0.01 levels, respectively. Due to the low number of non-Bt plot observations in 2008, we did not perform tests of significance for the difference between Bt and non-Bt for that year.

Table 4: Efficiency of cotton production

Year	Technology	Model (1)			Model (2)			Model (3)			Model (4)		
		GF	MF	MTR	GF	MF	MTR	GF	MF	MTR	GF	MF	MTR
2002	Bt	0.81 (0.21)	0.62 (0.20)	0.79 (0.20)	0.74 (0.20)	0.59 (0.17)	0.82* (0.16)	0.89 (0.16)	0.73 (0.22)	0.83 (0.18)	0.65*** (0.28)	0.48*** (0.25)	0.73*** (0.18)
	Non-Bt	0.70 (0.21)	0.55 (0.14)	0.83 (0.19)	0.63 (0.16)	0.54 (0.12)	0.89 (0.14)	0.85 (0.17)	0.73 (0.20)	0.86 (0.13)	0.49 (0.27)	0.34 (0.23)	0.68 (0.18)
2004	Bt	0.73$^{***,++}$ (0.21)	0.64$^{**,++}$ (0.18)	0.89$^{***,+++}$ (0.13)	0.67$^{***,+++}$ (0.17)	0.59$^{***,++}$ (0.14)	0.91$^{***,+++}$ (0.11)	0.84** (0.18)	0.76** (0.20)	0.90^{+} (0.11)	0.62$^{***,+++}$ (0.22)	0.51*** (0.21)	0.82$^{**,+++}$ (0.14)
	Non-Bt	0.65^{+} (0.20)	0.56 (0.15)	0.90^{+++} (0.15)	0.59 (0.14)	0.53 (0.10)	0.92^{+++} (0.11)	0.79^{+++} (0.20)	0.71^{+} (0.20)	0.89 (0.11)	0.50^{+++} (0.22)	0.39^{+} (0.19)	0.77^{+++} (0.15)
2006	Bt	0.78$^{***,+++}$ (0.21)	0.68$^{*,+++}$ (0.21)	0.88^{+} (0.16)	0.70^{+++} (0.19)	0.64^{+++} (0.18)	0.92^{+} (0.12)	0.89 (0.16)	0.80$^{***,++}$ (0.20)	0.90$^{***,+}$ (0.12)	0.64^{+++} (0.25)	0.58$^{***,++}$ (0.23)	0.91$^{***,+++}$ (0.13)
	Non-Bt	0.71$^{***,+++}$ (0.24)	0.57^{+++} (0.21)	0.83^{+++} (0.22)	0.65^{++} (0.20)	0.54^{+++} (0.18)	0.87^{+++} (0.20)	0.84 (0.20)	0.66^{++} (0.24)	0.78 (0.20)	0.56^{+++} (0.28)	0.44^{+++} (0.23)	0.83^{++} (0.20)
2008	Bt	0.81^{+++} (0.20)	0.67 (0.20)	0.84 (0.16)	0.72 (0.17)	0.62 (0.16)	0.88$^{***,+++}$ (0.11)	0.89 (0.16)	0.80 (0.21)	0.89** (0.13)	0.67 (0.22)	0.56 (0.21)	0.83$^{**,+++}$ (0.12)
	Non-Bt	0.73 (0.21)	0.51 (0.10)	0.75 (0.23)	0.73 (0.21)	0.51 (0.10)	0.75 (0.23)	0.87 (0.12)	0.62 (0.20)	0.71 (0.19)	0.68 (0.26)	0.45 (0.14)	0.70^{++} (0.18)
Overall	Bt	0.79*** (0.21)	0.66** (0.20)	0.85*** (0.17)	0.70*** (0.18)	0.62*** (0.16)	0.89*** (0.13)	0.88*** (0.17)	0.79*** (0.21)	0.89*** (0.13)	0.65*** (0.24)	0.55*** (0.23)	0.84*** (0.15)
	Non-Bt	0.68 (0.21)	0.56 (0.15)	0.86 (0.18)	0.61 (0.16)	0.54 (0.11)	0.90 (0.14)	0.83 (0.19)	0.71 (0.21)	0.86 (0.13)	0.50 (0.25)	0.37 (0.21)	0.73 (0.18)
Pooled sample		0.74 (0.22)	0.62 (0.19)	0.86 (0.17)	0.67 (0.18)	0.59 (0.15)	0.89 (0.13)	0.86 (0.18)	0.76 (0.21)	0.88 (0.13)	0.59 (0.25)	0.48 (0.24)	0.80 (0.17)

Model (1): directional distance function (DDF) with weak disposability; Model (2): DDF with strong disposability; Model (3): environmental production function (EPF) with weak disposability; Model (4): EPF with strong disposability. Efficiency is calculated with reference to the global frontier.

GF, group frontier; MF, meta-frontier; MTR, meta technology ratio.

*,**,*** : Difference between Bt and non-Bt plots in the same year is significant at 0.1, 0.05, and 0.01 levels, respectively, using the test described by Li et al. (2009); $^{+,++,+++}$: Difference with the same technology in the previous period is significant at 0.1, 0.05, and 0.01 levels, respectively.

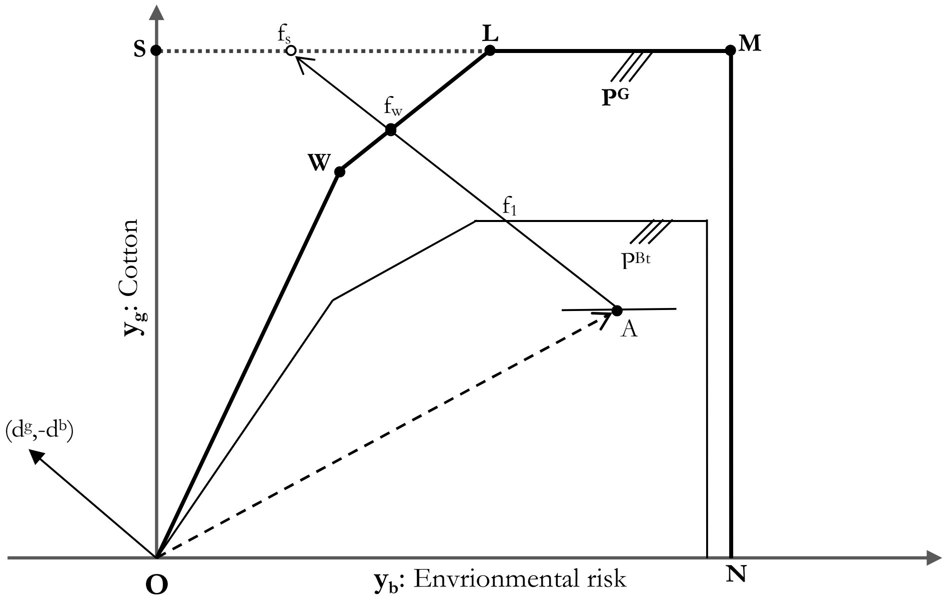
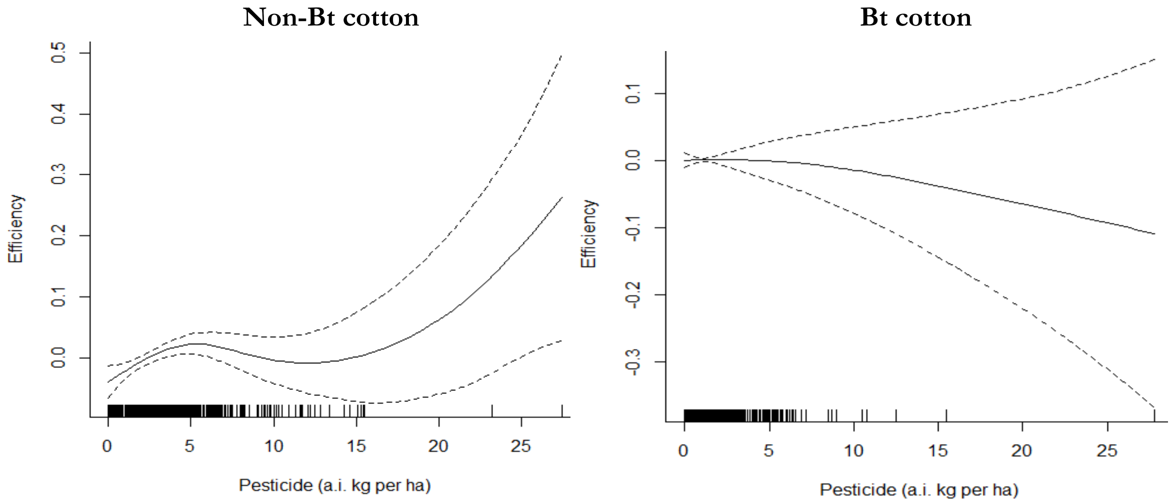
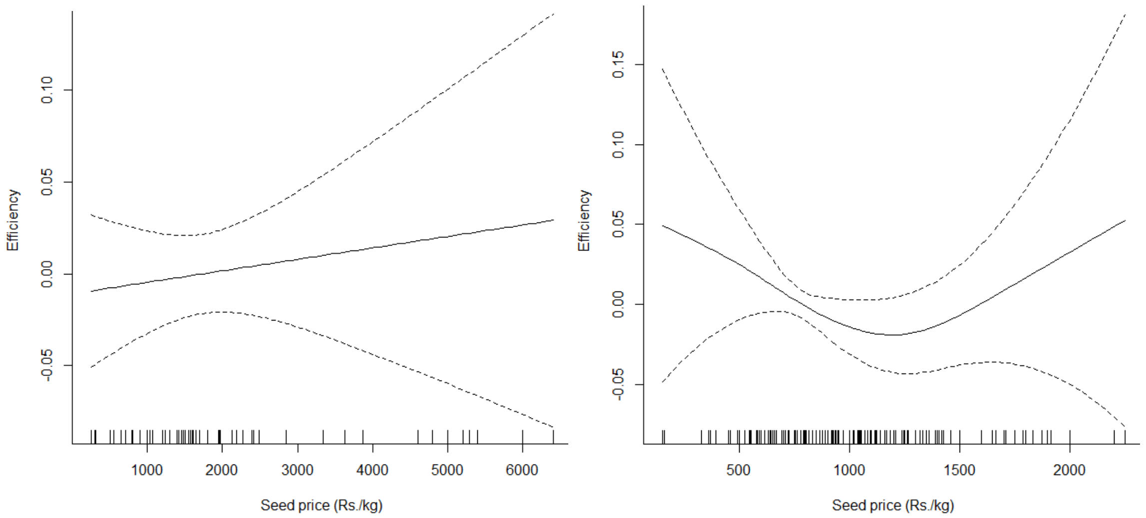


Fig. 1: Directional distance function in cotton production context



Note: Dotted lines indicate the 95% confidence interval

Fig. 2: Relationship between pesticide quantity and efficiency



a. 2002-2004 **b. 2006-2008**

Note: Dotted lines indicate the 95% confidence interval

Fig. 3: Relationship between Bt quality (seed price) and efficiency

Supplementary material

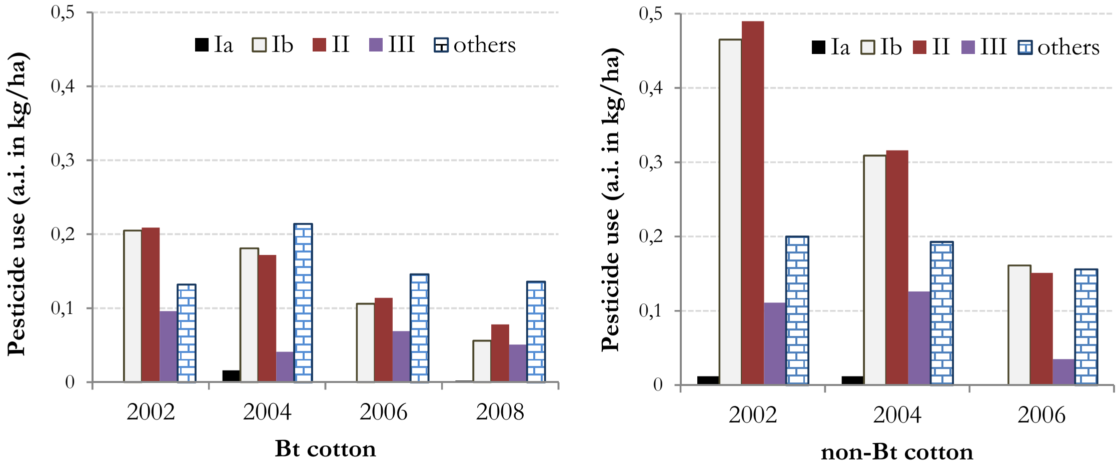


Fig. S1: Pesticide use in Bt and non-Bt cotton by WHO toxicity classes

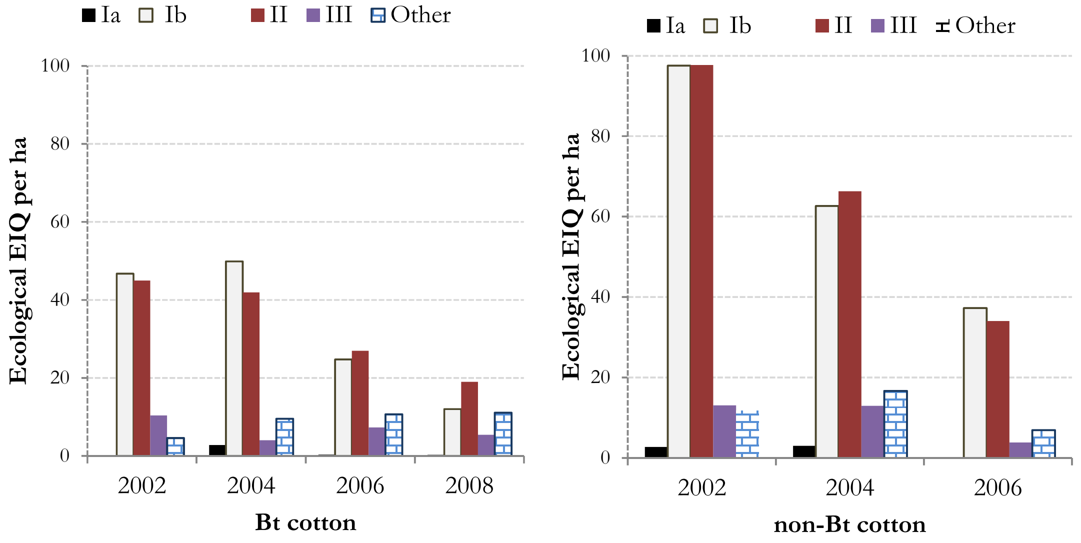


Fig. S2: Ecological risk of pesticide use in Bt and non-Bt cotton