RESEARCH ARTICLE

Adopting Hybrid Bt Cotton: Using Interrupted Time-Series Analysis to Assess Its Effects on Farmers in Northern India

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Abstract: More than a decade has passed since Bt cotton was introduced in India. It is now possible to use official cotton statistics to assess whether Bt cotton has had positive effects on farmers' lives and livelihoods. I use interrupted time-series analysis of data on insecticide costs, yields, and profits to examine trends before and after the introduction of Bt cotton in the States of Haryana, Punjab, and Rajasthan, in northern India. The conclusions from these analyses are mixed. The more expensive Bt hybrid seeds have lowered insecticide costs in all three States, but only in Rajasthan did yields increase. An important message of this paper is that conclusions about the effectiveness of Bt cotton are more nuanced than many researchers and commentators recognise. The paper does not refute the assertions about the success of Bt cotton, but it does show that the benefits are not evenly distributed across India.

Keywords: Bt cotton, causality, cotton statistics, insecticide, costs, interrupted time-series, northern India, profit, yield, Haryana, Punjab, Rajasthan.

Introduction

The effects of introducing genetically engineered (GE) or genetically modified (GM) cotton in India have been assessed in a number of research papers over the last 15 years, and their ramifications continue to be widely debated in civil society, in India and further afield. It is widely accepted (Financial Express Bureau 2018) – but certainly not uncontested (Gutierrez 2018) – that the introduction of this kind of cotton, often referred to as Bt cotton, has had a beneficial effect on production, trade, farmers' livelihoods, and the environment. On the other hand, successive Indian governments have been reluctant to fully embrace GE technology, leading to bans on the cultivation of Bt brinjal and herbicide-tolerant (HT) cotton, and to delays in introducing GE mustard. Arguments about reasons for farmers' suicides

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refuse to die down despite the absence of any evidence linking the introduction of Bt cotton to an increase in the suicide rate (Plewis 2014a; Plewis 2014b).

This paper adds to the corpus of research on the effects on farmers of adopting Bt cotton in three novel ways. First, it uses annual time-series of cotton statistics over several years, rather than choosing and comparing two time points with the attendant problems of selecting years and ignoring year-to-year variability. Secondly, it draws on the strengths of statistical modelling and statistical inference to generate plausible causal conclusions. Thirdly, it focuses on a range of relevant outcomes at the State rather than national level, and so allows for some spatial heterogeneity. To anticipate the paper's conclusions, the analysis demonstrates that the benefits of introducing Bt cotton in the northern region of India (Haryana, Punjab, and Rajasthan) are far from clear-cut.

Bt cotton is cotton "that expresses an insecticidal protein whose gene has been derived from a soil bacterium called *Bacillus thuringiensis*" (Kranthi 2012, p. 10), and so Bt cotton is resistant to some insects, notably those in the bollworm family. The adoption of Bt technology in India has been rapid and widespread, to the extent that most of the cotton grown in India now is Bt hybrid cotton. Although estimates of the use of Bt technology vary, from State to State as well as according to the source of the estimate, it is plausible to assume that at least 80 per cent of the cotton grown in each of the nine main cotton-growing States in India is Bt cotton. We should, however, recognise that the technology has changed with time: insect resistance has improved and farmers have been able to choose from a widening range of hybrid varieties (Kranthi 2012), although there is evidence of fraudulent selling (Pradeep 2017). Recently, there have been reports that farmers are growing illegal Bt and HT stacked hybrids because they believe these will reduce the cost of weeding (Shrivastav 2019).

Farmers' enthusiasm for Bt cotton has been questioned, however, by some cotton researchers, and is tempered by evidence of the growing resistance of insects, pink bollworms in particular, to this kind of cotton (Pulla 2018). Up to now, genetic engineering has been carried out only on hybrid seeds which were developed in India in the 1970s to improve yields. It is difficult to separate the yield advantages of these hybrids from any additional advantages accruing to Bt technology in the northern States where most farmers had used only straight varieties before the introduction of Bt hybrids in 2005. Kranthi (2015) has suggested that these hybrids were introduced in the northern region without adequate testing, and so the Bt cotton plants there were especially susceptible to attacks of whitefly and associated cotton leaf curl virus.

This paper analyses trends in three cotton farming outcomes – expenditure on insecticides, yield, and profit – in the States of Haryana, Punjab, and Rajasthan. In 2014–15, these three States accounted for 12 per cent of the area and 16 per cent of the production of Indian cotton (production was lower in 2015–16, mostly because the Punjab crop was badly affected by whitefly) (GoI 2017a, Table 4.21b). Only one-third of the area growing cotton in India is under irrigation but this figure is almost 100 per cent in the northern region, so crop yields there are less susceptible to variations in weather than in rainfed regions.

It is not possible, of course, with the aggregate data generated by time-series to establish how individual farmers responded to the opportunities offered by the new technology, but it is plausible to suppose that there will be statistically robust effects on all three outcomes. The technology was introduced primarily to reduce insecticide use and so we would expect this to show up as shifts in the time-series, although it is possible that farmers might use the savings from one kind of pesticide to buy more of another kind in the hope of increasing yields. Moreover, any reduction in use will be diluted to the extent that some farmers were previously unable to afford, or disinclined to use, insecticides against bollworms. We would also expect farmer profits to rise after Bt adoption. This is partly because of declining insecticide costs (albeit offset by increasing costs of the Bt seeds), and partly due to the increased yields that might arise from poorer farmers previously unable to afford the volume of insecticides needed to control bollworms, and from those farmers willing and able to substitute fertilizer, labour, and increased irrigation for the reduction in insecticide costs.

The paper is structured as follows: the next section critically examines previous research, followed by a discussion of data sources and measures of the outcome variables and Bt adoption, the methods used, and results. The paper concludes with a discussion.

Review of Research

There have been a substantial number of Indian farm studies analysing the effects of growing Bt cotton on a range of outcome variables (yield, profit, etc.). These studies contributed to a meta-analysis of studies of the effects of adopting GM technology, conducted by Klumper and Qaim (2014). Their conclusions – "on average, GM technology adoption has reduced chemical pesticide use by 37 per cent, increased crop yields by 22 per cent, and increased farmer profits by 68 per cent" – have been widely reported. Their overall conclusions, however, hide a lot of heterogeneity, only some of which the authors explain. Indeed, it is difficult to know how useful "on average" is in this context. Klumper and Qaim (2014) do, however, show that the benefits of GM technology seem to be greater for insect-resistant (i.e. Bt) crops in developing countries such as India, than for herbicide-tolerant crops in developed countries. The majority of the studies that focus on insect-resistant technology in developing countries are in fact studies of the impact of Bt cotton in India. Hence, we might infer that there have been substantial benefits both to farmers and to the Indian economy and environment from the adoption of Bt cotton.

One problem with the observational studies that contribute to Klumper and Qaim's meta-analysis is their potential for bias: selection bias arising from unmeasured differences between "Bt" and "non-Bt" farmers that are associated with outcomes, and cultivation bias arising from farmers giving more attention to nurturing Bt crops when comparing Bt and non-Bt plots on the same farm. The main drawback, however, is one of sampling: none of the studies included by them collected data from farms in India's northern region. Their conclusions cannot, therefore, be assumed to apply to Haryana, Punjab, and Rajasthan.

More recently, Ranganathan, Gaurav, and Halder (2018) have examined data from surveys of agricultural households in 2002 and 2012 that cover all nine cotton-growing States. They show that pesticide costs fell over the decade in question, in absolute terms and as a percentage share of total costs, for farmers growing cotton but not for farmers growing other crops. These reductions were particularly marked in the northern region. Their data provide a useful comparison with those used in this paper although they do not directly address the effect of Bt cotton on pesticide use.

In contrast to the numerous farm-level studies just discussed, there are at least three papers that have used official cotton statistics to assess the effect of the introduction and adoption of Bt cotton on outcome variables of interest at the State and national (i.e. macro) levels (Gruère and Sun 2012; Suresh *et al.* 2014; Srivastava and Kolady 2016).

Gruère and Sun (2012) focus on cotton yields and use annual data at the State level from the Cost of Cultivation Surveys (CCS), discussed in more detail below and covering the period from 1975 to 2009 (with gaps). They had little post-Bt data for the States of the northern region, where Bt cotton was introduced in 2005. They model the logarithm of cotton yields as a function of a set of input variables including fertilizer in order to mimic the approach taken by many in the farm-level studies. They conclude that, conditional upon the chosen input variables, Bt adoption did contribute to growth in cotton yield with yield rising by 3–4 per cent for every 10 per cent increase in the Bt adoption rate. Their conclusions only apply, however, at the national level; they do not allow for different specifications of their model for different States. For example, they include a rainfall variable as one of their controls, which is not applicable in the northern region where nearly all cotton is irrigated. Another criticism of their approach – one that also applies to the farm studies used in the Klumper and Qaim (2014) meta-analysis – is that some of the input variables in the model are arguably response variables in a more complex causal chain. As mentioned earlier, for example, farmers may choose to substitute more fertilizer and labour for insecticides to boost yields. Controlling for such variables, which are plausibly on the causal pathway, may lead to an underestimate of the Bt effect.

Srivastava and Kolady (2016) also use annual State-level data on yield from 1994 to 2011. They use an econometric model with explanatory variables that are similar but not identical to those used by Gruère and Sun (2012). Their conclusions are based on differences in linear trends between the pre- and post-Bt phases, allowing for differences between States in the year of Bt introduction. They obtain a positive and statistically significant change in yield trend after the introduction of Bt with yields increasing in each State by about 12 kg/ha every year. Much of my criticism of the Gruère and Sun (2012) approach also applies to Srivastava and Kolady (2016).

The approach taken by Suresh *et al.* (2014) is much more descriptive than the econometric approach of the other two papers. Suresh *et al.* divide the period between 1976 to 2009 into three phases for each State: an early hybrid phase between 1976 and 1991, a late hybrid phase from 1992 to 2001, and finally, and of most relevance to this paper, a Bt phase from 2002 to 2009. They also use data for each of the nine cotton-growing States from the CCS and consider a range of outcomes – yield, profit, and various costs of production. One of the drawbacks of their descriptive approach is that they do not allow for year-to-year variability in their outcome variables when estimating differences and trends: the paper is devoid of any estimate of statistical variation. Moreover, they estimate log-linear trend rates for variables that do not necessarily have such a relationship. And, most importantly, their definition of the Bt phase does not allow for the fact that in the northern region, Bt cotton was not officially approved until 2005. Consequently, their results for the northern region are not easy to interpret in terms of estimating a Bt effect, as they appear to be based on analyses that include data from several years *before* the introduction of Bt cotton.

Data and Measures

The focus of this paper is on changes in three cotton outcomes for each of the three States: (i) insecticide costs,[1] (ii) yield,[2] and (iii) farmer profits. In addition, some consideration is given to the area devoted to growing cotton and to seed costs. This section assesses the strengths and weaknesses of the measures and data sources used.

Measures of insecticide costs and farmer profits come from the Cost of Cultivation Surveys (CCS). These are annual sample surveys that collect data directly from farmers, as described in CSO (2008). The sample sizes in each northern State are fairly small – on average, about 100 in Haryana, about 80 in Punjab, and about 60 in Rajasthan.[3] It is not entirely clear what is included in insecticide costs, in particular whether the total also includes herbicides and fungicides. Nor is there any

[1] There is a case for using weight (kg/ha) of insecticide as an outcome but these data are not collected in the CCS.
[2] Production is divided by area and usually measured as kilograms per hectare (kg/ha).
[3] The Directorate of Economics and Statistics (DES), Ministry of Agriculture, makes available plot-level data over time which are potentially very useful to extend the analyses presented in this paper. However, weaknesses in documentation allied with concerns about definitions and weighting ruled out their use here.

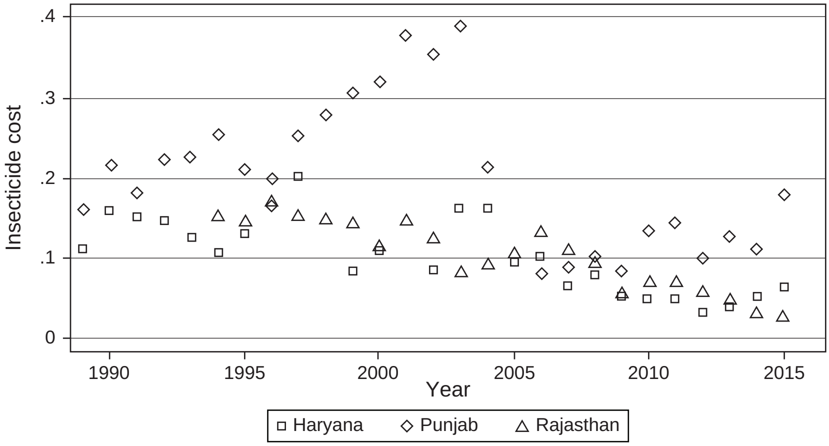

Figure 1 *Insecticide costs as a proportion of all operational costs, by year, Haryana, Punjab, and Rajasthan, 1990–2015*
Source: Cost of Cultivation Surveys (CCS).

separation of insecticide costs for different kinds of pests. To avoid problems caused by rising prices, I follow Suresh *et al.* (2014) and use insecticide costs as a proportion of all operational (i.e. variable) costs. Figure 1 shows how this proportion changes by year for each State. We see that the costs are much higher in Punjab than in the other two States. The quality of the estimates from CCS depends on the quality of sampling and field operations, the extent of farmer non-response (which is not documented), and the degree to which farmers are able to provide accurate answers to the many questions they are asked, especially if they grow more than one crop. Given the rather small sample sizes at the State level, the sampling will inevitably introduce random year-to-year variation.

There are three sources of data on cotton yields. Harvested cotton (*kapas*, sometimes known as seed cotton) contains two components of value: the more valuable lint and the less valuable cotton seed. The lint is usually extracted from the seed cotton at a ginning factory. The proportion of lint extracted from the harvested crop – the out-turn – varies by the variety of cotton planted and by factory, but averages at about 36 per cent. Some of the most widely used data on yields are those provided by the Cotton Advisory Board (CAB) by State and crop year (July to June), and published by the Central Institute for Cotton Research (CICR). They cover the period from 1991 to 2016. The data are based on arrivals at cotton ginning mills and are subject to revision for up to two years. Doubts have been expressed about the reliability of the data at State level as, among other things, they are based on incomplete returns from ginning mills and do not allow for cotton produced in one State being processed in a neighbouring State (U. C. Sud, personal communication). Since 2010, CAB has made an allowance for the fact that not all cotton is sent to the mills, but because the basis of this adjustment is not clear and it appears to be the same every year despite variation in production, I exclude their estimate of “loose cotton” from my analysis.

Data on yield of cotton are based on crop-cutting experiments of *kapas* carried out on randomly selected plots and adjusted by an (unknown) local out-turn figure, published for each State and year by the Directorate of Economics and Statistics (DES), Ministry of Agriculture, and cover the period from 1964 to 2016. Although the methodology is sound in principle, doubts have been expressed about the quality of data (Singh 2009). The third source of data on yield is the CCS: these surveys provide estimates of *kapas* yield from 1990 to 2015, based on farmer responses. They have been converted to lint here, assuming an out-turn multiplier of 0.36 for each State and year.

Table 1 gives the mean yields for each State, for the periods for which there are data on each measure. It shows that there are substantial differences between the different measures of mean yield within a State, with the CCS always greater (and more variable) than the CAB. The correlations between the three measures across time are, however, high, particularly for the DES and CAB estimates. Given the omission of loose cotton from the CAB estimates, one would expect them to be lower than those from DES, but this is not so for Rajasthan.

The definition of profit depends on the definition of farmer costs. Suresh *et al.* (2014) use two measures of costs, costs A2 and C2, with cost A2 covering costs of inputs, rent, taxes, and interest charges, and cost C2 adding the value of family labour and the rental value of owned land. The gross value of the cotton produced is then divided by one of these costs to give two measures of profit ratio, labelled A2 and C2. Values less than one indicate a loss. Profit ratio C2 is, by definition, smaller than profit ratio A2; C2 tends to be less variable and less prone to outliers than A2, and is also closer to what would usually be regarded as profit by economists. Thus, C2 is used here. The two rates are, however, highly correlated over time.[4] Figure 2 shows how profit

Table 1 *Mean yield (SD) and correlations for cotton yield measures, by State*, in kg per ha

Data source	Haryana	Punjab	Rajasthan
CCS	473 (166)	526 (202)	521 (156)
DES	487 (166)	544 (170)	358 (124)
CAB	408 (137)	439 (161)	421 (109)
r (CCS, DES)	0.89	0.95	0.77
r (CCS, CAB)	0.83	0.84	0.80
r (DES, CAB)	0.97	0.93	0.93

Note: All means and correlations are for the periods with complete data. Haryana: 1994 to 2015 (n = 22); Punjab: 1991 to 2015 (n = 25); Rajasthan: 1994 to 2015 excluding 1998 (n = 21).

[4] The estimates are Haryana: 0.86, Punjab: 0.98, Rajasthan: 0.90.

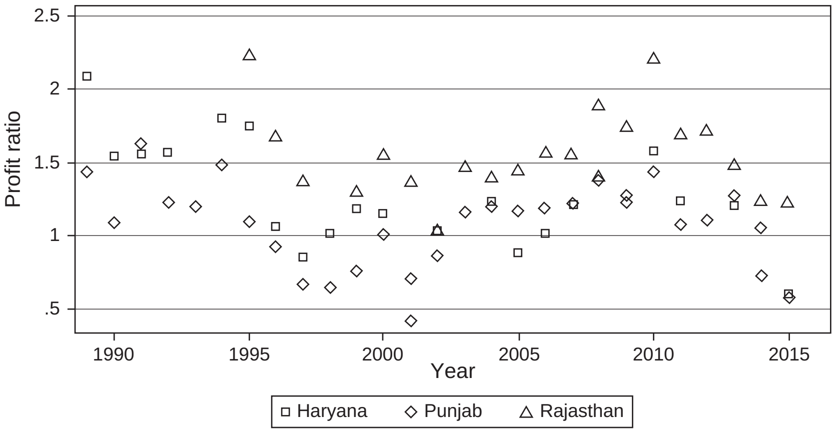

Figure 2 *Change in profit ratio C2 by year, Haryana, Punjab, and Rajasthan, 1990–2015*
Source: Cost of Cultivation Surveys (CCS).

ratio C2 varies by year for each State. Note that values below one (i.e. a loss) are not uncommon, especially in Punjab.

Finally, we turn to measures of Bt adoption rates for each year and State.[5] As there is no single definitive official estimate, we draw on data from a range of sources, both official and unofficial. Perhaps the most widely used source of data on Bt adoption, namely the International Service for the Acquisition of Agri-Biotech Applications (Choudhary and Gaur 2015), cannot be used here, as it only provides data for the northern region as a whole. State agricultural statistics for Punjab and Haryana give Bt adoption rates for 2005 to 2007; Global AgriSystem (2015) gives data for each year up to 2014; Kranthi (2012) provides rates from 2005 to 2011; Srivastava and Kolady (2016) give an average rate for the period 2009 to 2011; Monga (2008) gives figures for Bt area for 2005 to 2007 that can be transformed to a rate using DES data on cotton-growing areas; Gandhi and Namboodiri (2009) give a figure for 2005, Manickam, Gururajan, and Gopalakrishnan (2007) give one for 2006, and VIB (2013) for 2011. These different estimates were averaged and the smoothed estimates for each year are given in Table 2.[6] Note that the estimates for Rajasthan are always lower than those for Haryana and Punjab.

There are grounds to be sceptical about the estimates for Punjab for the early part of the period. The seed costs (Rs/ha) reported in the CCS for Punjab show a sharp rise in 2004 and the insecticide costs show a sharp fall at the same time. Moreover, Murugkar, Ramaswami, and Shelar (2006) show a marked increase in the use of proprietary hybrids from 2003 (11 per cent) to 2004 (51 per cent), even though Kranthi (2016) asserts that very few non-Bt hybrids were ever planted in the

[5] For all the sources quoted, Bt adoption rates are defined as “area under Bt cotton/all cotton area.” An alternative definition based on the number of farmers growing Bt cotton is not available.
[6] These were obtained using loess (or local regression) curves.

Table 2 *Estimated Bt adoption rates, by year and State, 2005–14,* in per cent

Year	Haryana	Punjab	Rajasthan
2005	0	10	0
2006	21	39	6
2007	46	62	19
2008	68	79	37
2009	83	88	56
2010	90	91	68
2011	93	92	71
2012	96	94	71
2013	98	96	71
2014	100	100	77

Note: 2015 and 2016 estimates assumed the same as 2014.

northern region. It is plausible that Bt hybrids were grown (illegally) in Punjab in 2004, but there is no evidence that this happened in Haryana or Rajasthan. This has some implications for our analysis in the next section.

Method

We would like to reach conclusions about the *causal* effect of the adoption of Bt cotton on our chosen outcomes. To reiterate, we expect insecticide use to go down, yields to increase, and, as a result of these and other changes, profits to increase with the use of Bt cotton. Causal inferences from observational data, including the aggregate observational data used here, are always open to criticism as randomised allocation of farmers to different growing practices is impossible. What we can do is to determine whether the results from our analyses are consistent with what we would expect to find if there was indeed a causal effect. Essentially, what we have is a set of interrupted time-series, the interruption brought about by the adoption of Bt technology. This interruption was not a one-off event, as we have seen from Table 2.

Our causal inferences would be strengthened if we were able to use data over time from a control group: for example, a cotton-growing State where Bt technology was never adopted. Unfortunately, no such control group exists and so we rely, in common with many other researchers who use interrupted time-series, on a comparison of trends before and after the introduction of the new technology. Nevertheless, we do recognise the possibility that other changes in, say, local agricultural policy, occurring at the same time as Bt adoption, could enhance or mask the true causal effect of the technology (or what Cook and Campbell [1979] term "history").

Our causal inferences depend on changes in the relation between outcomes and year from before and after the introduction of the technology. Consider a set of stylised relations between insecticide use and year as represented by Figures 3(a) to 3(d), which are all consistent with a causal effect: a downward trend that becomes more

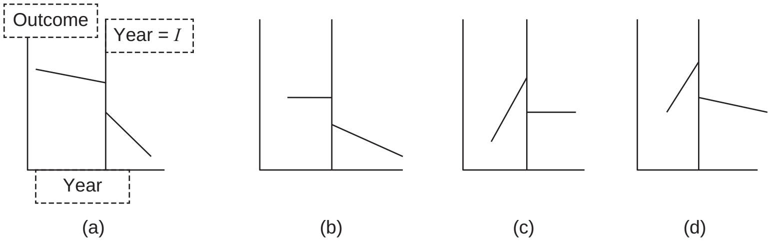

Figure 3 *Stylised relations between insecticide use and year*

marked at the start of the intervention (Year = I) in Figure 3(a), no trend before but a trend after the intervention in Figure 3(b), an upward trend before but no trend after the intervention in Figure 3(c), and a change in the direction of the trend in Figure 3(d).[7] In each case, there is a downward shift at the intervention point that reflects the expected reduction in insecticide use by the early adopters.

We can specify one general model to cover all the situations in Figure 3 for any outcome y:[8]

$$f(y_t) = \alpha d_{1t} + \beta d_{2t} + \gamma s_{1t} + \delta s_{2t} + \varepsilon_t, \quad t = 1 \ldots T$$

where:

$f(y_t) = \log \frac{y_t}{1-y_t}$ for insecticide (which is a proportion), y_t otherwise, for year t;

d_{1t} = 1 if $t < I$, 0 otherwise; d_{2t} = 1 if $t \geq I$, 0 otherwise so any differences between α and β represent a shift in the series at intervention point I;

s_{1t}, s_{2t} are linear splines (Harrell 2015; defined by *mkspline* in STATA) that join at knot I and defined so that δ represents the change in the slope of y on year after time I;

$E(\varepsilon_t \varepsilon_{t-k} \neq 0)$, $k \geq 1$ to allow for autocorrelation with lag k in the time-series.

The model assumes that there is a linear relation between outcome and year in both the pre-intervention (i.e. s_{1t}) and post-intervention (i.e. s_{2t}) phases. If the linearity assumption is not supported by the data, then causal inferences are unlikely to be warranted. If linearity is reasonable, then our inferences about the effects of the intervention are determined by whether the estimates of (a) the shift in level from before to after year I $(\beta - \alpha)$ and (b) the change in slope from before to after year I (δ) differ from zero more than would be expected by chance.

[7] We would expect the same pattern for yield and profit, except that the shifts and slopes would be in the reverse direction.
[8] The estimates from this model are easier to interpret than they are from a similar model used in Plewis (2014b).

The first linear spline (s_{1t}) is simply defined by calendar year. The second linear spline (s_{2t}) is defined in two ways: the first is based on calendar year; the second takes into account the fact that adoption did not increase linearly (as shown in Table 2), and so calendar year was transformed to a metric based on the adoption percentage in Table 2. Thus, for example, s_{2t} for Haryana for 2005–15 was defined as (0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10) when using calendar year, and (0, 1.1, 3.6, 5.8, 7.3, 8, 8.3, 8.6, 8.8, 9, 9) when using adoption percentage.[9] For Punjab, a slightly different method was used to take into account the evidence for earlier, possibly illegal, adoption. As well as using a knot at 2005 (a year earlier than Haryana and Rajasthan), a third pair of linear splines was defined with the knot at 2004 to reflect earlier adoption.

The essence of the analytical strategy that is followed to generate the results in the next section is as follows.

i. Assess the extent of auto-correlation (i.e. the best value of k).[10]
ii. Compare the fit of models that assume linearity with polynomial, usually quadratic, models.[11]
iii. If linearity is reasonable, fit the regression model above using PRAIS ($k = 1$) and NEWEY ($k > 1$) STATA procedures to allow for auto-correlation as described in Linden (2015).[12]
iv. Test whether there is any evidence for a structural shift in the time-series, and if there is, whether this is manifested through a shift in the intercept, a change in the slope or both. If there is no evidence of a structural shift, then we conclude that there is no causal effect of Bt adoption.[13]

If there is a causal effect of Bt adoption, then we expect:

a. A shift in level, using calendar year, that is greater for Haryana than for Rajasthan (where take-up is slower), and greater for Punjab when a start in 2005 rather than in 2004 is assumed.
b. A change in slope that is greater for the adoption metric than it is for calendar year, as the former should better reflect any linear "dose–response" relation. But for Punjab, we would expect the change in slope to be greater when a 2004 start is assumed.

[9] One disadvantage of the "adoption per cent" approach is that it assumes that the technology is unchanging, which, as we have seen, is probably not the case.
[10] The Cumby-Huizinga test from the STATA routine ACTEST was used.
[11] Orthogonal polynomials in s_{1t} and s_{2t} were used.
[12] As the number of households sampled in the CCS varied by year, the models were run with number of households as a weighting variable. The results were, however, essentially unchanged from the models that assumed equal weights.
[13] This is essentially a Chow test, but one that allows for autocorrelation.

Results[14]

Insecticide

The assumption of linearity is reasonable for all three States, and the null hypothesis of no structural shift is rejected in all analyses. The key results are given in Table 3, with those in bold being statistically significant at the 5 per cent level.

For Haryana, we find that:

i. The estimate of the downward shift in level is statistically significant and greater than it is for Rajasthan (−0.47 vs. +0.51).
ii. The estimate of δ – the change in slope – is greater in absolute terms for adoption per cent than it is for calendar year (0.090 vs. 0.057).
iii. The estimates follow the pattern depicted in Figure 3(b) – a constant proportion before the intervention (the estimate of γ is essentially zero) and a statistically significant downward trend afterwards.
iv. The predictions from the model indicate a fall of 61 per cent in the proportion of operational costs devoted to insecticides – from 0.12 in 2005 to 0.047 in 2015.

Table 3 *Model estimates (s.e.) for insecticide cost, by State*

Spline function	Coefficient	Haryana(3) n_1 = 17 n_2 = 10(4)	Punjab n_1 = 16 n_2 = 11(5)	Rajasthan(6) n_1 = 12 n_2 = 10
Calendar year 1(1)	γ	−0.011 (0.008)	**0.057 (0.016)**	**−0.063 (0.013)**
	δ	−0.057 (0.037)	<0.001 (0.018)	**−0.11 (0.018)**
	$\beta - \alpha$	**−0.47 (0.22)**	**−1.8 (0.21)**	**0.51 (0.12)**
	H_0: no structural shift	**F(2,23)=10.1, p<0.001**	**F(2,23)=39.2, p<0.001**	**F(2,18)=28.7, p<0.001**
Adoption per cent	γ	−0.010 (0.009)	**0.057 (0.016)**	**−0.066 (0.014)**
	δ	**−0.090 (0.022)**	−0.010 (0.020)	**−0.12 (0.040)**
	$\beta - \alpha$	−0.15 (0.12)	**−1.8 (0.28)**	**0.53 (0.13)**
	H_0: no structural shift	**F(2,23)=11.6, p<0.001**	**F(2,23)=130, p<0.001**	**F(2,18)=8.85, p<0.01**
Calendar year 2(2)	γ	n.a.	**0.076 (0.006)**	n.a.
	δ		**−0.061 (0.037)**	
	$\beta - \alpha$		−1.6 (0.30)	
	H_0: no structural shift		**F(2,23)=21.6, p<0.001**	

Notes: (1) Based on 2005 start (P) and 2006 start (H and R); (2) based on 2004 start (P); (3) 1993 interpolated as mean of 1992 and 1994; (4) n_1 and n_2 are numbers of observations before and after the start of the intervention; (5) n_1 = 15 n_2 = 12 for calendar year 2; (6) 1998 interpolated as mean of 1997 and 1999; n.a. = not applicable.

[14] The raw data used here are available on request.

For Punjab:

i. The estimates of the shift in level are substantial (1.6 to 1.8) and are in line with expectation.
ii. Also, as expected, the largest estimate of δ (0.061) is when the intervention is assumed to start in 2004; however, it is not statistically significant.
iii. From the estimate of γ (0.057), we see that insecticide use was increasing before the intervention.
iv. The predictions from the model indicate a fall of 65 per cent in the proportion of operational costs devoted to insecticides – from 0.37 in 2003 to 0.13 in 2015.

The results for Rajasthan are a little less clear-cut in that:

i. Insecticide use was falling before 2006 (−0.063/−0.066 from Table 3).
ii. There is an unexpected and substantial upward shift in level in 2006 (0.51/0.53), possibly as a result of other pest pressures and because Bt adoption was only 6 per cent then.
iii. There is a statistically significant decline in slope and the estimate of δ is a larger negative for adoption per cent (−0.12) than it is for calendar year (−0.11), in line with expectation.
iv. There is a 53 per cent fall – from 0.097 in 2005 to 0.046 in 2015 – in the predicted proportion of operational costs devoted to insecticides.

To sum up these results, there is good evidence that the introduction of Bt technology reduced the proportion of farmers' costs going to insecticides in all three States, although this evidence is a little stronger for Haryana than it is for Punjab and Rajasthan. These findings are consistent with those discussed by Ranganathan, Gaurav, and Halder (2018).

Yield[15]

The results for Haryana for the three measures of yield are given in Table 4. It is difficult to argue that there is any causal link from these estimates because (a) there is no consistent evidence for a structural shift, (b) the relation between yield and year after the introduction of Bt in 2006 is sometimes non-linear with yields initially rising but then falling. This non-linearity is accentuated by the very low yield in 2015, which has an important influence on the estimates.

The results for Punjab are given in Table 5. Again, it is difficult to make any causal link from these estimates. Although there is consistent evidence for a structural shift, the

[15] A possible disadvantage of using yield as an outcome is that it assumes that production is linearly related to area. This might not be so if more marginal land is used as cultivated area increases. The analyses were repeated with production as the outcome and area as a control variable. There was no evidence of a non-linear relation and the results were essentially the same.

Table 4 *Model estimates (s.e.) for yield, Haryana*

Spline function	Coefficient	DES n_1 = 42 n_2 = 11[2]	CAB n_1 = 15 n_2 = 11	CCS[3] n_1 = 12 n_2 = 10
Calendar year 1[1]	γ	3.3 (0.92)	−4.4 (6.7)	0.23 (7.4)
	δ	Quadratic, p < 0.01	8.5 (13)	Quadratic, p < 0.03
	$\beta - \alpha$	142 (44)	207 (87)	68 (151)
	H_0: no structural shift	F(3,48) = 25.8, p<0.001	F(2,22) = 3.9, p<0.04	F(3,19) = 5.27, p<0.01
Adoption per cent	γ	3.3 (0.93)	— [4]	—
	δ	Quadratic, p < 0.03	—	—
	$\beta - \alpha$	70 (49)	—	—
	H_0: no structural shift	F(3,48) = 14.8, p<0.001	F(2,22) = 3.4, p>0.05	F(2,20) = 0.8, p>0. 40

Notes: (1) Based on 2006 start; (2) n_1 and n_2 are numbers of observations before and after the start of the intervention; (3) data missing for 1991 and 1993; (4) estimates not relevant as there was no structural shift.

Table 5 *Model estimates (s.e.) for yield, Punjab*

Spline function	Coefficient	DES n_1 = 41 n_2 = 12[3]	CAB n_1 = 14 n_2 = 12	CCS n_1 = 14 n_2 = 12
Calendar year 1[1]	γ	4.5 (1.9)	Quadratic, p<0.001	Quadratic, p<0.02
	δ	−20 (5.6)	Quadratic, p<0.001	Quadratic, p<0.001
	$\beta - \alpha$	290 (67)	76 (127)	59 (88)
	H_0: no structural shift	F(2,49) = 15.0, p<0.001	F(5,20) = 6.5, p<0.001	F(5,20) = 33.6, p<0.001
Adoption %	γ	4.5 (1.9)	Quadratic, p<0.001	Quadratic, p<0.02
	δ	−19 (6.9)	Quadratic, p<0.01	Quadratic, p<0.01
	$\beta - \alpha$	301 (74)	31 (143)	39 (92)
	H_0: no structural shift	F(2,49) = 9.7, p<0.001	F(5,20) = 4.0, p<0.02	F(5,20) = 21, p<0.001
Calendar year 2[2]	γ	3.7 (1.8)	Quadratic, p<0.001	−4.8 (8.5)
	δ	−17 (5.6)	Quadratic, p<0.001	Quadratic, p<0.01
	$\beta - \alpha$	309 (62)	67 (137)	315 (81)
	H_0: no structural shift	F(2,49) = 15.5, p<0.001	F(5,20) = 6.1, p<0.01	F(3,21) = 31, p<0.001

Notes: (1) Based on 2005 start; (2) based on 2004 start; (3) n_1 and n_2 are numbers of observations before and after the start of the intervention.

relation between yield and year after the introduction of Bt in 2005 (or 2004) is sometimes non-linear with yields initially rising but then falling. Also, for the DES data, the estimate of δ is consistently negative. As for Haryana, the non-linearity is accentuated by the very low yield in 2015, which might have affected the conclusions.

The results for Rajasthan are given in Table 6. Here there is evidence of an effect on yield, although not for the CCS data where there is no evidence of a structural shift. But for DES and CAB, the post-intervention slope is higher than it was before 2006 (the estimate of δ is positive), and it is greater for the adoption per cent metric as expected. The shift in the intercept is, however, small.

Summarising these results, we can state that there is no consistent evidence of an effect of Bt technology on yield in Haryana and Punjab. It is reasonable to conclude that there was an effect in Rajasthan, with the predictions from the model indicating a 60 per cent increase in yield from 2005 to 2015.

Profits

The key results are given in Table 7.

The estimates of γ suggest that profits were falling in Haryana and Rajasthan, and were constant in Punjab, before the introduction of Bt. There is evidence of a shift in the intercept for Punjab, but as it is greater when a 2004 rather than a 2005 start is assumed, this is not in line with expectation. The estimates for Haryana and Rajasthan do not provide evidence of a positive effect of Bt technology on profits. Hence, on the basis of these analyses, it is difficult to argue that Bt technology had

Table 6 *Model estimates (s.e.) for yield, Rajasthan*

Spline function	Coefficient	DES $n_1 = 42$ $n_2 = 11^{(2)}$	CAB $n_1 = 15$ $n_2 = 11$	CCS$^{(3)}$ $n_1 = 11$ $n_2 = 10$
Calendar year 1$^{(1)}$	γ	4.1 (1.3)	−2.2 (4.3)	—$^{(4)}$
	δ	13 (3.9)	18 (8.2)	—
	$\beta - \alpha$	43 (43)	83 (56)	—
	H_0: no structural shift	F(2,49) = 6.0, p<0.01	F(2,22) = 4.8, p<0.02	F(2,17) = 2.21, p>0.13
Adoption %	γ	4.1 (1.4)	−2.2 (4.3)	—
	δ	17 (3.5)	23 (9.7)	—
	$\beta - \alpha$	25 (41)	57 (59)	—
	H_0: no structural shift	F(2,49) = 11.9, p<0.001	F(2,22) = 6.0, p<0.01	F(2,17) = 2.38, p>0.12

Notes: (1) Based on 2006 start; (2) n_1 and n_2 are numbers of observations before and after the start of the intervention; (3) data missing for 1998; (4) estimates not relevant as there was no structural shift.

Table 7 *Model estimates (s.e.) for profit ratio, by State*

Spline function	Coefficient	Haryana(3) n_1 = 16 n_2 = 10(4)	Punjab n_1 = 16 n_2 = 11(5)	Rajasthan(6) n_1 = 11 n_2 = 10
Calendar year 1(1)	γ	−0.061 (0.014)	—	−0.056 (0.017)
	δ	Quadratic, $p<0.09$	—	Quadratic, $p<0.03$
	$\beta-\alpha$	0.0019 (0.34)	—	0.099 (0.27)
	H_0: no structural shift	$F(3,21) = 4.8$, $p<0.02$	$F(2,23) = 2.22$, $p>0.13$	$F(3,16) = 9.1$, $p<0.001$
Adoption per cent	γ	— (7)	—	—
	δ	—	—	—
	$\beta-\alpha$	—	—	—
	H_0: no structural shift	$F(2,22) = 2.48$, $p>0.10$	$F(2,23) = 0.95$, $p>0.4$	$F(2,17) = 1.66$, $p>0.22$
Calendar year 2(2)	γ	n.a.	−0.042 (0.015)	n.a.
	δ		0.012 (0.026)	
	$\beta-\alpha$		0.58 (0.19)	
	H_0: no structural shift		$F(2,23) = 5.3$, $p<0.02$	

Notes: (1) Based on 2005 start (P) and 2006 start (H and R); (2) based on 2004 start (P); (3) 1993 missing; (4) n_1 and n_2 are numbers of observations before and after the start of the intervention; (5) n_1 = 15 n_2 = 12 for calendar year 2; (6) 1998 missing; (7) estimates not relevant as there was no structural shift.

benefits for farmers in terms of profits in any of the northern States.[16] Why might this be so?

Before the introduction of Bt cotton, seed costs were always a much smaller proportion of operational costs as compared to insecticide costs. But this changed after Bt was introduced: the new seeds were much more expensive and so the savings from decreased pesticide use were at least partially offset by the increased expense of the hybrid Bt seeds, seeds which cannot be saved by farmers each year in a way that varieties can be. We find (Table 8) that when we add seed costs from CCS to insecticide costs: (i) for Haryana and Rajasthan, there is no evidence of a structural shift in the series, with the implication that, on average, farmers transferred the savings they made on insecticides to buying more expensive seeds; (ii) for Punjab, however, there is clear evidence of a structural shift for both intercept and slope, so that the combined costs are reduced. It is therefore not entirely surprising that Bt cotton brought no benefit to farmers in terms of profit, because only in Punjab were the insecticide savings maintained after allowing for the pricier seeds and there was no effect on yields (and therefore income) in Punjab.

[16] Some additional support for this conclusion comes from the fact that farmers did not respond to the introduction of Bt hybrids by growing more cotton. In Haryana and Rajasthan, area increased steadily from the 1960s to around 2000 but has been flat thereafter; in Punjab, area decreased after 1990.

Table 8 *Model estimates (s.e.) for insecticide and seed cost, by State*

Spline function	Coefficient	Haryana[3] n_1 = 17 n_2 = 10[4]	Punjab n_1 = 16 n_2 = 11[5]	Rajasthan[6] n_1 = 12 n_2 = 10
Calendar year 1[1]	γ	— [7]	0.066 (0.0081)	—
	δ	—	−0.052 (0.016)	—
	$\beta - \alpha$	—	−0.79 (0.12)	—
	H_0: no structural shift	$F(2,23)$ = 0.08, $p>0.9$	$F(2,23)$ = 39.1, $p<0.001$	$F(2,18)$ = 2.69, $p>0.09$
Adoption %	γ	—	066 (0.0085)	—
	δ	—	−0.061 (0.019)	—
	$\beta - \alpha$	—	−0.74 (0.16)	—
	H_0: no structural shift	$F(2,23)$ = 0.15, $p>0.8$	$F(2,23)$ = 35.5, $p<0.001$	$F(2,18)$ = 2.06, $p>0.15$
Calendar year 2[2]	γ	n.a.	0.071 (0.012)	n.a.
	δ		−0.077 (0.021)	
	$\beta - \alpha$		−0.59 (0.15)	
	H_0: no structural shift		$F(2,23)$ = 18.0, $p<0.001$	

Notes: (1) Based on 2005 start (P) and 2006 start (H and R); (2) based on 2004 start (P); (3) 1993 interpolated as mean of 1992 and 1994; (4) n_1 and n_2 are numbers of observations before and after the start of the intervention; (5) n_1 = 15 n_2 = 12 for calendar year 2; (6) 1998 interpolated as mean of 1997 and 1999; (7) estimates not relevant as there was no structural shift; n.a. = not applicable.

Discussion and Conclusions

The primary justification for introducing Bt cotton was to reduce the use of pesticides, and the evidence indicates that this expectation was met in the three northern States. This reduction is likely to have had a beneficial effect on farmers' health (Kouser and Qaim 2011) and external benefits in terms of a reduction in pollution. Although the Bt technology is not designed to have a direct effect on yield, increases were expected as a result of reduced insect damage and the possible substitution of, for example, fertilizer for insecticides as well as from hybridisation. There was evidence to suggest a beneficial effect on yield in Rajasthan, but not in Haryana and Punjab where yields fell substantially in 2015 as a result of whitefly infestation. It is possible that, as more data become available after 2015, this reduction will have a smaller influence on the model estimates.

The analyses presented here were only possible because there are time-series data over a relatively long period and so it is possible to model pre-Bt and post-Bt trends at the State level. There might be important within-State heterogeneity, however, which it has not been possible to examine. The existence of three series for yield does complicate matters. There are also doubts about the quality of CCS data for yield, and all the data from CCS are based on relatively small samples. These issues need to be borne in mind when assessing my conclusions. It is also important to recognise that the validity of these conclusions rests on the assumption that any shift can be attributed to the introduction of the new technology, and not to other changes in, for example, cotton production and marketing that might have happened at the same time. Ideally, if it could draw on data from a control group or, even better, an established longitudinal study of cotton farmers of sufficient size, then reliable changes in outcomes and farming practices could be observed and attributed to the introduction of Bt seeds. Unfortunately, such datasets do not exist.

It is important to stress that the conclusions of this paper apply only to Haryana, Punjab, and Rajasthan: more detailed analyses for States in the central and southern regions of India are still needed, and such analyses need to be combined with farm-level studies. This is a topic for future study. What this paper does show is that conclusions about the effectiveness of Bt seeds are more nuanced than many commentators recognise.

Evidence for the success of Bt cotton in India comes from a number of sources but perhaps most tellingly from the cotton balance-sheet. Despite a steadily growing population, India has, since 2002, moved from being a net importer to a net exporter of raw cotton (GoI 2017b). Assertions by anti-GM groups that adopting Bt cotton has been a disaster for farmers are not supported by the evidence presented in this paper. Insecticide costs have gone down, bringing potential benefit both to farmers and to their communities. And, there is no evidence that profits have gone down. Nevertheless, it is also important to note evidence in the literature that:

> farmers base their choice of crops not only on absolute differences in profitability, but also on their evaluation of imperfections in the capital market, and that they factor in an understanding of the risks and uncertainties involved. (Ramakumar, Raut, and Kamble 2017, p. 131)

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