Agricultural biotechnology and crop productivity: macro-level evidences on contribution of *Bt* cotton in India

Shivendra Kumar Srivastava[1,*] and Deepthi Kolady[2]

[1]ICAR-National Institute of Agricultural Economics and Policy Research, New Delhi 110 012, India
[2]South Dakota State University, Brookings SD 57007, USA

While farm-level empirical studies demonstrate the contribution of *Bt* technology in increasing crop productivity, there are still questions about its contribution to long-term growth in productivity at the macro-level. Our study examines major technological and seed policy breakthroughs relevant for the cotton crop, and reviews their impact on overall performance of the cotton sector and agricultural biotechnology industry in India. Using state-level panel data on cotton production from all the major cotton-producing zones, we provide empirical evidences on structural change in the cotton yield since the introduction of *Bt* technology and its impact on long-term growth in productivity at the national level.

Keywords: Agricultural biotechnology, *Bt* cotton, genetic modification, macro-level productivity.

AGRICULTURAL biotechnology (agri-biotech) or genetic modification (GM) assumes significance in addressing the biotic and abiotic stresses in the agricultural sector. Since the commercialization of first GM crop in the US in 1996, the technology has witnessed widespread adoption by farmers across the globe. Currently, GM crops are commercially grown by 8 developed and 19 developing countries on 175.2 million hectares (m ha) area[1]. The increased yield, reduced cost of production, and higher net returns per hectare are the major drivers of widespread adoption of GM crops by farmers[2–4]. Despite being grown for more than 15 years, there are questions and concerns about the economic, environmental and health impacts of GM crops[5,6]. These concerns are affecting the research and development (R&D) of GM crops, especially in developing countries. For example, India, which has 91% of its cotton area under GM varieties, and allocates substantial resources to agricultural biotechnology, is giving mixed signals on the regulation and use of other GM crops[7]. Although the scientific regulatory authority approved the commercialization of *Bt* (*Bacillus thuringiensis*) eggplant in India in 2009, it is yet to be commercialized in the country due to the health, environmental and economic concerns associated with the GM technology. This regulatory uncertainty is affecting research investments into the agri-biotech sector with negative implications on social welfare[8].

In India, *Bt* cotton, the only GM crop allowed for commercial cultivation, has witnessed an impressive adoption rate. Since its commercial release in 2002, 1128 *Bt* cotton hybrids have been developed[9] and 7.2 million farmers have adopted this technology on 11.1 m ha area, accounting for 91% of total cotton area in the country. There is a stream of studies showing positive impacts of *Bt* technology[10–15]. All of these studies focus on one or two of the cotton-growing regions of India and examine short-term impacts of the technology in terms of reduced pesticide expenses, increased yields, improved health outcomes, increased farmers' net income and improved rural economy. Studies focusing on longer-term impact of the technology on crop productivity with a wide geographic focus are limited. The lack of empirical evidence on the longer-term impact of *Bt* technology from major cotton-producing states of different agro-climatic zones of the country is a major shortcoming, and critics of the agri-biotech use it as a justification for opposing the technology. The present study addresses this shortcoming and evaluates macro-level impact of *Bt* technology on cotton yield using comprehensive, balanced state-level panel data on cotton production variables from the top nine cotton-producing states in India.

Although there are limited number of qualitative studies linking *Bt* cotton adoption to farmers' suicides in rainfed areas of India[16], empirical studies either find no evidence on farmer suicides and *Bt* cotton adoption[17], or remain inconclusive[18]. The Governor of the Reserve Bank of India recently noted that farmer suicide is a complicated issue and formal finance is the key, a finding reported in the empirical literature[19,20]. Thus, social, economic, financial factors, and contextual factors might affect farmer suicides. Further, it is clear from the existing literature that it is a challenge to get the disaggregated data required for detailed empirical analysis. Although farmer suicide is an important issue by itself, it is beyond the scope of the present study.

*For correspondence. (e-mail: sksrivastava@ncap.res.in)

Background

Genetically modified (Bt) cotton: evolution, adoption and diffusion

Bt cotton technology was first developed and commercialized by the US company Monsanto in 1996. The technology comprises of isolation of a gene *cry1Ac* from a soil bacterium *B. thuringiensis* and its infusion into the cotton genome through genetic engineering to protect against bollworm complex (American bollworm, *Helicoverpa armigera*; Spotted bollworm, *Earias vittella*; Pink bollworm, *Pectinophora gossipiella*). In India, following a series of field trials and biosafety assessments, the Genetic Engineering Appraisal Committee (GEAC) approved the commercial cultivation of three *Bt* cotton hybrids developed by Mahyco–Monsanto Biotech (MMB – a joint venture between the Indian firm Mahyco and the US firm Monsanto) for central and southern cotton-growing states in April 2002. Subsequently, several other seed companies obtained license of Monsanto's *Bt* technology and developed many *Bt* hybrids. For the northern cotton-growing states, six hybrids were approved for commercial release for the first time in 2005. In 2006, GEAC approved the first two-gene event MON15985, commonly known as Bollgard®-II (BG®-II) developed by Mahyco and sourced from Monsanto[2]. The double-gene *Bt* cotton hybrids provide additional protection against *Spodoptera* (a leaf-eating tobacco caterpillar) along with the protection against bollworm complex. The double-gene *Bt* cotton farmers earn higher profit through cost savings associated with fewer sprays for *Spodoptera* as well as increasing yield by 8–10% over single-gene *Bt* cotton[21]. The approval of two more events named Event 1 (truncated *cry1Ac* gene) developed by the Indian Institute of Technology, Kharagpur in collaboration with J. K. Seeds Pvt Ltd, and GFM Cry1A (*cry1Ab* + *cry1Ac*) of Chinese Academy of Sciences (gene sourced by Nath Seeds Pvt Ltd) in 2006, broke the monopoly of MMB on *Bt* technology. Further, approval of the first public sector event known as BNLA-601 expressing the *cry1Ac* gene for commercial sale widened farmers' choice for *Bt* cotton hybrids and varieties in 2008. Using the event BNLA-601, the first public sector open-pollinated *Bt* cotton variety '*Bt* Bikaneri Nerma' and a hybrid were developed by ICAR-Central Institute of Cotton Research, Nagpur, in association with the University of Agricultural Sciences, Dharwad and ICAR-National Research Centre on Plant Biotechnology, New Delhi in 2008 and 2009 respectively. However, the event BNLA-601 was discontinued in 2010 and is under scientific validation and evaluation[21]. Two hybrids with a new event 'Event 9124 (*cry1C* gene)' of Metahelix Life Sciences Pvt Ltd were also approved for commercial cultivation in central and southern cotton-growing states in 2008. Until May 2012, a total 1128 *Bt* cotton hybrids (using six different events) were commercially released by 49 private companies[9]. Thus, the cotton seed market is dominated by proprietary seeds marketed mostly by domestic seed companies. The introduction of *Bt* technology brought foreign players into the cotton seed market, but their market presence is limited[22]. Although there have been a significant number of mergers and acquisitions in the agri-biotech industry since 2002, most of the domestic firms relied on licensing agreements from MMB to integrate biotechnology into their downstream seed production and marketing activities. It is evident from the fact that instead of Mahyco or MMB, companies such as Nuziveedu Seeds and Ankur Seeds come under the top 15 agri-biotech companies in India due to their dominance in the cotton seed market[23].

In addition to the six approved events, five new cotton events expressing dual *Bt* genes are at advanced stages of biosafety assessment and field testing. These new events would offer broad-spectrum insect-resistance properties and a new herbicide tolerance trait. The herbicide tolerance trait would allow farmers to efficiently control ubiquitous weeds, reduce labour cost, decrease erosion of fertile soil and conserve moisture, thereby increasing plant resilience to drought and substantially increasing cotton productivity and production[21]. Thus, during the last decade since 2002, the *Bt* cotton hybrid seed portfolio has evolved remarkably from single-trait monopoly situation to multi traits monopolistic situation giving farmers a wider choice for hybrid seeds and companies.

Bt technology has witnessed an impressive adoption rate and emerged as one of the fastest adopted crop technologies in the history of Indian agriculture. Within a decade after release, area under *Bt* cotton has increased remarkably at the rate of 90% per annum; it occupied 91% of total cotton area (12.2 m ha) in the country by 2011–12. The 91% adoption rate in India is fairly comparable with other mature biotech cotton markets like Australia (99.5% adoption), USA (94% adoption) and China (80% adoption)[21]. It is worth noting that *Bt* cotton has not only replaced non-*Bt* cotton, but also led to an increase in overall area under cotton cultivation from 8.44 m ha during triennium ending (TE) 2002–03 to 11.8 m ha during TE 2012–13, at an annual growth rate of 4.83%. Presently, Maharashtra occupies 36.61% of the total area under *Bt* cotton in the country, followed by Gujarat (22.05%) and Andhra Pradesh (17.10%).

The number of the farmers cultivating *Bt* cotton in India has increased from 50,000 in 2002 to 7.2 million in 2012 (ref. 21). These 7.2 million small and resource-poor farmers represented about 95% of the total cotton-growing farmers during 2012–13. Over the years, Indian farmers have shown greater preference for double-gene cotton hybrids over the single-gene hybrids. This is indicated by the large number of double-gene cotton hybrids developed and adopted by farmers. For example, in 2012 about 66% of *Bt* cotton hybrids developed contained

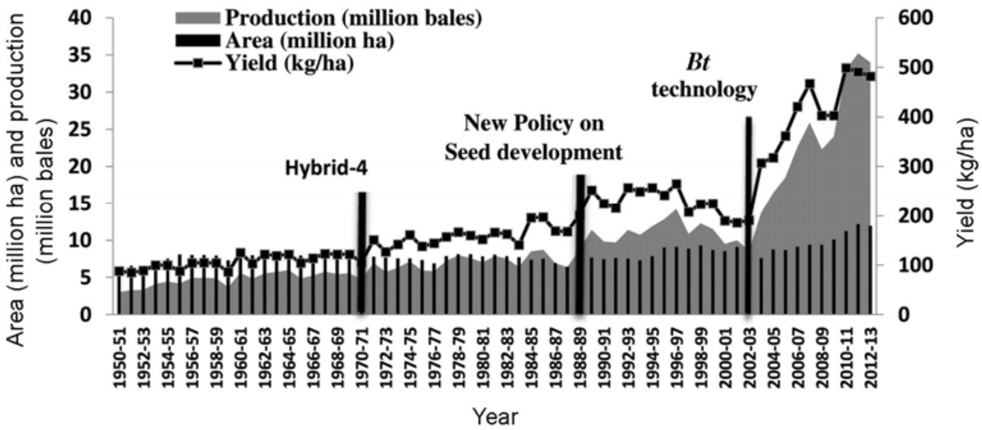


Figure 1. Trends in area, production and yield of cotton in India.

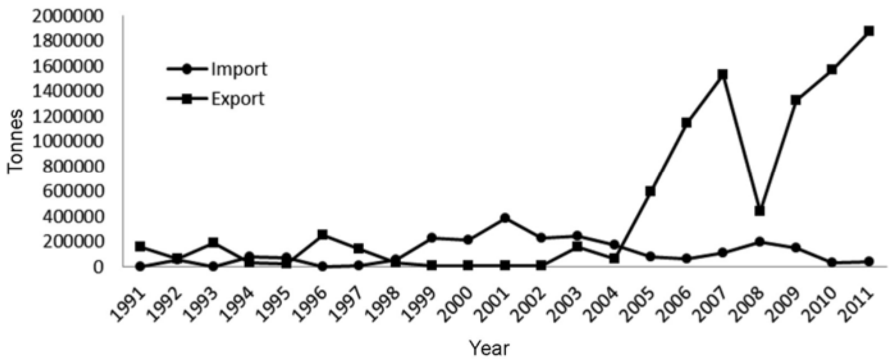


Figure 2. Export and import of cotton lint in India.

double-gene events and accounted for more than 90% of the total area under *Bt* cotton hybrids in the country.

Contribution of Bt technology in cotton production, trade and agri-biotech industry

Technological breakthroughs and policy reforms in the Indian seed sector has resulted in tenfold increase in cotton production during the past six decades (Figure 1). Cotton production has increased from just 3.04 million bales (1 bale = 170 kg) during 1950–51 to 36.10 million bales during 2012–13, at an annual growth rate of 3%. This was primarily due to the improvement in cotton yield from 88 kg/ha during 1950–51 to 482 kg/ha during 2012–13 at the rate of 2.55% per annum. It is to be noted that much of the improvement in cotton yield took place only during the recent decade after 2002–03. During the past 12 years (2002–03 to 2012–13) cotton yield has increased by 152% compared to only 117% increase during the preceding 53 years. It is worth mentioning that although hybrid technology was available since 1970, and seed policy reforms incentivized private sector participation in the cotton seed sector, adoption rate of hybrids was only about 50% until 2002. With the introduction of *Bt* cotton in 2002, both area under cotton and hybrid cotton have increased (see Figure 1 for area under cotton), resulting in substantial increase in cotton production and yield.

The economy wide benefits of structural change in cotton production since 2002–03 are reflected through the performance of trade and agri-biotech industry in India. Before 2002–03, production was not sufficient to fulfil the domestic demand of raw cotton and India was a net importer of cotton (Figure 2). But, the next decade witnessed decline in the share of import in total cotton supply from 12% during 2001–02 to 3% during 2012–13. Interestingly, the share of domestic consumption in total supply also declined from 81% during 2001–02 to 72% during 2012–13. This is due to the fact that bulk of the incremental cotton production was exported to earn foreign revenue. The annual growth in cotton export during 2001–02 to 2012–13 was 53.80% compared to the 4.61% growth in domestic consumption of raw cotton. This also suggests that because of the improved production and quality[24], the Indian cotton market has become export-oriented.

Similarly, agri-biotech industry (includes sale values from GM seeds, molecular markers and other related

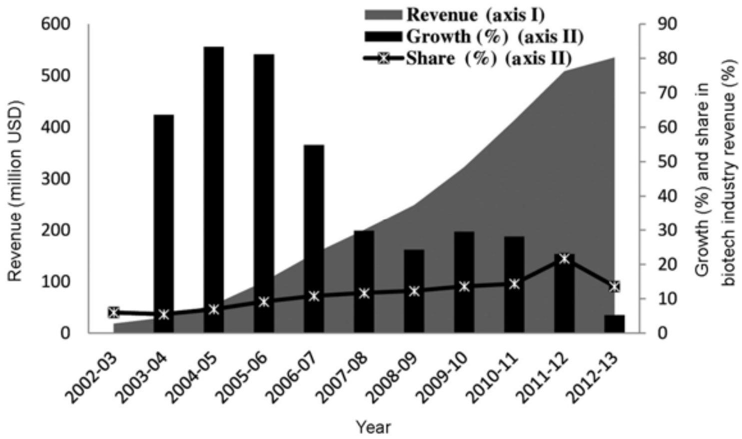


Figure 3. Performance of agri-biotech sector in India.

products with GM seeds constituting a dominant share) in India has witnessed an impressive performance since 2002–03 (Figure 3). The market revenue of agri-biotech industry has increased from 18 million USD (1 USD = 60 INR) during 2002–03 to 535 million USD during 2012–13, at annual growth rate of 40%. Consequently, the share of agri-biotech segment in total biotech industry in India has increased from 6% to 14% during the period 2002–2013. Interactions with industry personnel suggest that *Bt* cotton marketed mainly by the private sector has played a significant role in accelerating growth in the agri-biotech industry. However, it is to be noted that the quantum jump in the agri-biotech revenue during the initial years of commercial release of *Bt* cotton could not sustain in the successive years, resulting into deceleration in growth. This may be because of almost universal adoption of *Bt* technology by the farmers and also because of the uncertainty surrounding the regulation of agricultural biotechnology in the country as no new crop traits are entering the market[8].

It is evident from the above analysis that the structural change in cotton production, trend reversal from a net importer to a net exporter, and an impressive performance of agri-biotech industry all coincide with the commercial release of *Bt* cotton in India. This suggests the potential impact of *Bt* technology in the productivity improvement of cotton. However, few studies have criticized the performance of *Bt* technology and argued that it is not *Bt* technology, but favourable climate, adoption of hybrids, irrigation facilities and reduced incidence of pests that has led to the improvement in cotton yield[25–27]. The fact that the available literature on field-level impact of *Bt* cotton focuses on only limited number of cotton-growing states, strengthens the arguments of the critics.

Bt cotton and crop productivity

Production performance of cotton

Although India accounted for 26.95% of the world cotton area, its contribution to the world cotton production was only 9.66% in 2000, due to its lower yield. However, significant improvement in cotton yield during recent years has narrowed down this gap in India's share. During the period 2002–2013, cotton yield in India witnessed a significantly higher annual growth of 10% as compared to 1.54% growth in the average world cotton yield. Consequently, India's share in the world cotton production increased to 25% in 2013. Here, it is worth mentioning that in spite of this remarkable growth, average cotton yield in India (491 kg/ha) was still 31% lower than the average world yield (715 kg/ha) in TE 2013. Thus, efforts are needed to sustain growth in cotton yield through technological improvements and policy support.

We examine the production performance of cotton crop during the following four sub-periods: 1950–51 to 1970–71 (first period); 1970–71 to 1988–89 (second period); 1988–89 to 2002–03 (third period); and 2002–03 to 2012–13 (fourth period). We chose the above sub-periods based on the following three technology and policy interventions relevant to the cotton seed sector: first, Indian public sector introduced the first hybrid cotton (Hybrid-4) in 1970–71; second, India implemented new policy on seed development (NPSD) in 1988, which allowed entry of private sector in seed market; and third, India commercialized *Bt* cotton hybrids from the private sector in 2002.

During the first period, cotton production witnessed 2.48% growth per annum due to increase in area as well as yield (Table 1). After the introduction of hybrid cotton in 1970, yield accelerated at the annual growth rate of 2.43% until 1988–89. Although during 1970–71 to 1988–89 hybrids replaced 27% of the area under cotton varieties, total cotton area in the country declined marginally. This resulted into comparatively slow growth in production than in yield. Entry of private sector into the seed market since NPSD in 1988 increased the number of hybrids available in the market and improved farmers' access to hybrids[28–30]. This not only accelerated replacement of varieties with hybrids, but also brought additional area under cotton cultivation in the country. The adoption rate of hybrid cotton increased from 27.64%

during 1988 to 45% during 2002, and the total area under cotton registered 1.43% growth per annum. Although there was an increase in cotton yield during early years of the third period, the yield started to decline in the later years due to pest and disease infestation, and two successive severe droughts in 2000 and 2002 (Figure 1).

During the fourth period (post-*Bt* cotton period), cotton yield improved by 152% at the rate of 10% per annum, suggesting a structural change in cotton production and yield. Introduction of *Bt* cotton also had a positive effect on the area under cotton hybrids. The share of hybrids in total cotton area increased from 45% in 2002 to 91% in 2012. Interestingly, the post-*Bt* cotton period (2002–2012) witnessed two contrasting facts in cotton yield: first, a sudden jump in the yield even when the adoption of *Bt* technology was low and second, deceleration in the yield during the recent years despite almost universal adoption of *Bt* technology (Figure 1). The reason for the early jump in yield may be the presence of unauthorized *Bt* hybrids in farmers' fields, particularly in the western states long before their official approval in 2002 (refs 22, 31, 32). The deceleration in cotton yield during recent years may be because of several factors such as vast majority of inappropriate hybrids, inclusion of more marginal land into cotton production, increased damage by sucking pests, less adoption of refugia and declining area of inter-crops in the cotton cropping systems[33,34].

The deceleration in cotton yield due to increased secondary pest infestation has wider implications, particularly for an insect-resistance technology. The widespread adoption of *Bt* technology provided dual advantages of yield improvement by controlling bollworm infestation and reduction in insecticide use. The insecticide use in cotton cultivation witnessed significant reduction from 1.54 kg/ha before 2002 to 0.53 kg/ha by 2006 (Figure 4). This led to substantial reduction in plant protection cost and negative environmental externalities, as about 70% of the total insecticide was used to control bollworm. But, recent years have witnessed increased infestation of whiteflies in North India, and whiteflies, thrips and leaf hoppers across the country[35]. Although the present level of insecticide use in cotton cultivation (0.99 kg/ha) is still less than its use prior to 2002, rising trend in insecticide use puts economic burden on resource-poor cotton-growing farmers and raises concerns over the efficacy of the technology[18]. Nevertheless, the approval of new events with broad-spectrum insect resistance and a new herbicide tolerance trait is expected to accelerate the growth trajectory of *Bt* technology. Another alternative is to promote simpler production system strategies like cultivation of high-density short-duration cotton to ensure effective escape from insects[18,35].

A given level of yield is determined by a complex set of production inputs, infrastructure facilities, technology and weather-related factors rather than technology alone. This is evident from a comparative examination of cotton cultivation in Maharashtra and Punjab, which differ substantially in terms of input use and irrigation infrastructure, but exhibit the same level of *Bt* technology adoption (Table 2). Cotton is a rainfed crop with relatively less input use in Maharashtra, whereas it is completely irrigated with relatively high input use in Punjab. The level of *Bt* technology adoption rate is same for both the states, but Punjab produces more than double cotton per unit of land than Maharashtra. Further, due to assured irrigation, cotton yield in Punjab is stable despite witnessing higher rainfall deviation of –25.1%. Any attempt to quantify longer-term impact of *Bt* technology, therefore, must be preceded by controlling variations in other factors of production across different agro-climatic zones in India.

Table 1. Production performance of cotton in India

Particular	Area (million ha)	Production (million bales)	Yield (kg/ha)
Triennium average			
TE 1950–1951	6.27	3.22	87.33
TE 1970–1971	7.65	5.26	116.67
TE 1988–1989	6.92	7.34	179.67
TE 2002–2003	8.44	9.38	189.00
TE 2011–2012	11.80	34.07	490.67
Compound growth rate (%)			
1950–1970 (first period)	1.00	2.48	1.46
1970–1988 (second period)	–0.56	1.87	2.43
1988–2002 (third period)	1.43	1.76	0.36
2002–2012 (fourth period)	3.40	13.77	10.01

Empirical model

We hypothesize that if the introduction of *Bt* technology is contributing to crop productivity increase, this might be manifested in higher yields of commercial cotton. To test this hypothesis empirically, the following general form of panel yield model was used

$$\text{YIELD}_{it} = (\alpha + u_i) + \beta_1\text{SEEDEXP}_{it} + \beta_2\text{FERT}_{it} + \beta_3\text{INSECTEXP}_{it} + \beta_4\text{RAINFALL}_{it} + \beta_5\text{IRRI}_{it} + \beta_6\text{LABORUSE}_{it} + \beta_7\text{TREND}_{it} + \beta_8\text{BTTRENDINT}_{it} + v_{it}, \quad (1)$$

where YIELD_{it} is the cotton yield (kg/ha) in the *i*th state in *t*th year, SEEDEXP_{it} the real seed expenditure (Rs/ha) in the *i*th state in *t*th year, FERT_{it} the fertilizer use (kg/ha) in the *i*th state in *t*th year, INSECTEXP_{it} the real insecticide expenditure (Rs/ha) in the *i*th state in *t*th year, RAINFALL_{it} the actual rainfall (mm) in the *i*th state in *t*th year, IRRI_{it} the irrigation coverage (percentage of irrigated area in total cotton area) in the *i*th state in *t*th year, LABORUSE_{it} the labour use (h/ha) in the *i*th state in *t*th year, TREND_{it} the time values 1–18 for each year in the *i*th state, and BTTRENDINT_{it} is the product of *Bt* technology dummy (0: before 2002, 1: after 2002), and trend variable in the *i*th state and *t*th year.

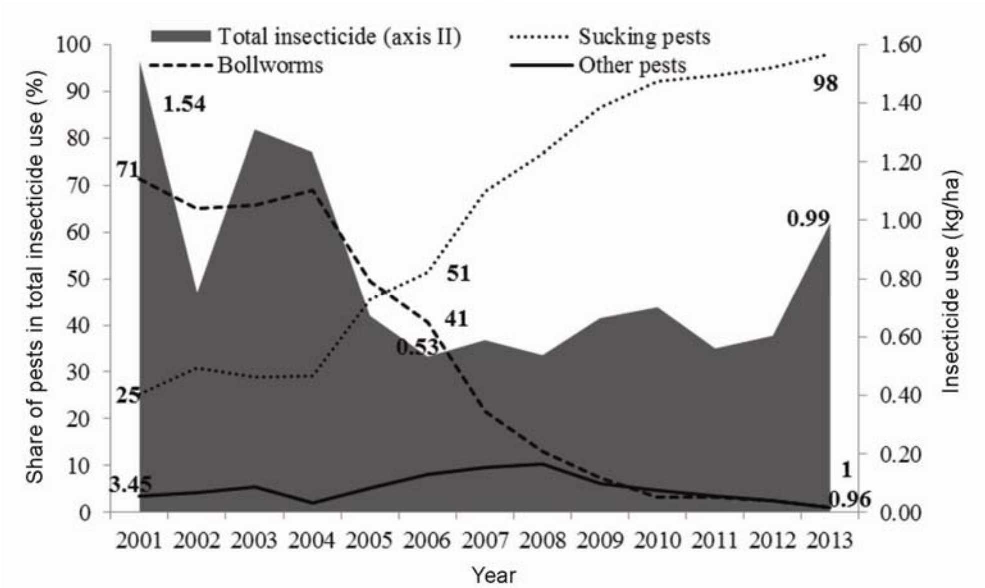


Figure 4. Trend in insecticide use for cotton in India.

Table 2. Regional variation in production technology of cotton, TE 2011–12

State	Seed (Rs/ha)	Fertilizer (kg/ha)	Insecticide (Rs/ha)	Irrigation coverage (%)	Rain deviation (%)	*Bt* adoption (%)	Yield (kg/ha)
Maharashtra	2967	216	1579	3	1.2	92	316
Gujarat	2614	202	2474	58	13.8	77	637
Andhra Pradesh	2728	248	2026	17	2.4	97	432
Madhya Pradesh	1926	82	1426	46	–10.7	90	413
Karnataka	2729	136	802	22	13.9	70	356
Tamil Nadu	1914	323	1373	26	13.5	64	528
Punjab	4895	211	4069	97	–25.1	92	680
Haryana	3874	148	1722	99	–19.7	95	652
Rajasthan	2915	123	1823	93	7.1	71	429

The model examines whether the rate of yield improvement of cotton increased following introduction of *Bt* cotton in India controlling for other relevant production-related variables. A positive and significant coefficient of the product of *Bt* dummy and trend (BTTRENDINT_{it}) would suggest that there is a structural change in the cotton yield since the introduction of *Bt* cotton.

Data

In this study we use state-specific panel data on commercial cotton production for the period 1994–95 to 2011–12 from the nine major cotton-growing states covering three distinct and major geographical regions, viz. northern region (Punjab, Haryana, Rajasthan), central region (Maharashtra, Madhya Pradesh, Gujarat) and southern region (Andhra Pradesh, Karnataka, Tamil Nadu). We assume that the positive effects of hybrid technology (1970), seed policy reforms (since 1988) and economy wide reforms (in 1991) may have already manifested in the commercial cotton yields since 1990s. The period 1994–95 was taken as the starting year to have almost eight years of data before and after the introduction of *Bt* technology. The secondary data on different aspects of cotton production were collected from the published sources of the Ministry of Agriculture, Government of India. The monetary variables (seed and insecticide expenditure) were expressed in real terms using Consumer Price Index for Agricultural Workers (1986–87 = 100). Table 3 presents the summary statistics of the variables used in the empirical model. It is to be noted that although *Bt* technology was introduced in 2002, it was targeted for the central and southern cotton-growing states. In northern region, *Bt* cotton was commercially released in 2005. Therefore, cut-off year for *Bt* dummy was different for different states based on year of commercial release of *Bt* cotton.

Results

Tables 4 and 5 present the results of panel data regression analysis to assess the marginal impact of *Bt* technology on cotton yield. The regression was preceded by several

Table 3. Summary statistics of variables used in the model (1994–95 to 2011–12)

Variable	Description	Mean	Minimum	Maximum	CV	Observations
Dependent variable						
YIELD	Cotton yield (kg/ha)	338	80	750	48.74	162
Independent variables						
SEEDEXP	Real seed expenditure (Rs/ha)	361	107	1056	57.72	162
FERT	Fertilizer use (kg/ha)	124	28	361	49.54	162
INSECTEXP	Real insecticide expenditure (Rs/ha)	458	17	2547	85.70	162
RAINFALL	Actual rainfall (mm)	826	230	1557	30.36	162
IRRI	Irrigation coverage (%)	49	3	100	72.02	162
LABORUSE	Labour use (h/ha)	812	264	1710	31.76	162
TREND	Time values for each year	–	1	18	–	162
BTTRENDINT	Product of *Bt* dummy (1 for *Bt* introduced in the state, 0 for no *Bt*) and trend variable (1–18 for each year)	–	0	18	–	162

Table 4. Diagnostic tests

Test	Null hypothesis	Test statistics	Probability	Remarks
Wooldridge test for autocorrelation	No first-order autocorrelation	*F* (1, 8) 19.345	0.0023	Presence of auto-correlation in panel data
Likelihood ratio test for heteroskedasticity	Data are homoscedastic	LRchi^2 (8) 33.21	0.0001	Presence of heteroskedasticity in panel data
Levin–Lin–Chu unit-root test for stationarity in yield	Panel contains unit root	Adjusted *t* – 2.07	0.0194	Yield panel series is trend-stationary

Table 5. Estimated coefficients of FGLS panel regression

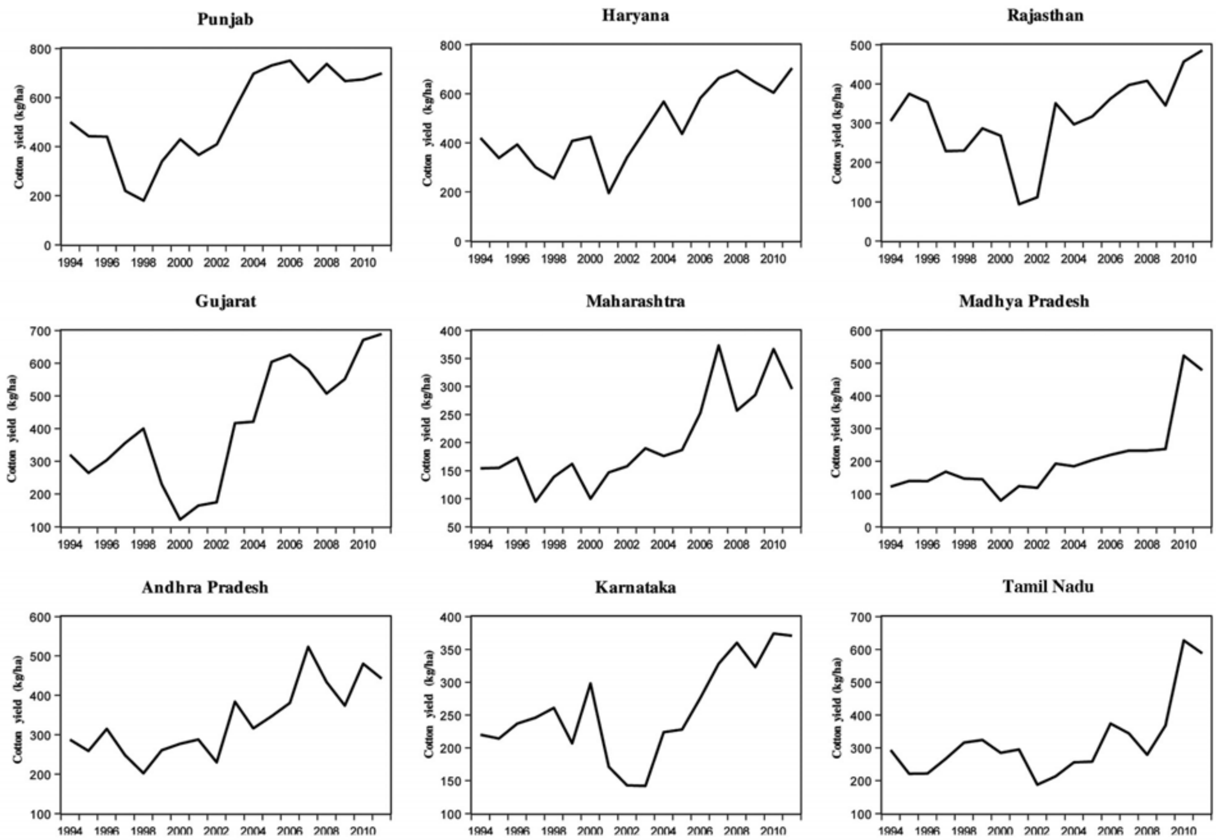
Variable	Estimated coefficient	Standard error
Constant	–46.843*	24.680
SEEDEXP (Rs/ha)	0.114***	0.013
FERT (kg/ha)	–0.149***	0.051
INSECTEXP (Rs/ha)	0.011	0.010
RAINFALL (mm)	0.023*	0.012
IRRI(%)	3.374***	0.309
LABORUSE (h/ha)	0.046***	0.017
TREND	1.664	2.392
BTTRENDINT	12.216***	1.849
Wald chi^2	1092.98***	
No. of observations	162	

***,**,*Significant at 1%, 5% and 10% level of significance respectively.

diagnostic tests to check the appropriateness of the data (Table 4). The results of the Wooldridge test and likelihood ratio test indicate the presence of autocorrelation and panel-level heteroskedasticity in the data respectively. The Levin–Lin–Chu test for unit root rejects the presence of unit root in the data. To address the issues of heteroskedasticity and autocorrelation, the model has been estimated using feasible generalized least square (FGLS) technique[36].

The positive and significant coefficient of the interaction term between *Bt* dummy and trend variables supports our hypothesis that there is a structural change in cotton yield growth during the post-*Bt* period. This empirical finding supports the descriptive analysis above, that since the introduction of *Bt* cotton and its widespread adoption from 2002, the Indian cotton sector has undergone significant changes mainly because of the increase in cotton productivity at the farmers' level. Since the model controls for major production inputs and weather parameters such as rainfall, the findings demonstrate the positive and significant effect of *Bt* technology on cotton crop productivity at the macro level.

As expected, among the other control variables, expenditure on seed, labour use, percentage of irrigation coverage, and rainfall have a positive and statistically significant effect on yield level. The negative and statistically significant sign of fertilizer variable was not expected. Previous studies have shown that the effect of fertilizer on crop yield will depend greatly on soil type and rainfall[37]. Since in our analysis, we use state-level data, we could not include a representative soil type for each of the states. As mentioned previously, it has been noted that with the introduction of *Bt* technology production of cotton in marginal areas, where yield performance is expected to be lower has increased. The statistically significant negative sign of the fertilizer variable may be capturing this as we control for both trend and rainfall in our model. Further, 'trend' variable was non-significant. A perusal of state-wise trend in yield (Appendix 1) indicates no specific trend up to 2002 and a visible upward trend afterwards across all the states. The upward trend in the later period is captured by the positive and significant '*Bt*-trend interaction' variable and thus 'trend' variable turned out to be non-significant.



Appendix 1. State-wise trend in cotton yield (kg/ha).

Conclusion and policy implications

The present study has provided empirical evidences on the long-term growth trajectory of cotton crop in India. The growth in the cotton sector is led by several technological innovations and policy decisions such as development of hybrids, NPSD, economic reforms and introduction of *Bt* cotton. But, *Bt* technology has changed the landscape of cotton crop and has become the fastest adopted technology in the history of Indian agriculture. Within a decade after its commercialization in 2002, totally 1128 *Bt* hybrids have been developed and *Bt* cotton hybrid seed portfolio has evolved remarkably from single-trait monopoly situation to multi-traits monopolistic situation, giving farmers a wider choice for seeds and boosting the agri-biotech industry in the country. Consequently, *Bt* hybrids have replaced almost the entire area under non-*Bt* varieties in the country. However, in spite of almost universal adoption, there exists wide variation in cotton yield across cotton-growing states due to differences in climatic conditions, infrastructural developments and input utilization pattern. The state-level panel data specification provides an advantage to control these variations while evaluating the impact of *Bt* technology on cotton productivity. The findings confirm a structural change in yield levels since the introduction of *Bt* technology and its positive impact in improving cotton yield at the macro level.

The manifestations of this impact are reflected through the reversal in India's position from a net importer to a net exporter of cotton, impressive growth in agro-biotech industry and narrowing down of difference between average yields of India and the world. However, it is worth mentioning that cotton yield, though improved, is still 31% lower than the average world yield and recent years have witnessed stagnation in the yield due to a complex set of inter-related factors. Further, secondary pest infestation in cotton crop is on the rise, raising concerns among farmers and researchers. This suggests that the country needs to continue its R&D investments in technology and develop supportive policy for such R&D investments from both public and private sectors. The release of new traits offering pest resistance and herbicide tolerance will contribute positively in reversing the yield stagnation experienced in many crops, including staples such as rice and wheat. An early decision on regulatory policy based on scientific evaluation and its effective and transparent implementation will provide a boost to the agri-biotech industry and address some of the concerns of critics of GM crops. Replication of success of *Bt* cotton in other crops will provide the Indian farmers upward mobility from poverty.

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