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Long-term impacts of *Bt* cotton in India

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Most scholarship on the closely-watched case of genetically modified *Bacillus thuringiensis* (*Bt*) cotton in India has focused on short-term impacts and has also ignored other major changes in India's cotton agriculture. This Perspective combines several data sources over a 20-year span to provide long-term comparisons of *Bt* adoption with yields and other inputs at both countrywide and state-specific scales. *Bt* cotton adoption is shown to be a poor indicator of yield trends but a strong indicator of initial reductions in pesticide use. Yield increases correspond to changes in fertilizer and other inputs. *Bt* cotton has continued to control one major cotton pest, but with *Bt* resistance in another pest and surging populations of non-target pests, farmers now spend more on pesticides today than before the introduction of *Bt*. Indications are that the situation will continue to deteriorate.

The fate of *Bacillus thuringiensis* (*Bt*) cotton in India is one of the most closely-watched situations in the spread and impact of genetically modified (GM) crops. Intense interest in this one case results from several factors. GM crop debates turned to smallholder farming in the developing world after Europe's cold reception of GM products in the mid-to-late 1990s (refs. [1–3]). India was the world's largest cotton planter but its cotton sector was one of the world's most troubled, tormented by insecticide-resistant Lepidopteran pests and known for farmer suicides[4,5]. Since *Bt* traits were intended to control Lepidopterans, the potential for a dramatic impact seemed great. The 2002 release of *Bt* cotton in India was followed by a flurry of field research on farm-level impacts. The pace of research has slowed since the early 2010s, but interest in the case has continued unabated[6].

Much of the writing on effects of *Bt* cotton in India has bifurcated into contradictory narratives that have been dubbed "technological triumph or abject failure"[7]. The triumph narrative, forwarded by industry-supported commentators and by most peer-reviewed publications by applied economists, hinges largely on (1) controlled comparisons of *Bt* adopters and non-adopters during the first few years of release and (2) the countrywide surge in cotton yields after 2002. The failure narrative in its most pronounced form, forwarded by many non-governmental organizations and environmentalist activists, cites cases of crop failure and an alleged link between *Bt* seeds and farmer suicide, while more nuanced versions challenge the timing and sustainability of *Bt* cotton's positive impacts. The contradictions in narratives has itself become a topic of analysis, with writers emphasizing the incompatible views on what counts as evidence[8] and how different systems for authenticating knowledge tend to bias findings[9,10].

While there is no such thing as a final word on the role played by *Bt* technology in a situation that continues to be dynamic, we are here able to provide a new analysis of unprecedented scope, time depth and detail. First, in contrast to previous short-term studies, this analysis combines data on the 17 years of *Bt* cotton cultivation with the three preceding years to reveal 20-year trends. Second, in contrast to previous studies of production dynamics at the scale of the entire country or one or a few sample loci, it analyses countrywide and distinctive state-level patterns. Third, in contrast to previous studies attributing production trends exclusively to *Bt* adoption, it considers other key trends in Indian cotton production technologies. Finally, in contrast to previous studies treating pest resistance as a static property, it explicitly considers the changing dynamics of insect pests and longitudinal data on insecticide spraying. The findings do not readily conform to either the technological triumph or abject failure narrative. *Bt* cotton has provided durable resistance to the key Lepidopteran pest American bollworm, although it is impossible to isolate this effect from effective new insecticides that were adopted just before *Bt* seed. However, long-term trends of yield rise correspond very poorly to the history of *Bt* adoption, a discordance that is particularly striking at the state level. Cotton yield increases are explained much better by other technological changes, most notably by rising use of fertilizer. Unfortunately, the increase in fertilizer-intensive *Bt* seeds has worsened the predation by non-Lepidopteran pests. This, coupled with rapidly spreading *Bt* resistance in the pink bollworm, has led Indian cotton farmers to now spend more on insecticides than before they adopted *Bt* seed.

The agroecological context of cotton in India

To understand the effects of *Bt* cotton, one must first appreciate historical pest dynamics into which the technology was introduced. In India, cotton is preyed on by both Lepidopteran caterpillars and Hemipteran sap-sucking bugs. Lepidopterans mainly eat the cotton bolls (hence 'bollworms') and, in recent times, India's two most damaging bollworms have been the polyphagous American bollworm, also known as *Helicoverpa armigera* (Hübner) (ABW; an Old World species), and the oligophagous cotton-feeding pink bollworm (PBW; *Pectinophora gossypiella*, Saunders). Other Lepidopteran pests are the spotted bollworm (*Erias* sp.) and the cotton leafworm (*Spodoptera litura*), a defoliator. Sucking pests suck sap from leaves; important examples are the leaf hopper (*Amrasca devastans*, Distant), whitefly (*Bemisia tabaci*, Gennadius), cotton aphid (*Aphis gossypii*, Glover), mealybug (*Phenacoccus solenopsis*, Tinsley) and mirid bug (*Creontiades* sp.).

Indian farmers have an ancient history of successful cultivation of indigenous 'desi' cotton species (mainly *Gossypium arboreum*), but the problematic modern regime began to take shape in the 1990s with the spread of New World (*Gossypium hirsutum*) hybrids[11]. *Hirsutum* hybrids were significantly more input-intensive than desi seeds: hybrid seeds themselves were a purchased input, and lacking resistance to Asian pests they were also insecticide-intensive. This introduced an era of rising capital costs in cotton farming coupled with serious agro-ecological and entomological instability. Early spraying was mostly of synthetic pyrethroids aimed at controlling

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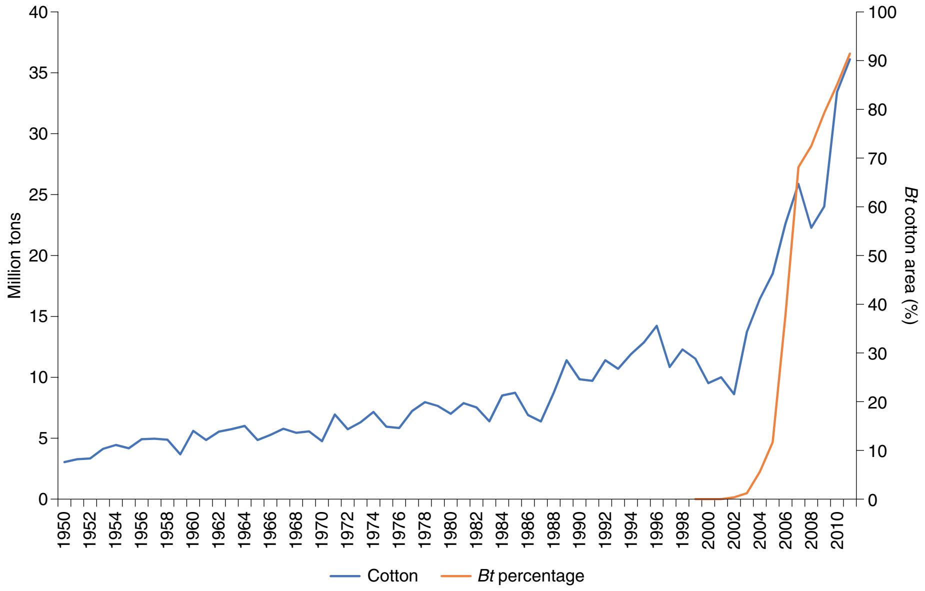

Fig. 1 | Depiction of the 'technological triumph' of *Bt* cotton in India. Data on production and *Bt* area are from the Indian MA. The International Service for the Acquisition of Agri-Biotech Applications cites these data as evidence for "the phenomenal rise in cotton production…attributed to the wide scale adoption of *Bt* cotton"[54].

the PBW and cotton leafworm, which led to the emergence of ABW as a 'monster' resistant to the full array of insecticides[12] and to surging whitefly populations. Farmers quickly found themselves on an 'insecticide treadmill', perpetually seeking sprays with new modes of action while resorting to escalating spraying regimens. The resulting cycle of mounting insecticide costs, fickle yields and debt, exacerbated by a shortage of applicable knowledge or experience, pushed many farmers to suicide. The international press took notice when suicides spiked to several hundred in Andhra Pradesh in 1998 (refs. [4,13]), and the problem has continued to date.

At the same time that cotton pest problems were worsening in India, commercial *Bt* cotton seeds were being developed in the United States. *Bt* is a soil bacterium containing *Cry* genes that encode crystal proteins which are fatal to some Lepidopteran caterpillars when ingested. *Bt* cotton was released in the US in 1995 and China in 1997, providing control of PBW in both countries[14]. But it was in the troubled cotton sector of India where a transformative impact was hoped for, and Monsanto and their Indian partner, Mahyco, began field testing in 1998. In 2002, *Bt* seeds were approved for sale in central and southern India, and three Mahyco seeds containing the single *Cry1Ac* gene appeared on the market. These seeds were adopted only on a very small scale. In 2005, *Bt* technology was approved for northern India; that year, seeds with combined *Cry1Ac* and *Cry2Ab* genes were released country-wide. *Bt* cotton adoption began to surge in 2005, and conventional brands disappeared from shops in many areas. *Bt* seeds were entirely hybrids, and these years also saw the rapid replacement of varieties with hybrids: the percentage of cotton area planted to hybrids rose from 32.9% in 1996–1997 to 71.47% in 2009–2010 (ref. [15]) and 93.0% in 2011 (ref. [16]).

This sketch has treated *Bt* seed as an isolated technology, but its deployment in India has coincided with other highly consequential developments, some of which are considered in this Perspective.

Isolating *Bt* effects is rough terrain

Given the global interest in this case, it is not surprising that the years immediately following the release of *Bt* cotton saw many studies attempting to isolate the technology's farm-level effects. However, this body of research is nowhere near as conclusive as we would like, or as many of the studies claim to be. The 'failure' narrative noted previously sees *Bt* cotton as an outright agronomic failure and a cause of worsening farmer debt and suicide[17–19], and it has many adherents internationally[20]. However, studies purporting to show inferior performance were generally not peer reviewed (for critical reviews of these, see refs. [10,21]). This perspective is often illustrated with cases of individual farmer suicides or spates of suicides where *Bt* seeds had been grown. Attributions of suicides to *Bt* seed often skirt the fact that suicides were a major problem well before the release of *Bt* seed[4], and that suicide rates have not risen as *Bt* cotton has been almost universally adopted in India[5].

But the 'triumph' narrative of *Bt* cotton[22] also has significant problems. *Bt* cotton is explicitly credited with tripling cotton production during 2002–2014 and doubling of global cotton market share in production[23], and long-term trend graphs do show a surge in yields just as the new seeds were released (Fig. 1). That *Bt* seed deserves credit for this jump in yields is supported by over a dozen peer-reviewed studies reporting claims of yield advantages as well as sharp drops in insecticide use and improved farmer profits[24,25]. But empirical study of early effects of GM crops is, as one economist pointed out, 'rough terrain' indeed[26], as *Bt* traits have been crossed into hundreds of different hybrid lines and planted over a wide geographical area under conditions of rapidly changeable weather, insect ecology and other agricultural technologies (for critical analysis by economists of the difficulties of such research, see refs. [26,27]).

The controlled comparisons of early *Bt* adopters and non-adopters, while interesting, are compromised by three forms of bias. Selection bias results from early adopters being an unrepresentative group of high producers. Crost et al.[28] concluded that more than half of *Bt*'s supposed yield effect was due to selection bias. Recognizing how this can inflate benefit estimates, Kathage and Qaim[29] took pains to control for selection bias, finding a 24% yield increase between 2002–2008. The modest yield effect of 4% per year is in line with Stone's panel comparison of villages before and after adoption of *Bt*, which showed an 18% yield increase between 2003–2007 (ref. [30]). But while these studies find common ground on modest annualized yield effects in the 4–5% range, we note that, with the vagaries of weather and pest populations, India cotton yields often rise or fall by over 10% per year, even without major technological change.

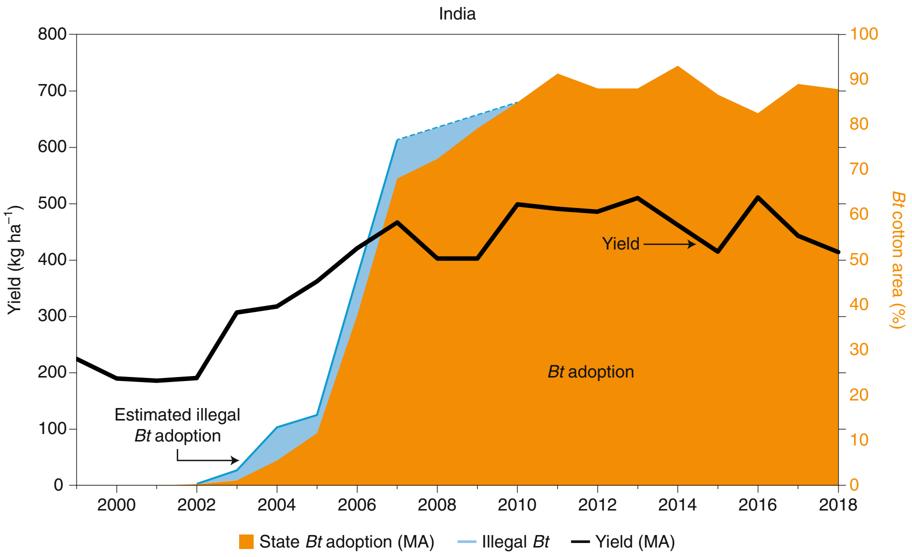

Fig. 2 | Countrywide cotton yield and *Bt* adoption. MA yield data are indicated on the left axis. MA data on *Bt* adoption (the orange area) and estimated illegal *Bt* adoption using method 1 (the blue area) as explained in the main text are indicated as percentages of total cotton area on the right axis (the illegal *Bt* area is added to the legal *Bt* adoption to show estimated total *Bt* percentage). For instance, legal and estimated illegal adoption for 2005 were 11.7% and 4.0%, totalling 15.7%). We have no basis for estimating illegal plantings after 2007, but price controls instituted that year shrunk the cost advantage illegal seeds, and the dotted blue line simply suggests a disappearance of illegal plantings over the next few years.

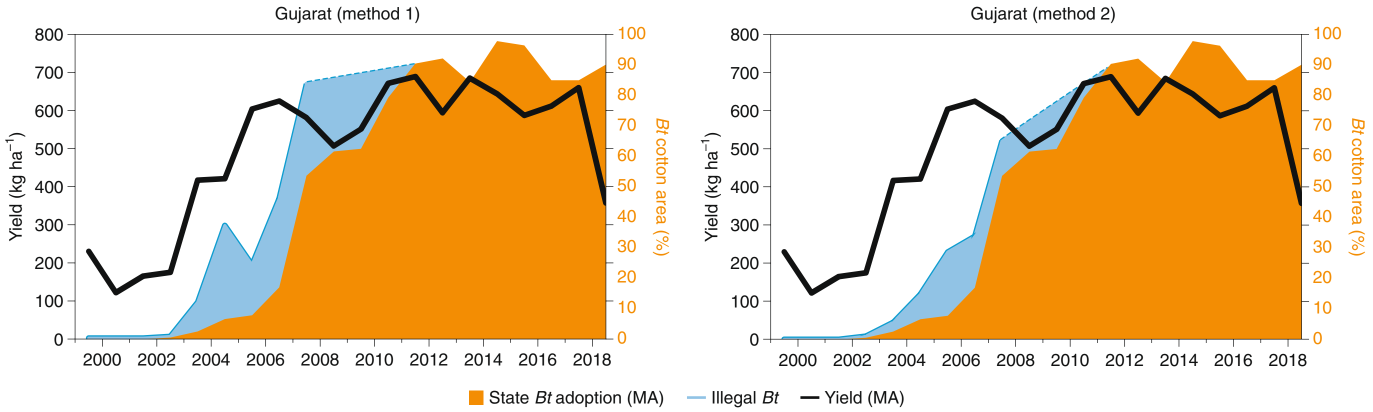

Fig. 3 | Gujarat cotton yields and *Bt* adoption. Two methods of estimating illegal *Bt* adoption are shown, as discussed in the main text. As in Fig. 2, MA yield data are indicated on the left axis. MA data on *Bt* adoption (the orange area) and estimated illegal *Bt* adoption (the blue area) are indicated as percentages of total cotton area on the right axis (The illegal *Bt* area is added to the legal *Bt* adoption to show estimated total *Bt* percentage). We have no basis for estimating illegal plantings after 2007, but price controls instituted that year shrunk the cost advantage illegal seeds, and the dotted blue line simply suggests a disappearance of illegal plantings over the next few years.

Cultivation bias occurs when seeds that are relatively costly, or for which the farmer has particularly high expectations, are planted in preferred locations and given special care. In its first few years of availability, when it was much touted and very expensive, *Bt* seed often received preferential treatment and additional fertilizer and irrigation[31,32].

Time term bias occurs when short-term outcomes are measured rather than the more consequential long-term outcomes: that is, researchers "yield to the temptation to study outcomes that are readily measured rather than those that are important"[33]. Intense scrutiny of short-term outcomes is particularly problematic for Indian cotton given that the suicidal, debt-ridden farmers whose fields were swarming with resistant insects in the early 2000s had eagerly adopted the hybrid–insecticide package because of initial short-term profits the decade before[30]. Kathage and Qaim[29] also regret that most studies neglect long-term effects for short-term impacts, but they then analyse only the first seven years of cultivation. This is still a short time in the highly dynamic conditions of Indian cotton farming, and conclusions about 'sustainability' of pesticide reductions based on this time frame[34] are of dubious value, as we discuss in the later section titled 'Insecticide use'.

Longer-term effects can be studied through trend analysis, most commonly by charting yields over the period during which the technology was adopted. The study of long-term trends avoids all three forms of bias, although it is sensitive to other changes in production during the period studied, as discussed below. Studies of *Bt*-related trends have generally failed to take other changes into account (for example, Fig. 1), the notable exception being Gruere and Suns'[35] long-term panel analysis; they estimated *Bt* seeds to have contributed to 19% of yield growth, but found other production

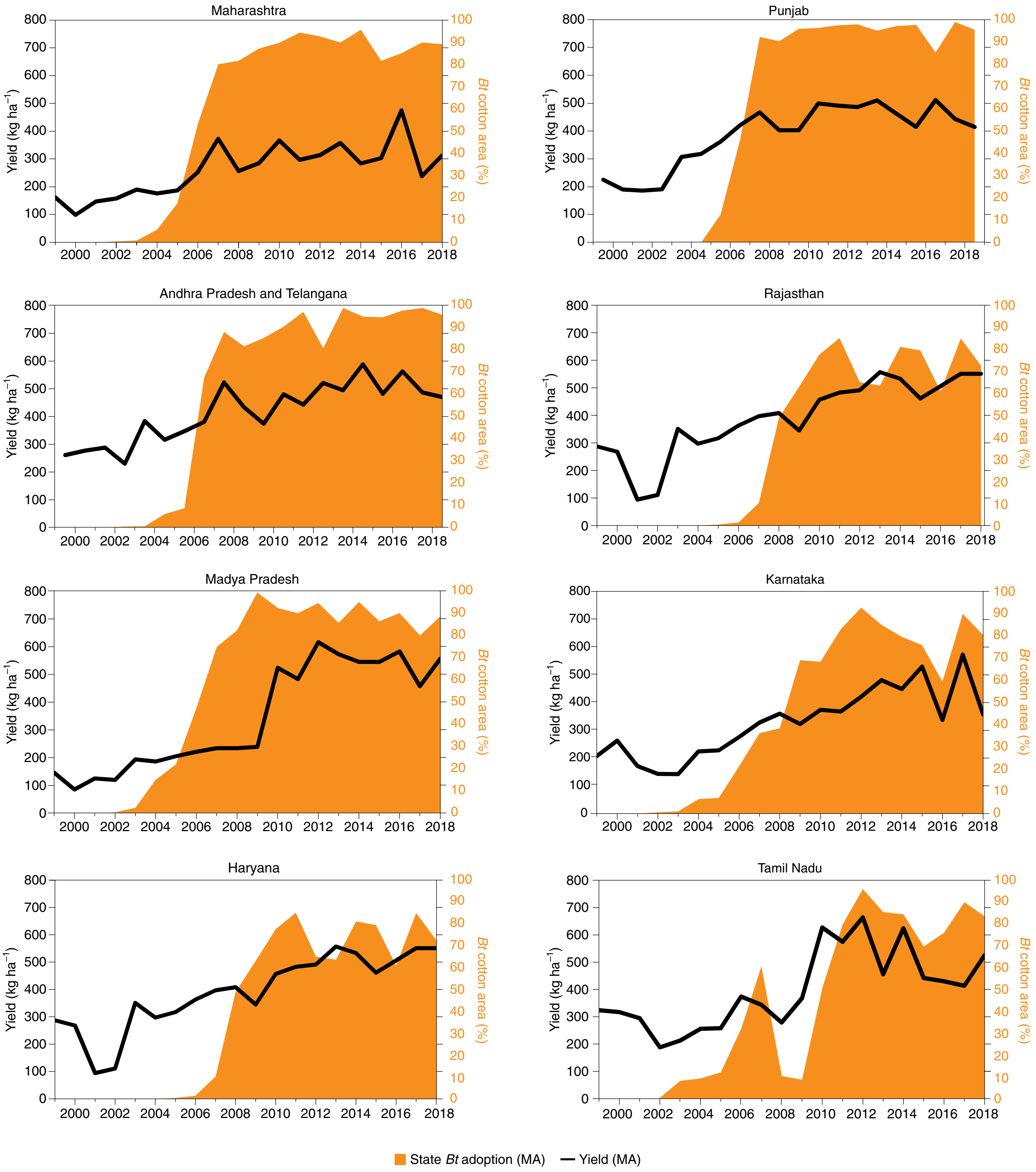

Fig. 4 | State-specific cotton yields and *Bt* adoption. MA yield data are indicated on the left axis. MA data on *Bt* adoption (the orange area) are indicated as percentage of total cotton area on the right axis.

factors to have also been significant. Our trend analysis combines data on 20 years of cotton cultivation in India with statistics on several years prior to the approval of *Bt* seed, looking first at yield trends.

Bt seeds and yield trends

Most attention has been focused on how *Bt* technology has impacted yields or productivity per unit area. *Bt* traits are intended to curtail losses to insect predation rather than to increase yield potential, but since insect attacks are so persistent, this could obviously result in higher yields than what would have been obtained with conventional seed. We analyse this effect by comparing trends in yields with adoption of *Bt* seeds.

Cotton yields are compiled by the Directorate of Economics and Statistics at the Ministry of Agriculture (MA). Yields are also

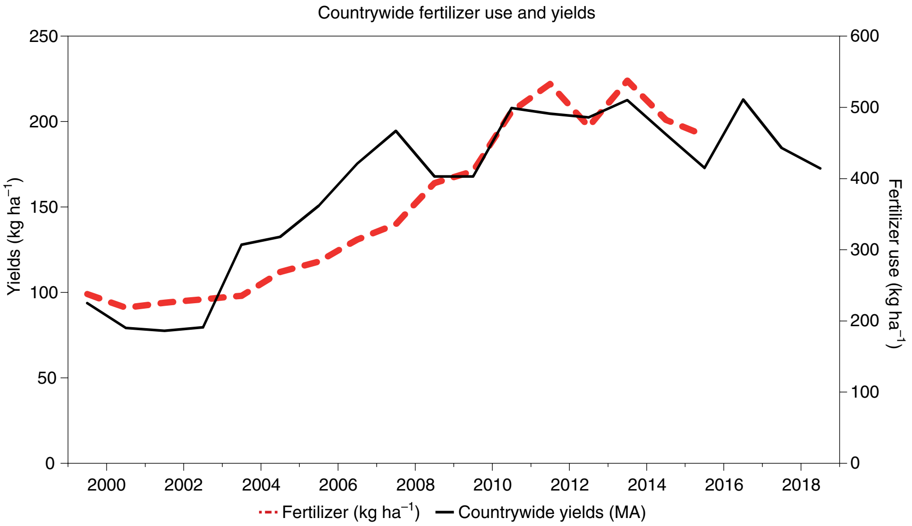

Fig. 5 | Countrywide cotton yields and fertilizer use. Data compiled by MA. Fertilizer use data are unavailable after 2015.

estimated by the Ministry of Textiles, as shown in the Extended Data. Statistics for legal *Bt* seed purchases compiled by the MA provide percentages for *Bt* adoption for the entire country and for each cotton-producing state. We also estimate illegal plantings using the methodology discussed below.

Figure 2 depicts countrywide trends in cotton yield and *Bt* adoption. *Bt* cotton was approved and entered input shops in the 2002 season, and countrywide cotton yields surged in 2003–2004. But *Bt* seeds were clearly not adopted on a significant scale until 2005, after which time most of the yield increase had occurred. Even taking into account estimates of illegal *Bt* plantings, only 3.4% of the country's cotton area was under *Bt* in 2003, hardly enough to explain the 61% jump in yields. By 2005, *Bt* adoption was still only 15.7%, but yields were 90% over 2002 levels. As we show below, there is an explanation for the rise in yields, but it was clearly not caused by *Bt* adoption.

The 2005 season marked the beginning of a three-year period of rapid adoption of *Bt* seed. These years were generally good for cotton production: by 2007, *Bt* adoption had risen to 81% and yields were 41% over 2004 levels. It is true that yields were already on the upswing before *Bt* cotton became popular, but the new seeds contributed to the continued rise by controlling ABW and especially PBW in the late season when farmers stop spraying because it damages bolls. *Bt* adoption corresponded to a sharp drop in Lepidopteran spraying shown below. However, countrywide yields stagnated after 2007, even as adoption continued to rise. By 2018, yields were lower than in the years of rapid *Bt* adoption.

But these countrywide trends admix diverse and distinctive state-level differences that are more revealing as to *Bt* seeds' effects (or lack thereof)[5,12]. We look first at the key state of Gujarat, India's top cotton producer and the main contributor to the early-2000's rise in yields. The state has a history of illegal *Bt* plantings that do not appear in official statistics, and while precise measures are impossible, estimates are needed because some have hypothesized that illegal plantings may explain the rise in yields[35,36]. Navbharat 151 was a Gujarat cotton brand found in 2001 to contain the still unapproved *Bt* transgene. It was reportedly discovered on 10,000 ha that year[37], although this acreage was based on no systematic data collection. Navbharat 151 was removed from the market by 2002, but some Gujarati farmers continued to plant farm-bred *Bt* and F-2 seeds[38,39]. Based on fieldwork in four Gujarat districts between 2003–2007, Ramaswami, Lalitha and colleagues provide two bases for estimating illegal plantings. The plot sampling by this research group cannot be used to project state-wide *Bt* cotton area, but we assume their observed proportions of legal to illegal plantings for those years are broadly reliable[40]. We applied these proportions to MA figures on legal *Bt* sales and have reduced the non-*Bt* area accordingly. Estimates based on this method appear as the blue area in Figs. 2 and 3. Our second estimate of illegal *Bt* plantings is derived from the economists' estimates of countrywide illegal *Bt* area between 2002–2007, based on seed industry representatives, industry publications and newspaper accounts[41]. We have assumed that 90% of the total illegal area was in Gujarat, and compared these areas to total cotton area recorded by the MA. Estimates based on this method appear as the blue area in Fig. 3 but not in other state-specific figures, as the estimated areas for other states are low.

Figure 3 shows Gujurat's conspicuous yield surge after 2002, rising 245% in the next three years. The spread of legal *Bt* is patently incongruous with this yield trend. Taking into account the estimated illegal plantings improves the fit somewhat, but the fit is still poor: Gujarat's biggest year-to-year percentage increase by far was the 138.3% jump in 2003 when *Bt* adoption was only 5.2%. *Bt* seeds were only widely adopted after the dramatic yield surge ended in 2006, which began a long period of yield stagnation.

Figure 4 shows India's other top cotton-producing states for the years 1999–2018. Maharashtra was India's second biggest cotton producer at the time *Bt* was released. Yields here were at a nadir in 2000, after which they began a steady climb until 2009, with no visible change as *Bt* seeds were adopted; by 2017, yields were lower than in 2006 when *Bt* began to spread.

Andhra Pradesh (here lumped with Telangana) saw a rapid spread of *Bt* seed in 2005–2007, a pattern also reflected in Stone's panel study of four villages where *Bt* adoptions climbed from <1% in 2003 to>99% in 2008 as yields rose by 18%[30]. But this yield rise was part of a steady climb in yields starting in 1999, meaning it had already been underway for six years when *Bt* seed was adopted. There was no change in yield growth rate with *Bt* adoption. Madhya Pradesh, too, shows no correlation between *Bt* adoption and yield improvement.

The northern states of Punjab, Haryana and Rajasthan are key because the trends here combined with Gujarat account for much of the rise in countrywide yields in the early 2000s. But yield jumps in these states are also incongruous with *Bt* adoption, with all three states showing strongly increasing yields in the years prior to *Bt* adoption and no observable boost as *Bt* spread. Note that neither the legal nor illegal *Bt* hybrids from Gujarat were suitable for north India's shorter growing seasons, nor were any resistant to the leaf curl virus that devastates cotton in the northern states. In Punjab,

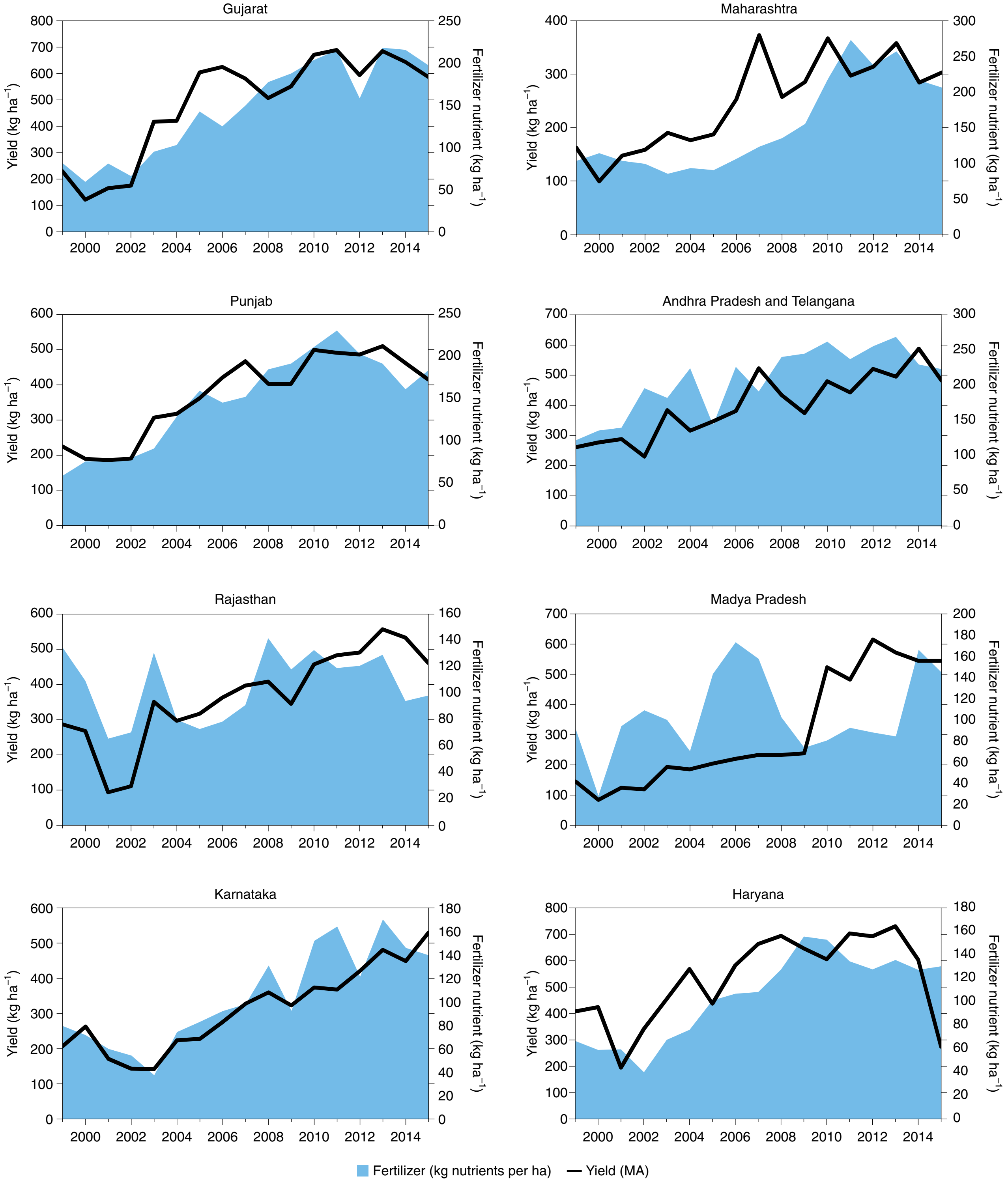

Fig. 6 | State-specific cotton yields and fertilizer use. Yield data is indicated on the left axis. Fertilizer use for cotton, indicated in kg ha^{-1} on the right axis, is depicted by the coloured areas. Only data up to and including 2015 were compiled by the MA.

yields rose 90% between 2001–2004; *Bt* seeds were only released in 2005, after which yields fluctuated but did not trend upward overall. In Haryana, yields rose 198% from 2001 to 2006 before *Bt* cotton was adopted, after which yields stagnated. In Rajasthan, yields jumped in 2003 before settling into a steady climb, which was well established before *Bt* seeds were adopted and which did not increase with *Bt* seeds. Note that the yield climb in Rajasthan in 2003 is nearly identical to that in Gujarat, although officials at the Central Institute for Cotton Research confirm that virtually no illegal *Bt* cotton was planted in Rajasthan that year.

Karnataka also shows a steady 12-year yield rise beginning before *Bt* seeds were adopted, with the growth in yields not accelerating as the seeds were adopted.

That yield increases did not correspond to *Bt* adoption at either the countrywide or the state-wide level has been noted before[9,10,12,35], but the cause of the increases has only been broached in technical

Fig. 7 | New technologies that affected cotton pest management in 2003. These posters in a farm inputs shop in Warangal District, Andhra Pradesh (now Telangana), advertised the insecticides Avaunt and Tracer. Very few farmers adopted *Bt* seeds, but farmers adopted these new insecticides rapidly[30].

bulletins[12]. But explanations for the yield rises are not hard to find if one looks beyond *Bt* seed, as we discuss in the next section.

Explaining yield trends

While almost all attempts to isolate the yield effects of *Bt* cotton have ignored trends in other agricultural technologies, the early 2000s were a time of particularly consequential change in irrigation facilities, insecticides and especially fertilizer.

Irrigation infrastructure. Gujarat, which accounted for much of the country's cotton yield surge, was undergoing large-scale improvements in irrigation facilities just before and during those yield increases. Improvements included construction of the Sardar Sarovar dam and more than 65,000 check-dams and farm ponds between 2000–2003. Analysts at the Institute for Resource Analysis and Policy went so far as to conclude that the 'growth' seen in the recent past in Gujarat is nothing but a good recovery from a major dip in production during the drought years of 1999 and 2000, which was due to four consecutive years of successful monsoon and bulk water transfer through the Sardar Sarovar project[42]. Between 2003–2011, the percentage of cotton land under irrigation in the state rose from 44.7% to 69.5%.

Fertilizer. More consequential than changes in irrigation was the rise in fertilizer usage during the 2000s. Although the *Bt* trait itself does not affect the plant's fertilizer response or needs, it has been bred almost exclusively into water-intensive and fertilizer-intensive hybrids. Indian agricultural institutes recommend use of at least twice as much fertilizer for hybrids as for varieties, and after several years of continuous cotton cultivation, soils require progressively more fertilizer. Fertilizer use on cotton in India more than doubled from 1.2 metric tonnes in 2006 to 2.7 metric tonnes in 2013; average use rose from 98 kg ha^{-1} in 2003 to 224 kg ha^{-1} in 2013 (ref. [12]). The additional fertilizer was generally routed to fields of the expensive *Bt* seeds, a pattern of cultivation bias confirmed in studies that monitored fertilizer use[28,43,44].

Figure 5 compares countrywide fertilizer use and yields for cotton. At this scale, there appears to be a loose relationship but no surge in fertilizer use in the key years of 2003–2004 when yields surged. But by looking at the inter-state variation subsumed in this graph, it becomes clear that fertilizer use is a strong predictor of yields.

Figure 6 compares yields and fertilizer use for cotton-producing states[12]. The correspondence between the two variables is especially notable in Gujarat and the northern states, which accounted for most of the countrywide surge in yields. The correlation between yields and fertilizer trends is particularly strong due to a more positive fertilizer response in these relatively well-irrigated areas.

Insecticide use. Introductions of new insecticides have also been important. Note that the appearance of new insecticides is not in itself cause for celebration, as the 'insecticide treadmill' has the overall effect of maintaining an unstable and expensive form of cultivation that undermines farmer skill[45,46]. However, each turn of the treadmill often brings temporary boosts in productivity, and several insecticides with new modes of action appeared in 2000–2002 and were being adopted in the years that cotton yields were climbing. Notable for bollworm control were spinosad (brand name Tracer) and indoxacarb (brand name Avaunt). Conducting ethnography in Andhra Pradesh in the first year of *Bt* cotton's introduction, Stone found that almost no farmers planted *Bt* seed and many were unaware of it, but most farmers were talking about these new and effective, but expensive, insecticides (Fig. 7). The neonicotinoids acetamiprid and imidacloprid were also introduced around this time, important both as seed treatments and as sprays for control of sucking pests.

The arrival of these new insecticides helps explain the specific jump in yields in 2003 (Fig. 8). Cotton growers set a record for insecticide expenditure per hectare in 2003, a fact that is obviously inconsistent with the attribution of yield increases to illegal *Bt* cotton, which protected itself from major Lepidopteran pests.

Bt cotton's spread in the middle of the decade led Lepidopteran spraying to drop sharply (Fig. 8). Total insecticide expenditure per hectare reached a low point in 2006, and Lepidopteran spraying expenditures continued to drop until 2011. *Bt* cotton's impacts were most positive in the years 2004–2012 when yields were relatively strong in most states (Fig. 4). While fertilizer, irrigation (especially in Gujarat) and the new insecticides pushed cotton yields upward, the *Bt* trait contributed by controlling both the ABW and PBW during these years. Pesticide poisonings dropped significantly during this period[47]. However, data from up to 2008 were also used to claim that the pesticide reductions were 'sustainable'[34]. Scientists who study agriculture should know better. It is true that polyphagous ABW has not developed resistance to *Cry* toxins, as other crops provide natural refuges and ensure reproduction of *Bt*-sensitive individuals[48]. However, the dedicated cotton-feeding PBW developed resistance by 2009 (ref. [49]), much as it had in China[50]. By 2009, the near ubiquity of *Bt* plants promoted the rapid spread of resistant PBW. By 2015, the PBW 'nightmare' was the stuff of headlines[51], and bollworm spraying was climbing quickly again (*Bt* seeds have continued to control the relatively less important spotted bollworm, but they have never been effective against cotton leafworms).

But Fig. 8 shows an even larger problem than Lepidopterans: surging populations of sap-sucking insects that thrive on fertilizer-intensive hybrids. The *hirsutum Bt* hybrids are highly vulnerable to these insects, unlike the public-sector varieties that were in wide use in the 1990s. Figure 8 shows that in 2007, as *Bt* adoption surged, so did expenditures for spraying targeting sucking pests. By 2013, the cost of insecticide per hectare topped the pre-*Bt* value in 2001. By 2018, Indian cotton farmers were spending an average of US$23.58 per hectare, 37% more than the pre-*Bt* high, and the situation with both PBW and sucking pests was deteriorating.

Conclusions

Our analysis of long-term trends shows that *Bt* cotton did make a positive contribution in India. *Bt* seeds sharply reduced predations by ABW, an effect that has endured due to the insect's ecology. *Bt* seeds also initially provided good control of the PBW, a previously intractable late-season pest. *Bt* seeds were responsible for the sharp falloff in spraying for Lepidopterans beginning in 2005 when adoption first began to surge.

However, we find that the technology's benefits have been modest and largely ephemeral. *Bt* adoption has been conspicuously incongruous with positive yield effects. Changes in other inputs, including irrigation, insecticides and especially fertilizer use, correspond better to yield rises. Moreover, *Bt* seeds' positive effects on

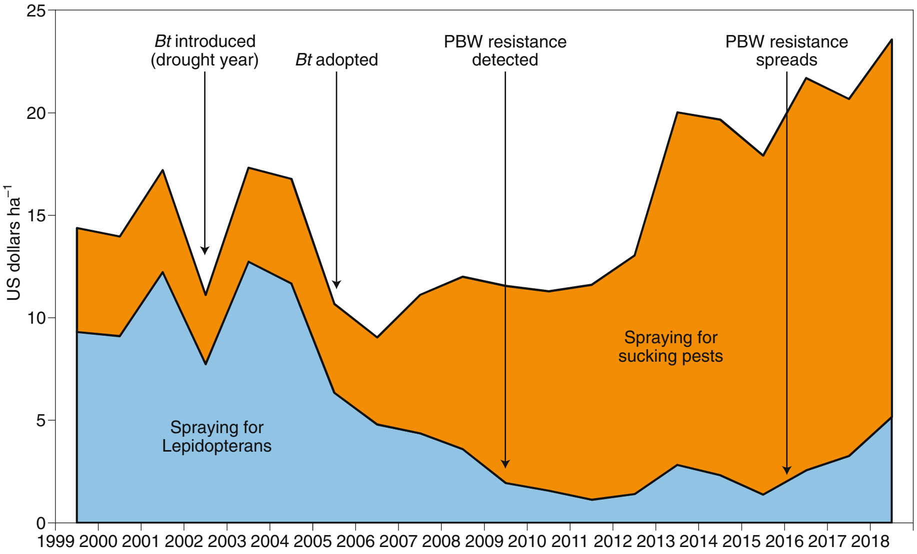

Fig. 8 | Countrywide expenditures on insecticides for cotton production. Data are from Kranthi[55] and Srivastava and Kolady[56], updated with information sourced from the market research firm Tech-SciResearch Pvt Ltd, Noida, India, and cross-checked in interviews with pesticide industry executives.

spraying were fleeting. Countrywide yields have not improved in 13 years, and Indian cotton farmers today are spending more per hectare on insecticide than they did before *Bt* began to spread.

The changes in inputs to Indian cotton production in the early 2000s are not only important because they largely explain the surge in yields that has been uncritically attributed to *Bt* seed. The rising input dependence of Indian cotton farming is also important because it has pushed farmers into an increasingly capital-intensive production regime, even as they continue to face considerable risk from year-to-year agroecological and market vagaries. Capital-intensive cotton farmers elsewhere in the world enjoy economic safety nets that are lacking in India[52]. While several studies have credited *Bt* seed adoption with increased profits[53], these are average short-term profits; cotton farmers now face stagnated yields along with ominously rising costs for insecticide and increasing costs for seed, fertilizer, irrigation and even herbicide[45]. In the decade following 2005, when *Bt* seed began its rapid spread across Indian cotton farms, per-hectare costs for seed rose by 78%, for insecticide by 158%, for fertilizer by 245% and for labour by 275% (due to legislation unrelated to *Bt* seed), with the overall production cost of seed cotton rising by 143% (data compiled by the MA). It now appears that *Bt* cotton's primary impact on Indian agriculture will be its role in this rising capital-intensiveness rather than any enduring agronomic benefits.

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Author contributions

K.R.K. and G.D.S. contributed to the data analysis and writing of this Perspective.

Competing interests

The authors declare no competing interests.

Additional information

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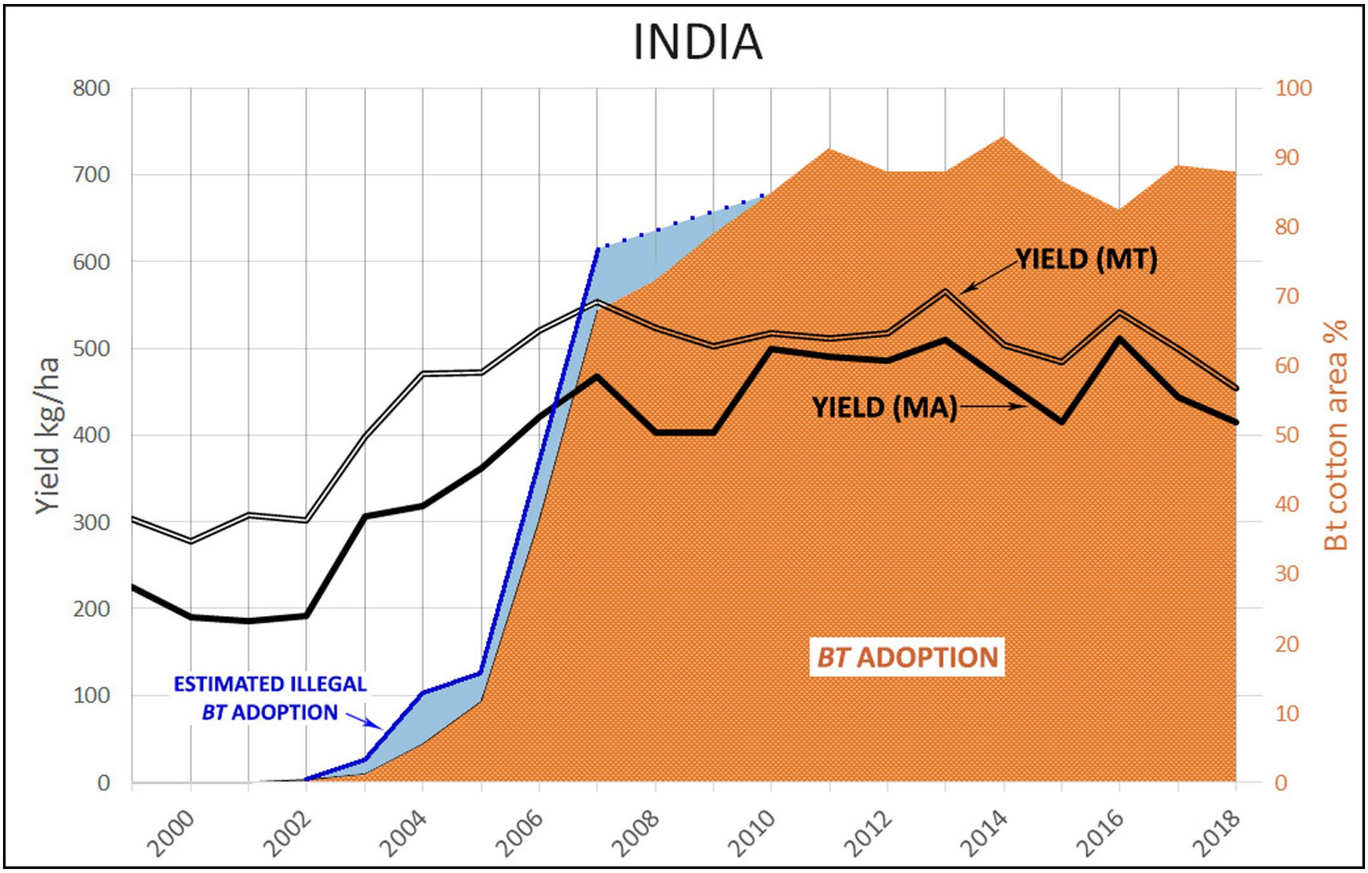
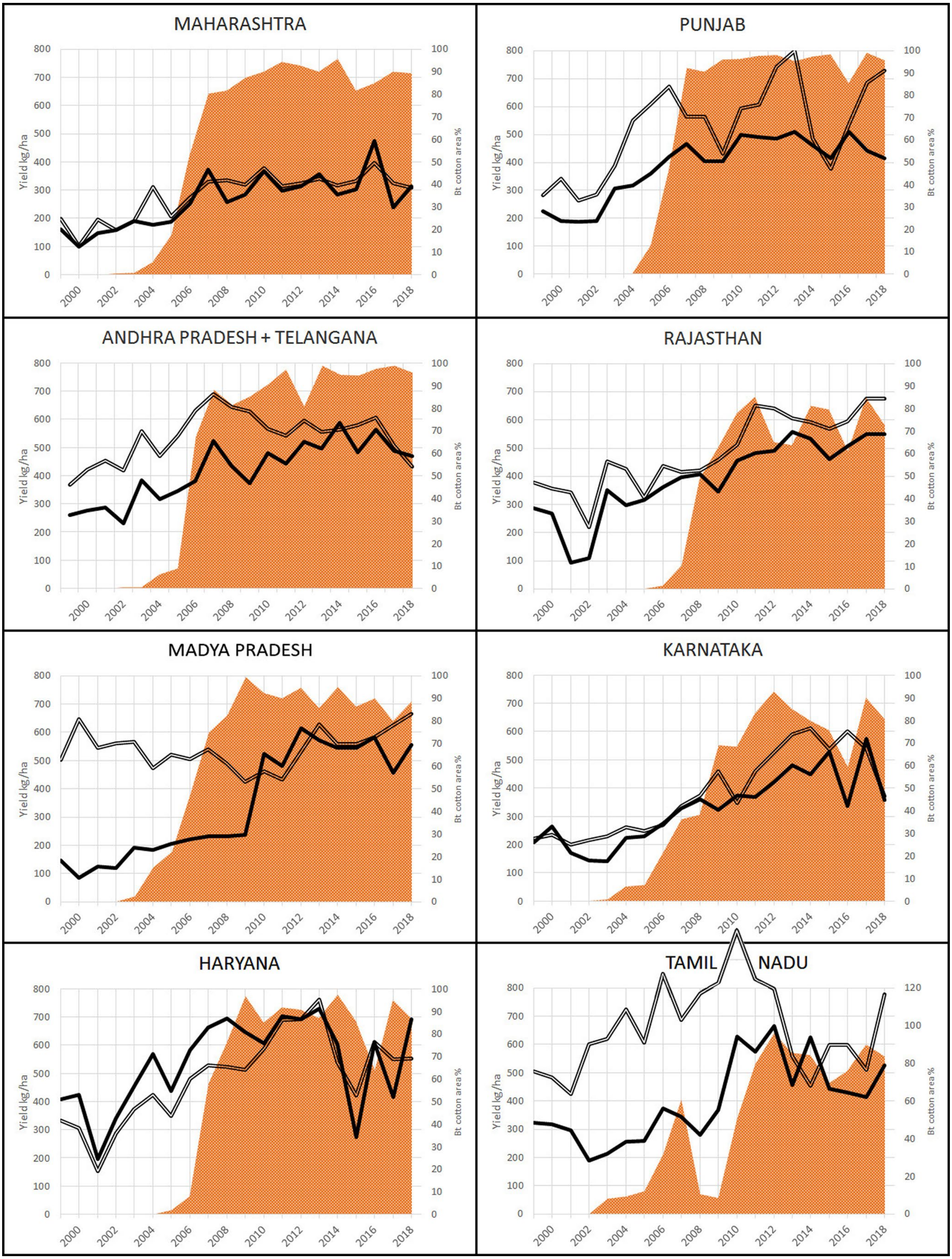
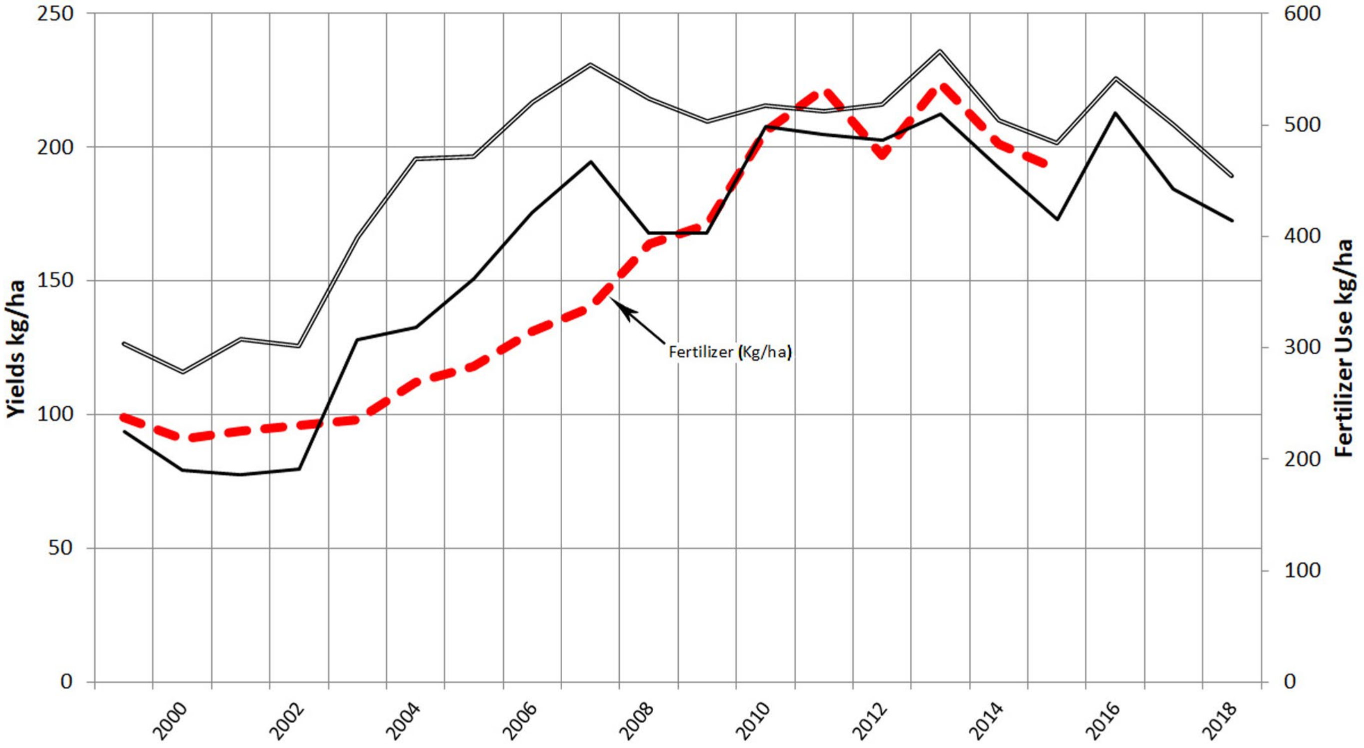


Extended Data Fig. 1 | Countrywide cotton yield and Bt adoption. This depicts the same data as in Fig. 2 but with Ministry of Textiles yield estimates indicated by the double line.

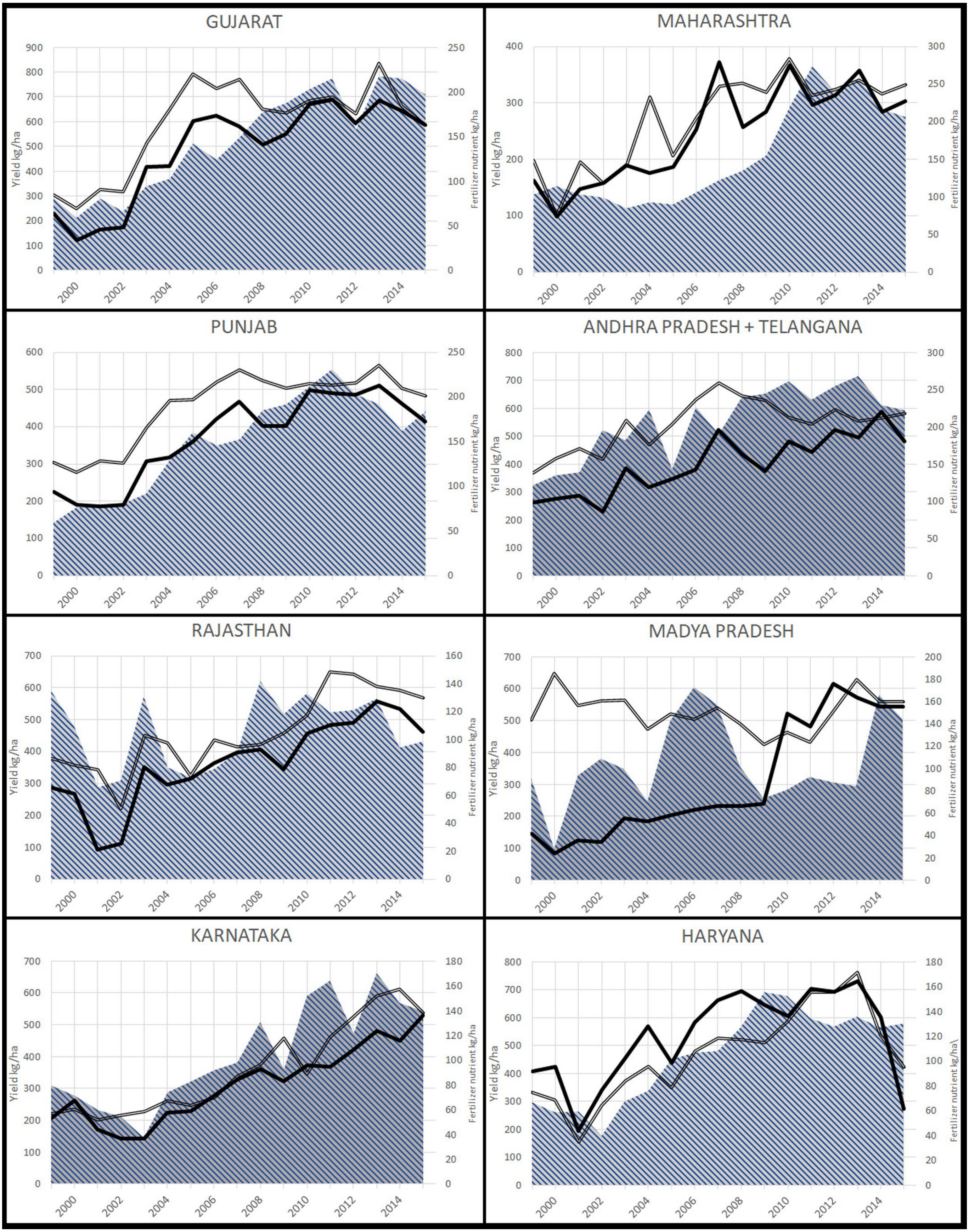
Extended Data Fig. 2 | Gujarat cotton yields and Bt adoption. This depicts the same data as in Fig. 3 but with Ministry of Textiles yield estimates indicated by the double line.



Extended Data Fig. 3 | State-specific cotton yields and Bt adoption. This depicts the same data as in Fig. 4 but with Ministry of Textiles yield estimates indicated by the double line. Note that the vertical scale for Tamil Nadu has changed slightly to accommodate the MT estimates.



Extended Data Fig. 4 | Countrywide cotton yields and fertilizer use. This depicts the same data as in Fig. 5 but with Ministry of Textiles yield estimates indicated by the double line.



Extended Data Fig. 5 | This depicts the same data as in Fig. 6 but with Ministry of Textiles yield estimates indicated by the double line. Note that the vertical scale for Gujarat, Andhra Pradesh, Rajasthan and Karnataka has changed slightly to accommodate the MT estimates.