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The ICAC Recorder

International Cotton Advisory Committee

Photograph: Keshav Kranthi, ICAC

SPECIAL ISSUE: Cotton in India: Long-Term Trends & Way Forward

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The ICAC Recorder

Editorial

Indian cotton presents a complex case study — 'on the surface -all is well' but yields are low. Cotton is grown in three distinctly different agro-ecological zones each with its own soil types and weather. India grows all four of the cultivable cotton species. It has the largest acreage under cotton, which is grown in 11 to 12 million hectares by 8 to 10 million farmers in small holdings of 1 to 2 hectares mostly.

India is unique also because it is the only country in the world that has chosen to grow hybrid cotton, which now occupies 90% to 94% of the planted area. India has mechanised farms and irrigated farms. India probably has the largest cotton research network and also the largest number of cotton scientists in the world.

Nonetheless, cotton yields remain low and have been stagnant for at least 15 years. India's 15-year average yield of 511 Kg/ha is 44% lower than the global average and the country ranks 37th in yields — below least-developed countries such as Myanmar, Ethiopia and Bangladesh but also below a few rainfed and resource-poor African nations such as Cameroon and Cote D' Ivoire. That's in spite of the fact that India:

- Is essentially saturated with cotton hybrid technology and double-gene-*Bt*-cotton,
- Has high fertiliser use and ready access to pesticides,
- Cultivates 4.2 million hectares of irrigated cotton, and
- Utilises mechanisation and other technologies.

There are several African countries that don't to have those advantages yet are ahead of India in yields. It is therefore a mystery why cotton yields are low in India. Some experts argue that the low yields are because of the large area (8.0 million hectares) that is rainfed. Others argue that it's due to the vast number of resource-poor small holder farms. Some even go so far as to argue that the weather, climate, monsoon and soils are unsuitable for cotton in a majority of the regions in the country. Unfortunately, none of these arguments appear valid. As mentioned above, Cameroon and Cote D 'Ivoire are completely rainfed and use almost negligible quantities of fertilisers and pesticides, and have no access to hybrids or *Bt*-cotton, but post better yields than India. The average land holding size in China is half that of India but the cotton yields are three times higher.

India receives very good rainfall, from 800mm up to 1200 mm, in rainfed regions during the cotton growing season. Sadly, the 15-year average yields in the fully irrigated 1.5 million hectares of northern India are also low at 567 Kg/ha, which is 37% lower than the world average (of which, only 45% of cotton irrigated). The weather and climate in India are ideally suited for cotton production, which is why it has been grown in the sub-continent over thousands of years. So, what is wrong with Indian cotton? Why are the yields so low? A correct diagnosis is critical to tearing down the yield barriers because if the diagnosis is right, solutions are possible — but if the diagnosis is wrong there can be no solution.

Theoretically, Indian yields should be very high, but they are not.

- Cotton plants need good sunshine, warm conditions and water — especially during the boll formation stage for good yields — and India has all these conditions in abundance.
- The country has access to all technologies that are available to the cotton sector elsewhere in the world.
- Commendable scientific progress has been made by 200+ cotton scientists over the past 50 to 60 years and many excellent varieties and hybrids were developed in India. Government policies are farmer-oriented and protect growers from risk and uncertainty.

But the lint yields remain stubbornly low. If everything is so ideal for cotton cultivation what could be going wrong? We certainly can't change the weather to suit cotton, but we can change the cotton agronomy to suit the weather, and we can ensure that the crop water requirements match the monsoon pattern.

For example, a critical analysis shows that India opted for a long-duration crop (>180 days) that, unfortunately, suffers from extreme thirst when it needs water the most — during boll formation. In other words, India implemented a long-season system that render plants vulnerable to drought and insects. That needs to change. In Australia, Brazil, China, Mexico, Turkey and USA, the cotton season rarely extends beyond 160-170 days and cotton agronomy is designed to match monsoon patterns in rainfed regions. Yields in these countries are 2-5 times higher than in India. Could a reductionist approach help to unravel the mystery of low yields in India and explain why some countries achieve 3 to 5 times higher yields than India using the same level or even fewer inputs?

This edition of the Recorder is an attempt to do exactly that. India's complexity manifests in its long-term trends and the diversity of agronomic practices in its eleven cotton-growing states. This special issue on Indian cotton will walk you through the production trends used in each of India's 11 cotton-growing states to enable readers to conduct their own independent analysis and diagnosis. Though the article sounds prescriptive in its terminal part, my intention was only to balance the narrative so that the reader wouldn't blame me for having pointed out the failings without attempting to guide towards possible solutions.

- Keshav Kranthi

The ICAC Recorder

Cotton in India: Long-Term Trends & Way Forward

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Introduction

India has an ancient cotton history that dates back to its earliest civilisations. According to historian Henry Lee (1887) India was the country of cotton; Egypt, of flax and China, of silk. It is widely believed that cotton has been grown and used in India for more than 5,000 years (Santhanam and Sundaram, 1997). There is also evidence that cotton was cultivated on the Pacific coast of Chile and Peru in parallel times. Historically, India was known to cultivate two species: *Gossypium arboreum* and *G. herbaceum,* which are commonly called 'Desi-cotton'. From 1790 to 1793, two species — *G. hirsutum* (American cotton) and *G. barbadense* (Egyptian cotton) — were introduced into India. As of now, India has the unique distinction of being the only country that grows all four cultivated species of cotton on a commercial scale.

Prior to independence, from 1930 to 1940, cotton was cultivated on 8.0 to 10.0 million hectares (M ha) in India. Yields were about 100 kg/ha to 120 kg/ha. About 0.8 million tonnes (Mt) to 0.9 Mt of cotton were utilised by 400 existing mills with a capacity of about 10,200 spindles and 210,000 looms. At the time of its independence, Pakistan's textile capacity was only 0.012 Mt but it had the advantage of large tracts of irrigated land for cotton production.

When India gained independence in 1947, cotton was cultivated on 4.3 M ha with a production of 0.57 Mt comprising of 67% medium staple and 33% short staple cotton from 97% Desi varieties (65% *G. arboreum* and 32% *G. herbaceum*). The area increased to 5.9 M ha and production increased to 0.6 Mt in 1950. However, yields declined from 171 kg/ha in 1945 to 103 kg/ha in 1950. During 'The Partition', the cotton mills remained in India and the regions that were suitable for long staple cotton went to Pakistan. Therefore, efforts were intensified in India to produce long staple cotton that suited the mills.

Cotton research in independent India has been carried out mostly by government organisations. For 20 years after independence cotton research was conducted under various government projects. In 1967, the All India Coordinated Crop Improvement Project (AICCIP) was set up at Coimbatore by the Indian Council of Agricultural Research (ICAR). In 1976, the Central Institute for Cotton Research (CICR) was established at Nagpur and the AICCIP was merged into it. Research was focused mostly on agronomy and breeding of the American cotton species *Gossypium hirsutum*. The Indian spinning mills preferred the longer and stronger fibres of *G. hirsutum* species so cotton scientists focused more on genetic improvement of *G. hirsutum* varieties and hybrids, which produced longer and stronger fibres compared to the Desi cotton species. Until recently, a total of 393 cultivars have been developed in India mostly by the public sector institutions and notified/approved by the Ministry of Agriculture. Amongst these, 171 are *G. hirsutum* varieties, 68 *G. arboreum* varieties, 19 *G. herbaceum* varieties, 6 *G. barbadense* varieties, 78 intra-*hirsutum* hybrids, 23 HXB (*G. hirsutum* x *G. barbadense*) inter-specific hybrids and 4 inter-specific (*G. hirsutum* x *G. arboreum*) hybrids.

Until 1970s, insect pests such as jassids, *Amrasca biguttula*, the leaf worm *Spodoptera litura* and the pink bollworm *Pectinophora gossypiella* were considered major production constraints in India. In 1980s the changes in crop composition from Desi species to *G. hirsutum*, from open pollinated varieties to hybrids, and the introduction of synthetic pyrethroid insecticides changed the pest dynamics drastically to result in the emergence of the whitefly, *Bemisia tabaci*, and the American bollworm *Helicoverpa armigera* as the most damaging pests. The leaf curl virus disease surfaced as a new menace in north India during the same time. In 1990s, the American bollworm developed resistance to almost all the recommended insecticides as farmers resorted to indiscriminate use of insecticides and tank-mix combinations to combat the new pests, thus resulting in higher levels of insect resistance. *Bt*-cotton was introduced into India in 2002 mainly to control the insecticide-resistant American bollworm. *Bt*-cotton is a product of genetic modification (GM) that was designed to express insecticidal toxin genes derived from the soil bacterium *Bacillus thuringiensis* mainly intended to kill bollworms. In 2002, *Bt*-cotton hybrids were approved for commercial cultivation in central and southern India. In 2006 *Bt*-cotton was approved for cultivation in north India. To date, more than 3000 *Bt*-cotton hybrids have been approved for cultivation, mostly as 'truthfully labelled seed'. These interventions and the emphasis on *G. hirsutum* resulted in the decline of area under Desi cotton to 25.0% of the total cotton acreage in India by the year

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2000. By 2011, *Bt*-hybrids replaced almost all of the Desi cotton area except for 8%-10% area in north India where farmers still prefer a few *G. arboreum* varieties because they are immune to the dreaded leaf curl virus.

Today, India has the largest cotton acreage and the highest production in the world. Cotton holds a prominent place in India's economy by providing strong export earnings from raw-cotton, yarn, fabric and garments — in addition to providing direct employment to 35-40 million people.

Cotton is cultivated on about 12 M ha in 11 states of India by about 10 million farmers. The average cotton farm size in India was estimated to be 1.08 hectares in 2015/16. Cotton area in India increased significantly from 9.41 M ha in 2008 to 12.18 M ha in 2011. The area remained high thereafter. With an acreage of 12.6 M ha and the world's highest production of 6.12 Mt in 2019, India accounted for 36.5% of the global cotton area and 22.9% to global cotton production. However, despite having 35% irrigated area and adoption of best available technologies, Indian lint yields have been low with a 15-yr average of 511 kg/ha with a global rank of 37, behind even a few resource-poor rainfed African countries. From 2007-2016:

- Seed costs increased by 72%;
- Insecticide quantity increased by 30% and costs increased by 135%;
- Fertiliser quantity increased by 33% and costs increased by 178%;
- Labour costs increased by 237%;
- Cultivation costs increased by 174%;
- Production costs increased by 140%; and
- Net profits increased by 35%.

Therefore, low yields and high cultivation costs are the two main challenges for Indian cotton.

There is an urgent need to identify the key constraints that can be circumvented to develop strategies to increase India's yields to at least the global average. That means perspectives must be derived from long-term data to provide a a complete background and enable the development of informed strategies and solutions. This special issue deals with greater details on the long-term state-wise and national trends in area, production, productivity (yield) and input usage so as to facilitate data inputs for proper analysis of the cotton conundrum in India. This article also attempts to suggest strategies to double cotton farmers' income in India in a sustainable manner.

Methodology

Data on cost of cotton cultivation in India were derived from http://eands.dacnet.nic.in/ of the Directorate of Economics and Statistics (DES) and the Commission for Agricultural Costs and Prices (CACP), http://cacp.dacnet.nic.in/ Ministry of Agriculture, Government of India. CACP uses the concept 'C2' for cost of cultivation which includes all actual expenses in cash and kind incurred in production by owner + interest on value of owned capital assets (excluding land) + rental value of owned land (net of land revenue) and rent paid for leased-in land + imputed value of family labour, which is estimated by taking into account statutory minimum or actual wage, whichever is higher. The DES and CACP data provide state-wide details of C2 including the costs incurred on seeds, fertilisers, insecticides, human labour etc.; the amount of fertilisers and seeds used as well as the details of seed-cotton produced and its market value. As in April 2020, complete C2 data with details on the imputed value of all the inputs were available only until 2016. These data were considered for all the calculations on input costs for the period from 1999 to 2016. Data on area, production, productivity, exports, imports, market prices etc., were derived from reports of the Cotton Advisory Board (CAB), Ministry of Textiles, Government of India; http://www.cotcorp.gov.in and http://agmarknet.nic.in/. Data on state-wise *Bt*-cotton area from 2002 to 2019 were obtained from the Directorate of Cotton Development, Ministry of Agriculture, Government of India.

Agro-Ecology of Cotton in India

There are eleven main cotton growing states in India. The north zone comprises of three states: Punjab, Haryana and Rajasthan. The central zone is comprised of Maharashtra, Gujarat and Madhya Pradesh and the south zone has Telangana, Andhra Pradesh, Karnataka, Tamil Nadu and Orissa. Maharashtra, Gujarat and Telangana have the largest area under cotton. The three states account for 70.0% of India's cotton area.

Cotton in India is cultivated in three distinct agro-ecological regions (north, central and south) in varied soils, climates, and agricultural practices. Cotton in the north zone is grown primarily under irrigated conditions, while the irrigated area in the central zone is 23% and south zone is 40%. In central and south India, rainfall ranges from 700mm to 1200mm coupled with aberrant precipitation patterns over the years leading to large-scale fluctuations in production. Cotton is grown on 4.2 million hectares of irrigated area (4.4% of India's irrigated arable land). About 65% to 67% of India's cotton is produced under rain-fed conditions and 33% to 35% is on irrigated lands. The 33% to 35% irrigated cotton area is distributed across the country with 38% of the irrigated area in Gujarat, 36% in north India and the rest 26% in MP, AP, Karnataka, TN and other states. The main cotton growing states — Gujarat, MP, AP, Maharashtra, Orissa, Telangana and Karnataka — receive good rains of 800mm to 1000mm during the cotton season and use about 20mm to 40mm of supplemental irrigation per hectare from check dams (in Gujarat), farm ponds, bore wells and canals. The three states in north India, Punjab, Haryana and Rajasthan, receive 400mm to 600mm of rainfall and use about 200mm to 350mm for irrigation through canal water and wells.

Figure 1. Cotton growing states in India

Cotton is sown in April-May in north India, June-July in central India and July-September in south India. Cotton in north India is harvested in about 180 days, but in central and south India the cotton season generally extends for 180-240 days especially with late-season rainfall in September to November. Hybrid cotton (*Bt*-Bollgard-II) is grown on 90% to 94% of the area. Hybrid seeds are expensive and because of the bushy growth, sowing is done sparsely in a rectangular or square pattern. The most commonly followed spacing is 90 x 90cm or 90 x 120cm in irrigated conditions and 90 x 30cm or 90 x 60 cm in rainfed conditions. Due to sparse plant population of 11,000 to 16,000 plants per hectare, plants grow for long durations and multiple pickings (4-5) are common. Due to long duration of the crop, the boll-formation stage encounters terminal stress of water and nutrients, especially in rainfed regions, thereby leading to poor yields. Fertiliser recommendations for Nitrogen, Phosphorus and Potash (N:P:K) are 120:60:60 kg/ha in irrigated conditions and 90:45:45 kg/ha in rainfed conditions with slight variations according to soil types, varieties and hybrids.

North Zone

Cotton in North India is grown on 1.4 to 1.5 million hectares in Punjab, Haryana and Rajasthan. About 98% of the cotton area is irrigated. Yields range at 500 kg/ha to 700 kg/ha. The crop is grown under irrigated conditions on loamy, alluvial and sandy soils from May to October. The main cropping system is cotton-wheat. The primary challenges are salinity, a decreasing water table, whiteflies and cotton leaf curl virus disease. Until the introduction of *Bt*-cotton in 2006 in north, only self-pollinated varieties of *Gossypium hirsutum* and *G. arboreum* were cultivated in the three states. Currently north India is almost saturated with *Bt*-cotton hybrids. However, about 5%-10% of the area is occasionally allocated to varieties of the *Gossypium arboreum* species due to their resilience against whiteflies and the cotton leaf curl virus. The north Indian states underwent a radical shift from large tracts under Desi cotton until the 1960s and then to the majority of the area under open-pollinated varieties until 2005, followed by a sudden transition to hybrid cotton, mainly *Bt*-cotton, after 2006. The area in Punjab has been declining for the past 20 years but has been relatively constant in Haryana and Rajasthan. Bhatinda, Firozepur, Muktsar and Mansa are the major cotton producing districts in Punjab. About 80% of the cotton production comes from Sirsa, Hisar & Fatehabad in Haryana state. Cotton is grown in Ganganagar, Hanumangarh, Bhilwara, Nagaur, Banswara and Jodhpur districts in Rajasthan. About 50%-60% of cotton production comes from the Sriganganagar district.

Central Zone

The central zone has the largest acreage under cotton — 6.8 million to 7.5 million hectares. Cotton is grown in black alluvial soils that are less fertile due to soil degradation, runoff, erosion and nutrient losses. Due to erratic rainfall, the crop often encounters moisture stress. Apart from *Bt*-hybrids, the Desi species *G. arboreum* and *G. herbaceum* cotton are also grown in 5-6% of the area in the region. Farmers prefer the Desi cotton species due to salinity-tolerance of the *G. herbaceum* varieties and drought tolerance of the *G arboreum* varieties. Maharashtra is the largest cotton growing state in the country with about 3.8 million to 4.2 million hectares. Farmers are resource poor and cultivate cotton mostly with bullock-drawn implements and manual labour. Cotton is grown primarily under rainfed conditions in the state with about 2.7% of the area under irrigation. The soils in Maharashtra are shallow, medium and deep with > 30% clay content. Cotton is intercropped with pigeon pea, sorghum, cowpea, black gram, green gram, etc. The yields are low at 300 to 380 kg/ha. Cotton is grown in three major regions: Khandesh, Vidarbha and Marathwada. The main cotton growing districts are Yavatmal, Aurangabad, Nanded, Jalgaon, Buldhana, Parbhani, Beed, Akola, Amravati, Dhule, Wardha and Nagpur. Cotton in Gujarat is grown on 2.8 million hectares with 58.7% under irrigation. The general yields are 700 to 800 kg/ha. Gujarat has emerged as a major cotton growing state over the past 20 years. Cotton in Gujarat is grown in the alluvial and black cotton soils of Surendranagar, Bhavnagar, Rajkot, Amreli, Ahmedabad, Vadodara, Jamnagar, Bharuch and Surat. In Madhya Pradesh, cotton is cultivated on about 0.5 to 0.6 million hectares in black medium to shallow soils in the Malwa plateau (Indore, Dhar and Dewas), and in deeper and heavier soils in Nimar (Khargone and Khandwa). The major cotton growing districts are Khargone, Dhar, Barwani, Khandwa, Burhanpur, Chhindwara, Dewas and Jhabua. About 60% of cotton in MP is irrigated. Yields range from 600 to 650 kg/ha.

South Zone

The south zone has 2.5 to 3.5 million hectares under cotton. Cotton is grown in five states that have predominantly alluvial, black and red soils. Telangana is the largest cotton-growing state in the south zone (1.4 to 1.9 million hectares) with irrigation ranging from 10% to 12.5%. Yields are about 600 kg/ha. Karnataka grows cotton on 0.5 to 0.6 million hectares with 27.2% under irrigation. Cotton is intercropped with red gram and a few other legume crops. The yields are about 550 to 700 kg/ha. Cotton in Tamil Nadu is grown in sandy and red soils on about 0.15 to 2.0 million hectares with 26.5% area under irrigation. Yields range from 650 to 800 kg/ha. Odisha in the central western part of India is a recent addition to the list of cotton growing states with an area of 0.12 to 0.15 million hectares under cotton cultivation with about 10% irrigation. Yields average at 350 to 400 kg/ha. Cotton in south India is grown either as a sole crop or inter-cropped with onion, chilli, pigeon pea, cowpea, black gram, maize or jowar. Cotton-rice rotation is followed in Andhra Pradesh, Tamil Nadu and a few other parts of south India. The major cotton growing districts in Andhra Pradesh are Kurnool, Guntur, Anantapur, Prakasam and Krishna. Cotton in Telangana is grown in Adilabad, Karimnagar, Warangal, Nalgonda and Khammam districts. The main cotton growing districts in Karnataka are Haveri, Dharwad, Mysore, Gadag, Gulberga, Bellary and Raichur. Cotton in Tamil Nadu is grown in sandy and red soils in Perambalur, Tiruchirapalli, Salem, Dharmapuri, Villupuram and Madurai.

Area and Production

Cotton was cultivated on 8.0 M ha to 10.0 M ha in India from 1930 to 1940. Cotton area decreased to 4.3 M ha in 1946, after which it increased to 8.08 M ha by 1955. From 1954 to 1994 cotton area ranged from 6.46 M ha to 8.36 M ha with an average of 7.7 M ha. From 1995 to 2006, cotton area averaged at 8.71 M ha in a range from 7.67 to 9.29 M ha.

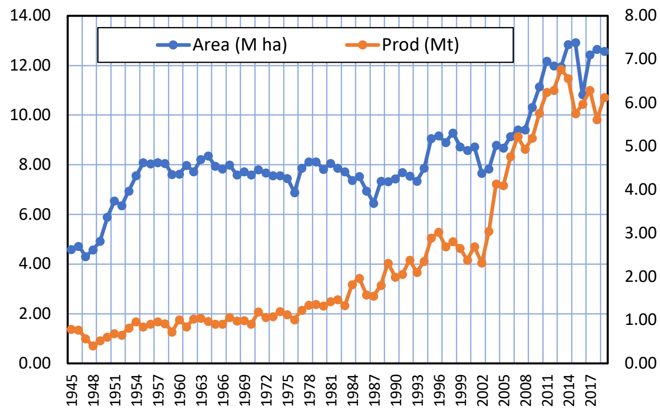


Figure 2. Area and production 1945-2019

National

Despite a consistent average acreage of 7.7 million ha from 1954 to 1994, cotton production increased from 0.84 Mt in 1954 to 2.35 Mt in 1994. Though the trends in area and production appear to be correlated after 1997, constant yield increases were apparent with the narrowing gap between area and production over time. A significant increase in area after the introduction of *Bt*-cotton in 2002 clearly contributed to an increased production.

Punjab

Cotton acreage increased steadily from 0.43 M ha in 1966 to 0.72 M ha in 1982, after which the changes were dramatic in a range from 0.45 M ha to 0.76 M ha from 1983 to 2011. Area declined from 0.56 M ha in 2011 to 0.24 M ha in 2018. The trends in production followed the trend in area.

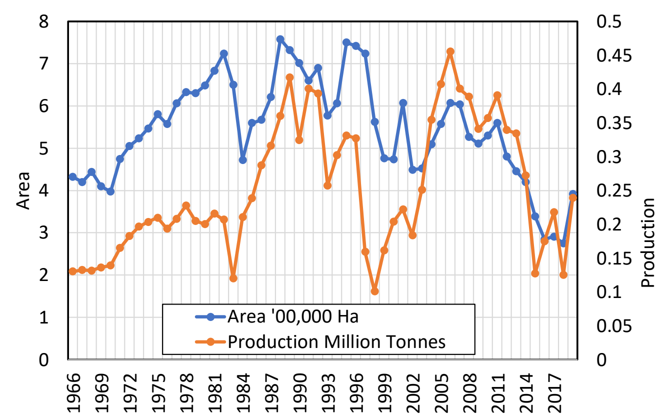


Figure 3. Area and production in Punjab 1966-2019

Haryana

Area increased more than threefold from 0.183 M ha in 1966 to 0.652 M ha in 1996. From 1997 to 2018, cotton area kept fluctuating regularly in a range between 0.445 M ha to 0.665 M ha before reaching a record high of 0.7 M ha in 2019. Insect pests such as whiteflies, *Helicoverpa armigera*, the leaf curl virus disease and market prices influenced the changes in acreage.

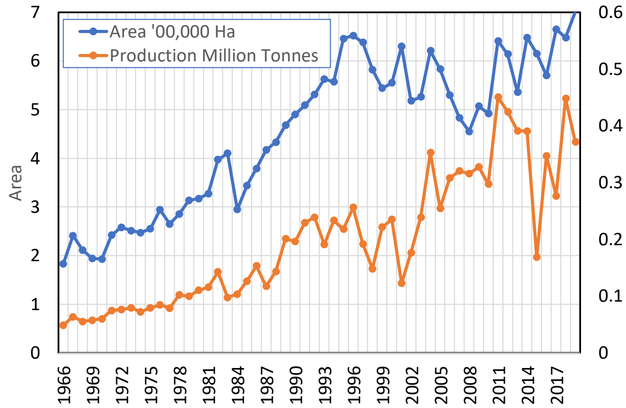


Figure 4. Area and production in Haryana 1966-2019

Rajasthan

Area increased from 0.25 M ha in 1966 to 0.65 M ha in 1996. Cotton acreage crashed to 0.34 M ha in 2003 followed by annual fluctuations of 0.3 M ha to 0.5 M ha from 2004 to 2016. Area was higher than 0.58 M ha from 2017 to 2019. Production followed a trend that was similar to the trends in area. From 0.03 Mt in 1966, production increased to 0.23 Mt in 1996 and fell to 0.04 Mt in 2003. Until 2010, production was almost stagnant at an average of 0.13 Mt but increased rapidly to a record level of 0.41 Mt in 2019.

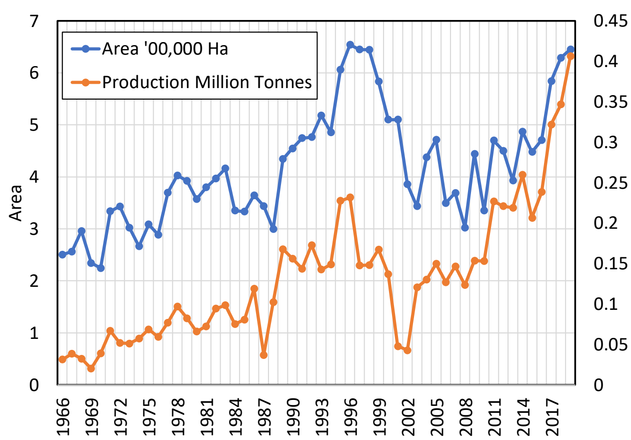


Figure 5. Area and production in Rajasthan 1966-2019

Gujarat

Cotton area was 1.5 M ha to 1.8 M ha before 1982 but declined to 0.72 M ha in 1987 and remained at less than 1.2 M ha for the next seven years, mainly because of the high damage levels inflicted by whiteflies and *Helicoverpa armigera*. Cotton area increased from 1.1 M ha in 1993 to an all-time high of 2.9 M ha in 2011. Area has been high from 2012 to 2019 at 2.4 to 2.7 M ha. Cotton production in Gujarat was less than 0.5 million tonnes (Mt) prior to 2002 with exception of three years from 1996 to 1998 when it was at slightly higher levels. Production increased after 2002 to reach a record high of 2.0 Mt in 2011, after which it followed a declining trend until 2019.

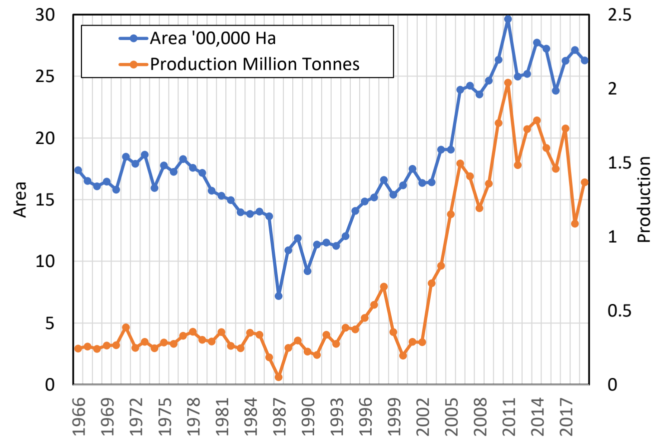


Figure 6. Area and production in Gujarat 1966-2019

Madhya Pradesh

Cotton area was 0.82 M ha in 1966 but declined gradually to 0.47 M ha in 1992. Area increased later to 0.7 M ha by 2011 and declined again to a range of 0.1 M ha to 0.2 M ha until 2019. Cotton production in the state was low at 0.03 Mt to 0.08 Mt from 1996 to 2002. Production increased from 0.04 Mt in 2000 to 0.147 Mt in 2009, but jumped suddenly to an all-time high of 0.37 Mt in 2012. Production remained at higher levels of 0.27 Mt to 0.34 Mt after 2012. The sudden jump in production from 0.145 Mt in 2009 to 0.34 Mt needs to be understood properly.

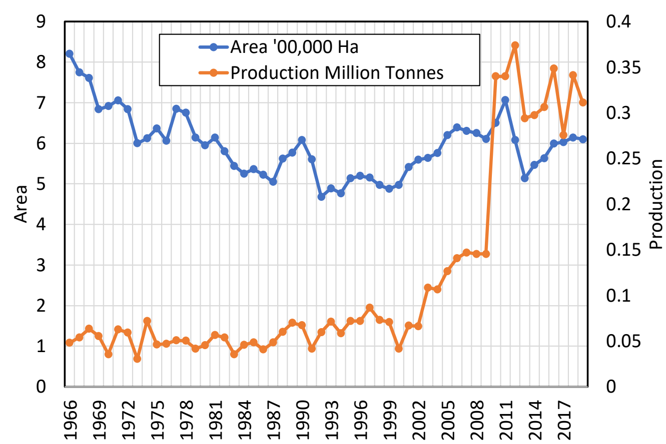


Figure 7. Area and production in Madhya Pradesh1966-2019

Maharashtra

Cotton acreage averaged 2.6 M ha from 1966 to 1994. Area increased to an average of 3.0 M ha from 1995 to 2008 before finally reaching a high average of 4.1 M ha in subsequent years until 2019. Production in Maharashtra was low at 0.08 Mt to 0.37 Mt for 26 years from 1966 to 1992, after which it increased slightly to a range from 0.297 Mt to 0.537 Mt from 1994 to 2005. Production doubled from 2006 to 2019 with a record high level of 1.8 Mt in 2016.

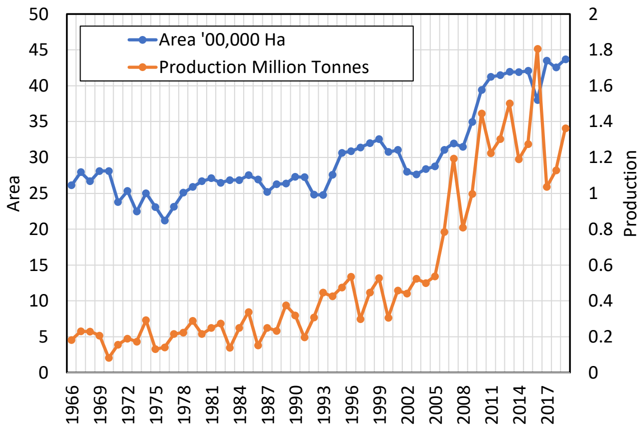


Figure 8. Area and production in Maharashtra 1966-2019

Andhra Pradesh

Cotton area was 0.3 million hectares (M ha) prior to 1972 but increased later to 1.28 M ha in 1998. High infestation levels of whiteflies and *Helicoverpa armigera* resulted in

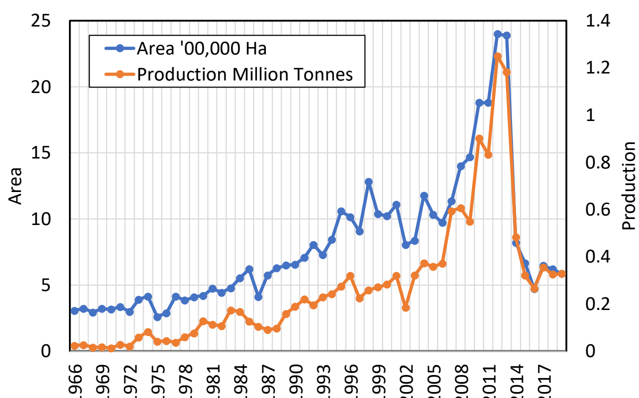


Figure 9. Area and production in Andhra Pradesh 1966-2019

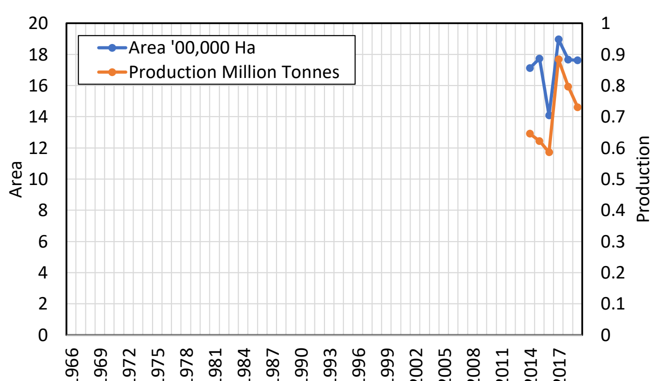


Figure 10. Area and production in Telangana 2014-2019

decline in area until 2006 after which area increased rapidly to 2.4 M ha in 2012 and 2013. The Telangana region was separated from Andhra Pradesh, because of which cotton area in the state was reduced to a range of 0.47 M ha to 8.21 M ha after 2014. Cotton area in Telangana ranged from 1.7 M ha to 1.8 M ha from 2014 to 2019, with an exception of 1.4 M ha in 2016.

Karnataka

The average cotton area from 1966 to 1983 was 1.0 M ha after which it declined rapidly to 0.41 M ha in 1986. From 1988 to 2000, the area fluctuated between 0.5 M ha to 0.7 M ha but slumped again to an average of 0.4 M ha from 2001 to 2008 and later to an average of 0.57 M ha from 2009 to 2019. The average cotton production in Karnataka from 1966 to 2006 was 0.1 Mt, which increased to an average of 0.23 Mt from 2007 to 2019.

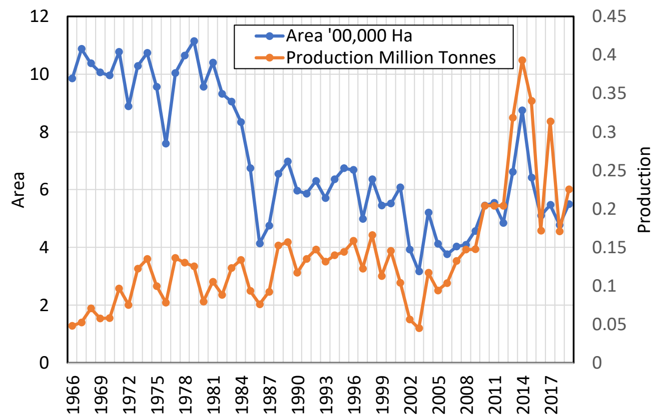


Figure 11. Area and production in Karnataka 1966-2019

Tamil Nadu

Cotton occupied relatively larger tracts of 0.3 to 0.4 M ha before 1973 in the state. From 1980 to 2000, cotton area fluctuated annually in a range from 0.17 M ha to 0.27 M ha after which it declined to 0.07 M ha in 2002 and remained at lower acreages of 0.1 to 0.17 M ha from 2003 to 2019. Cotton production in Tamil Nadu was generally within a

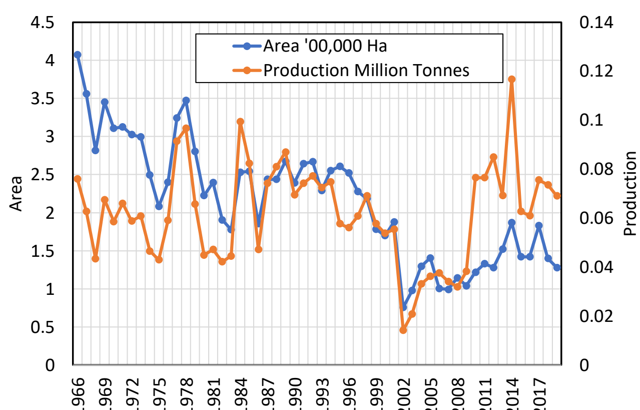


Figure 12. Area and production in Tamil Nadu 1966-2019

range of 0.04 Mt to 0.1 Mt, with exceptions from 2002 to 2009 when it was less than 0.05 Mt and in 2014 when it was more than 0.1 Mt.

Orissa

Cotton had a negligible area in the state before 1993. However, the acreage increased gradually from 0.007 M ha in 1994 to reach a record area of 0.17 M ha in 2019. Cotton production followed a similar growth trend, increasing from 0.001 Mt in 1994 to a record high of 0.077 Mt in 2018.

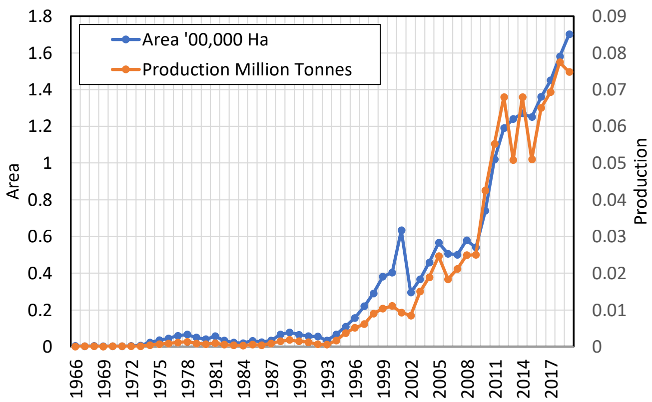


Figure 13. Area and production in Orissa 1966-2019

Yields (Data from the Textile Ministry)

Yields increased at a slow pace from 89 kg/ha in 1948 to 133 kg/ha in 1960 followed by a stagnant phase until 1970. However, yields exploded from 1971 on, reaching 173 kg/ha in 1983 and almost doubling to 330 kg/ha by 1996. The doubling of yields from 1971 to 1996 can be attributed to new crop production and protection technologies as well as the new varieties and hybrids developed under the All India Coordinated Cotton Improvement Project.

National: Data show that national yields increased from 308 kg/ha in 2001 to 470 kg/ha in 2004 when the area under *Bt*-cotton was only 5.59%. Again, as in the data of the Ministry of Agriculture, it cannot be presumed that yields in this small area of 5.59% may have increased so high and that the non-*Bt* farms continued to produce yields of 308 kg/ha — equivalent to the pre-*Bt* era. Though the trend in yield increases from 2005 to 2007 appears to slightly correlate with the increase in *Bt*-cotton area, the correlation disappears almost completely after 2007, with yields decreasing as area increased under *Bt*-cotton until 2011 and with no specific trends thereafter.

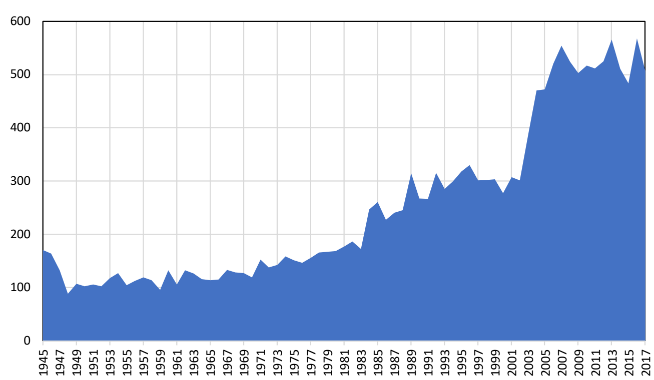


Figure 14. National Yield (kg/ha) 1945-2017

North Zone

The average yields of north India reflect three clear trends. The first pattern shows a decline in yields from 497 kg/ha in 1991 to a low of 223 kg/ha in 1999, followed by a second pattern of increases to 729 kg/ha in 2013 and a third trend of the decline to 458 kg/ha in 2015 due to severe whitefly infestation. There has been a constant debate in India whether the yields increased in north India because of *Bt*-cotton. Perusal of the CAB data show that the average yields of north India were 497 kg/ha in 1991 but followed a declining trend in the subsequent seven years to reach 223 kg/ha in 1998 and remained low until the year 2002. Low yields were mainly due to higher levels of damage caused by *Helicoverpa armigera*, whiteflies and the leaf curl virus. Several factors such as newly introduced insecticides, increased fertiliser usage and good weather contributed to an increasing trend in yields that reached an average of 549 kg/ha in 2006 when *Bt*-cotton was just introduced and had almost negligible area under it. Though yields increased in the subsequent years, the trends were guided by varieties that were tolerant to the leaf curl virus and higher usage of fertilisers rather the adoption of *Bt*-cotton.

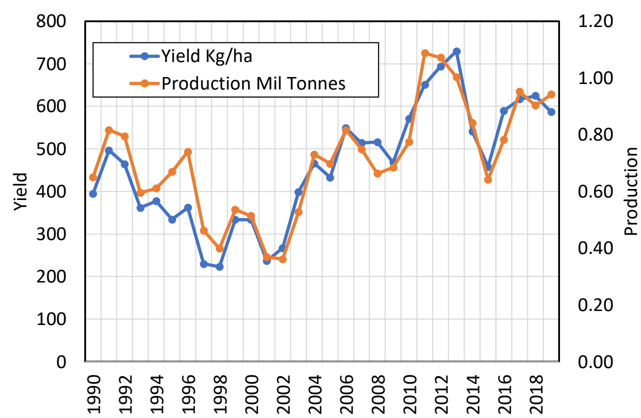


Figure 15. North zone yield (kg/ha) 1990-2019

Punjab

Data showed three clear trends in yields of Punjab with a decline from 611 kg/ha in 1991 to 151 kg/ha in 1998 and a subsequent discontinuous increasing trend to 800 kg/ha in 2013, followed by a slump again to 376 kg/ha in 2015 despite 100% irrigation and 97.10% area under *Bt*-cotton.

Yields in Punjab increased from 262 kg/ha in 2001 to 551 kg/ha in 2004 before *Bt*-cotton was introduced. The average yield was 579.5 kg/ha in 11 years from 2007 to 2017 with an average of 94.98% area under *Bt*-cotton. The yield was 610 kg/ha in 2005 with 12.57% area under *Bt*-cotton but declined to 486 kg/ha in 2014 and 376 kg/ha in 2015 with 97.10% area under *Bt*-cotton. Yields in Punjab were high at 611 kg/ha in 1991, but slumped to 151 kg/ha in 1998, mainly due to the leaf curl virus, whiteflies and the American bollworm. Yields increased to 672 kg/ha in 2006 because of newly introduced insecticides that effectively controlled insect pests. *Bt*-cotton was introduced in 2006 in north India, but the yields dropped over the next four years to less than 600 kg/ha due to whitefly and leaf curl virus damage in the newly introduced hybrids. A few new *Bt*-cotton hybrids that were tolerant to the leaf curl virus were introduced after 2010 and the yields increased subsequently to reach an all-time high of 800 kg/ha in 2013. Yields declined again to 376 kg/ha in 2015 due to severe whitefly infestation that was triggered by weather and a few insecticides. Because of timely remedial measures that were followed, yields recovered back to 672 kg/ha in 2017.

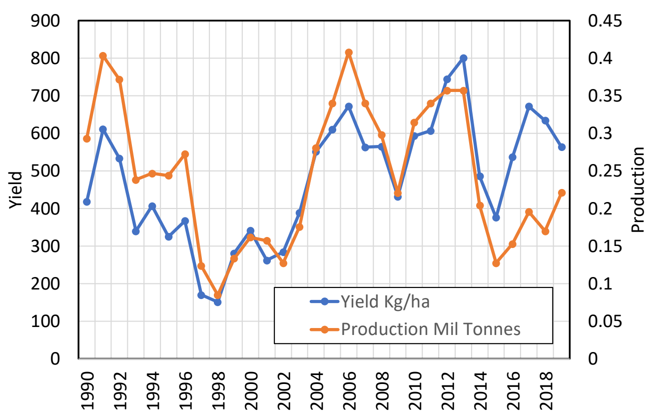


Figure 16. Punjab yield (kg/ha) 1990-2019

Haryana

Data showed that yields in Haryana increased from 153 kg/ha in 2001 to 424 kg/ha in 2004 before *Bt*-cotton was introduced. Yields increased to 528 kg/ha in 2007 when *Bt*-cotton area was 57.76% but decreased to 511 kg/ha when the *Bt*-area increased to 96.65% in 2009. The average yield was 598 kg/ha in 9 years from 2009 to 2017 with an average of 88.10% area under *Bt*-cotton. CAB data of Haryana showed yield trends that were similar to Punjab. Yields were relatively high at 470 kg/ha in 1991, but, declined to 204 kg/ha in 1998 and further down to 153 kg/ha in 2001. The main causes for low yields were whiteflies, leaf curl virus and the American bollworms. With the introduction of neonicotinoid insecticides which were most effective for the control of sucking pests and spinosad, emamectin benzoate, indoxacarb and chlorantraniliprole which effectively controlled the bollworm *Helicoverpa armigera*, yields recovered to 481 kg/ha by 2006 before the introduction of *Bt*-cotton. The growth trend subsequently continued to increase and reached a peak of 761 kg/ha in 2013 due to the introduction of new hybrids such as Bio-Seed 6488, Bunty, Bio-Seed 6588, Raghav, Bayer 7007 and RCH 650 that were tolerant to the leaf curl virus combined with the season-long effective bollworm control provided by *Bt*-cotton. Yields declined to 422 kg/ha in 2015 due to severe whitefly infestation after which they recovered to a four-year average of 567 Kg/ha.

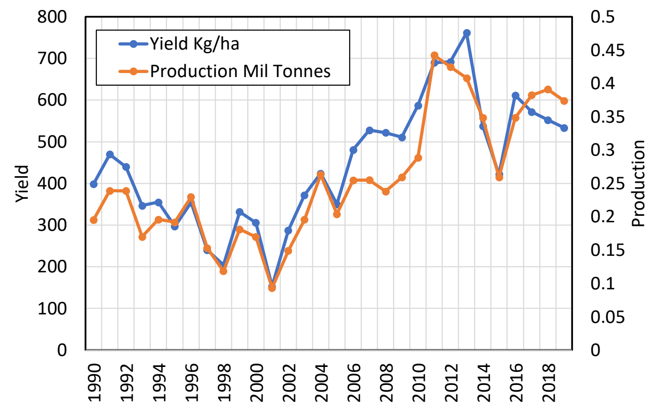


Figure 17. Haryana yield (kg/ha) 1990-2019

Rajasthan

Yields in Rajasthan increased from 343 kg/ha in 2001 to 452 kg/ha in 2003 before *Bt*-cotton was introduced. Yields in Rajasthan followed a pattern that is partly similar to Haryana and Punjab. Yields declined from 411 kg/ha in 1993 to 220 kg/ha in 2002, followed by a constant rising trend to reach 700 kg/ha in 2018. The average yield was 422 kg/ha in 2008 when the *Bt*-cotton area was 48.84% and 459 kg/ha in 2009 when the *Bt*-cotton area was 63.06%. Yields increased only after 2009. Yields in Rajasthan suffered for a long time because of the cotton leaf curl virus and only partly due to bollworms. It is common knowledge in Rajasthan that though yields increased after 2010, this appeared to have happened because of a few short-season (150 days) high yielding *Bt*-hybrids such as Bioseed 6488, Bunty, Bioseed 6588, Raghav, Bayer 7007 and RCH 650 which were tolerant to the cotton leaf curl virus and became popular after 2009 to occupy about 75 to 80% of the *Bt*-cotton area in Rajasthan. *Bt* does not appear to have a role to play in yield increase in Rajasthan, because data from the All India Coordinated Cotton Improvement Project (unpublished data of All India Coordinated Cotton Improvement Project -AICCIP) clearly show that *H. armigera* infestation on non-*Bt* Desi cotton and non-*Bt G. hirsutum* was negligible after 2004. Low bollworm infestation may have been possibly due to a significant decline of synthetic pyrethroids which are believed to have triggered the American bollworm in India and elsewhere in the world as a major pest of cotton and partly due to the increase of *Bt*-cotton area, which was only 10.3% until 2007 in Rajasthan.

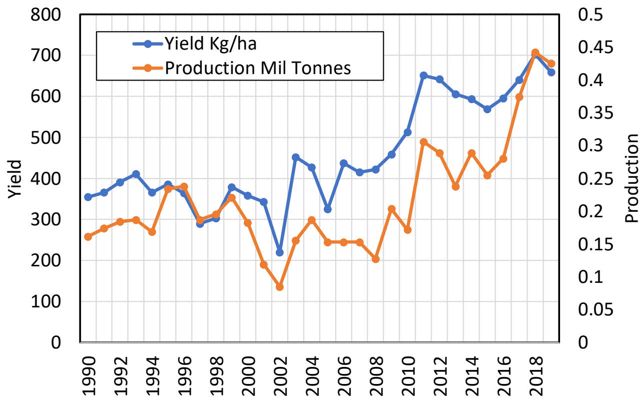


Figure 18. Rajasthan yield (kg/ha) 1990-2019

Central Zone

Cotton yields in the central zone were low in a range of 140 kg/ha to 297 kg/ha until 2002. The average yields increased to 522 kg/ha in 2007, primarily influenced by the enhanced fertilizer use which led to higher yields mainly in Gujarat and also partly in Maharashtra and Madhya Pradesh.

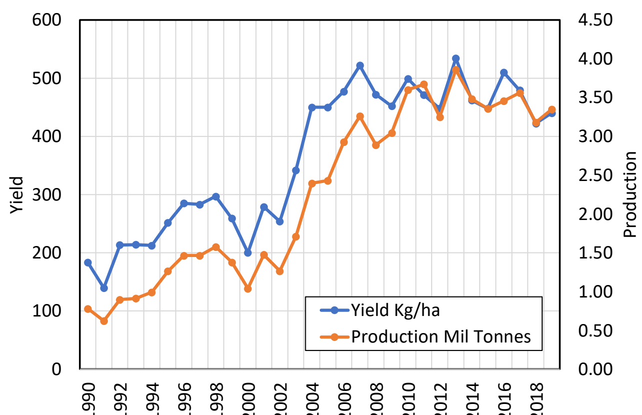


Figure 19. Central zone yield (kg/ha) 1990-2019

Gujarat

Yields in Gujarat increased from 328 kg/ha with 0% *Bt*-cotton in 2001 to 794 kg/ha in 2005 when the area under *Bt*-cotton was barely 7.82% and yield trends did not have any relationship in subsequent years with the adoption rate of *Bt*-cotton. CAB data showed that yields in Gujarat doubled from 227 kg/ha in 1991 to 502 kg/ha in 1998. However, for four years in a row from 1999 to 2002 erratic monsoon and drought brought the yields down to an average of 300 kg/ha during the period. With good monsoon and irrigation projects in the subsequent years, the state bounced back to harvest record yields of 794 kg/ha in 2005. Several authors claim that the sudden increase in yields was because of *Bt*-cotton, but the argument collapses because the area under *Bt*-cotton in 2005 in Gujarat barely reached 7.82% and our field records showed that on the area under illegal *Bt*-cotton in the state could not have been more than 10.0% of the area in 2005. However, though the area under *Bt*-cotton increased to 92.11% in 2012, yields declined to a range of 633 to 772 kg/ha during the subsequent years from 2006 to 2012. Yields were low at 587 to 674 kg/ha from 2014 to 2017 with 85 to 97.84% of the area under *Bt*-cotton. Therefore, the link between *Bt*-cotton adoption and yield increase in Gujarat looks very unconvincing.

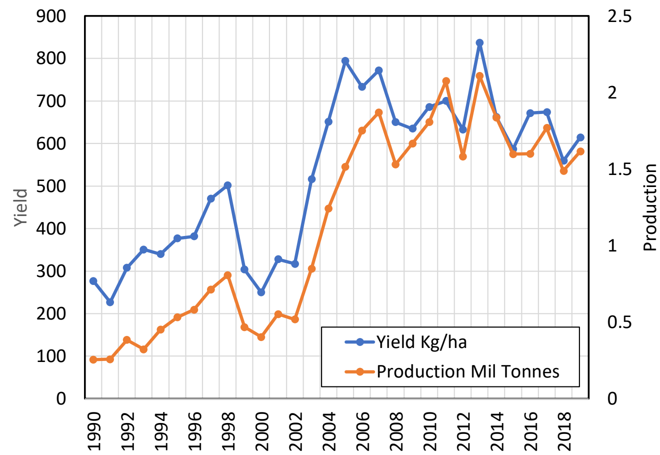


Figure 20. Gujarat yield (kg/ha) 1990-2019

Madhya Pradesh

According to the CAB data, cotton yields in Madhya Pradesh were 740 kg/ha in 1997 and 647 kg/ha in 2000 before the introduction of *Bt*-cotton. Yields declined significantly after the introduction of *Bt*-cotton and averaged at 525.7 kg/ha from 2002 to 2017. Yields plummeted to 424 kg/ha despite the area getting saturated with *Bt*-cotton at 99.34% in 2009.

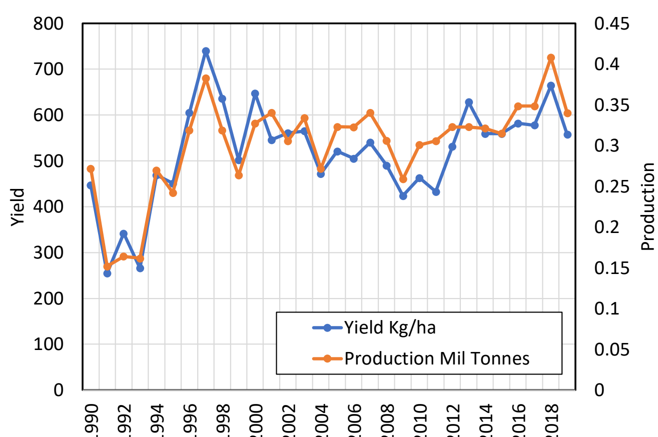


Figure 21. Madhya Pradesh yield (kg/ha) 1990-2019

Maharashtra

Cotton yield increased from 195 kg/ha in 2001 to 311 kg/ha in 2004 with just 5.70% area under *Bt*-cotton. With more than 88.0% area under *Bt*-cotton during 11 years from 2007 to 2017, the state average yield was low at 339 Kg/ha. The average yields of 339 kg/ha are equivalent to the average yields of resource poor African countries where neither *Bt*-cotton nor hybrids are cultivated. The CAB data showed radically different yield trends compared to the data of Ministry of Agriculture.

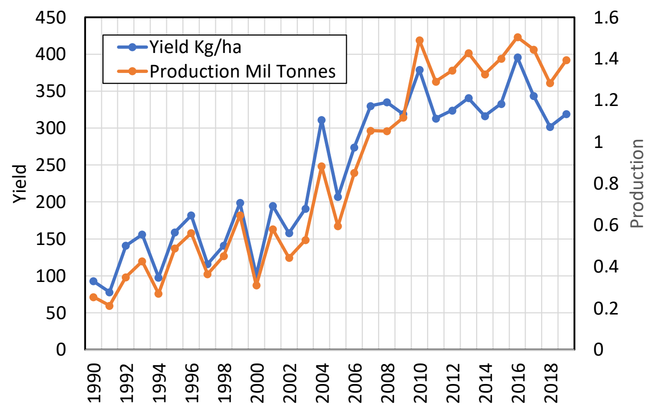


Figure 22. Maharashtra yield (kg/ha) 1990-2019

South Zone

During the years 1990 to 2002, yields in south zone were less than 400 Kg/ha, with an exception of 465 kg/ha in 1994. Yields increased above 500 kg/ha after 2006 and were 540 kg/ha to 604 kg/ha during 2006 to 2017. A clear increasing trend in yields was noticeable from 368 kg/ha in 2003 to 603 kg/ha in 2007.

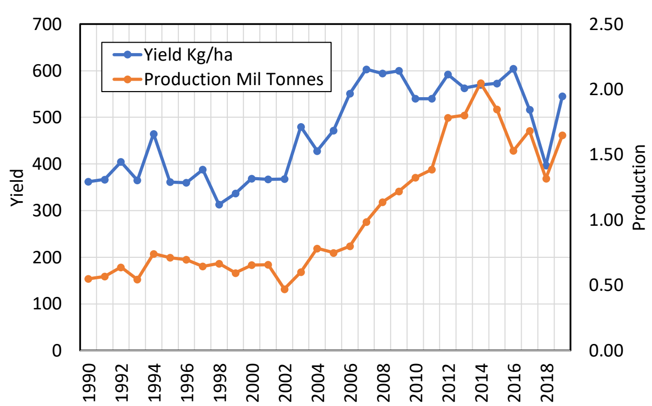


Figure 23. South zone yield (kg/ha) 1990-2019

Andhra Pradesh

Data showed that cotton yields in Andhra Pradesh were high at 662 kg/ha in 1994 and increased from 454 kg/ha in 2001 to 557 kg/ha with just 0.60% area under *Bt*-cotton in 2003. Yields averaged at 601.6 kg/ha over 11 years from 2007 to 2017 when the area under *Bt*-cotton averaged at 92.20% to show that yield trends did not correlate with area under *Bt*-cotton.

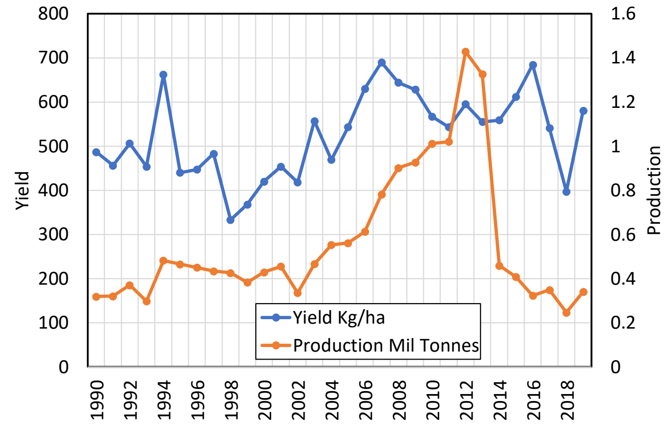


Figure 24. Andhra Pradesh yield (kg/ha) 1990-2019

Telangana

Telangana became a separate state in 2014. CAB data showed that yields were 570 kg/ha to 579 kg/ha from 2014 to 2016 but declined in subsequent years.

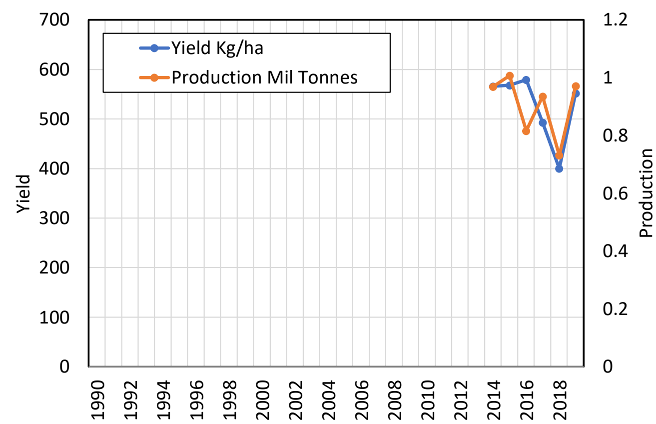


Figure 25. Telangana yield (kg/ha) 1990-2019

Karnataka

Cotton yields in Karnataka averaged at 245 kg/ha during the 17-years period from 1990 to 2006. Yields were 235 kg/ha in 2000 before *Bt*-cotton was introduced and continued to be low at an average of 244 kg/ha within a range of 216 to 270 kg/ha from 2002 to 2006 after *Bt* cotton was introduced in 2002. Yields increased to 526 kg/ha in 2012 with 92.8% of the area under *Bt* cotton; but declined after 2014.

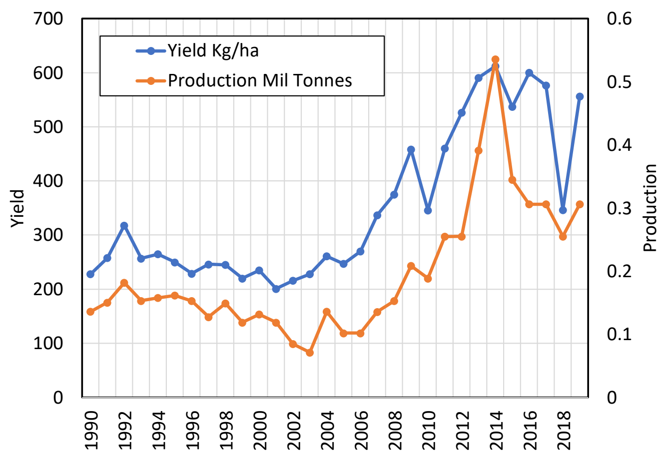


Figure 26. Karnataka yield (kg/ha) 1990-2019

Tamil Nadu

Yields in Tamil Nadu were below 400 kg/ha prior to 1998. Subsequently, cotton yields averaged at 471 kg/ha from 1999 to 2001 before the introduction of *Bt*-cotton. The yields increased to an average of 752 kg/ha over the 10-year period from 2002 to 2011 with *Bt*-cotton area at an average of 27.2%. The yield reached a peak of 1003 kg/ha in 2010 when the area under *Bt*-cotton was 50.8%. However, yields plummeted to 585.5 kg/ha when the *Bt*-cotton area increased to an average of 83.64% during the 6-year period from 2012 to 2017

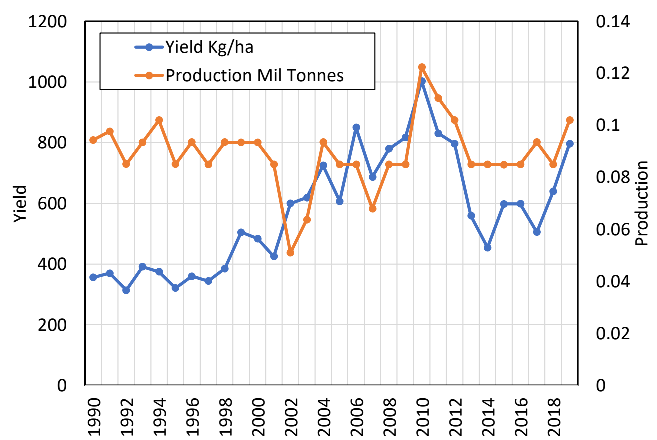


Figure 27. Tamil Nadu yield (kg/ha) 1990-2019

Orissa

CAB started publishing data for Orissa only from 2010. Data showed that yields ranged between 535 kg/ha to 580 kg/ha during 2011 to 2014 and were less than 500 kg/ha in 2010 and the period after 2014.

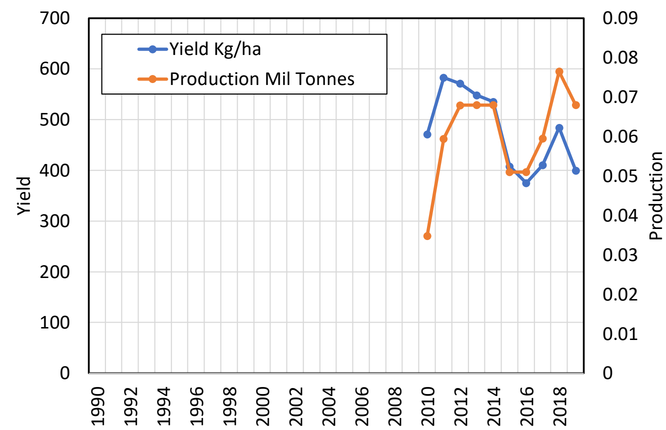


Figure 28. Orissa yield (kg/ha) 1990-2019

Yields (Data from the Ministry of Agriculture)

National

Yield data of the Ministry of Agriculture show an increasing trend of national yields from 186 kg/ha in 2001 to 307 kg/ha in 2003 with a small increase of 1.2% in *Bt*-cotton area. It cannot be presumed that the increase in national average yields to 307 kg/ha were due to incredibly high yields in this small (1.2%) area of *Bt*-cotton while the non-*Bt* farms continued to produce yields of 186 kg/ha that were equivalent to the pre-*Bt* era. If that were to be so, the yields in *Bt*-cotton farms should have been 17,645 Kg/ha. Though the increasing yield trend from 2004 until 2007 appears to relate with the increase in *Bt*-cotton area which reached 68.13% in 2007, the relationship disappears almost completely after 2007 despite an increase in the area at 85% to 93.14% until 2015.

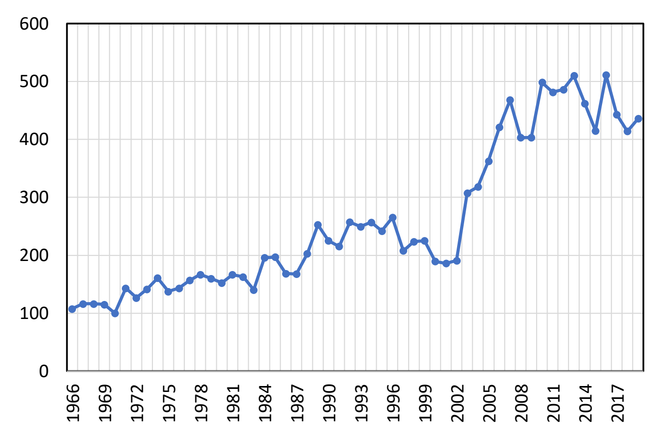


Figure 29. National yield (kg/ha) 1966-2019

Punjab

Punjab harvested yields at 300 kg/ha to 376 kg/ha from 1966 to 1982. Yields increased to levels of 426 kg/ha to 607 kg/ha during the 13-years period from 1984 to 1996. Subsequently, yields in Punjab increased from 366 kg/ha in 2001 to 697 kg/ha in 2004 before *Bt*-cotton was introduced. The average yield was 662 kg/ha in 11 years from 2007 to 2017 with an average of 94.98% area under *Bt*-cotton.

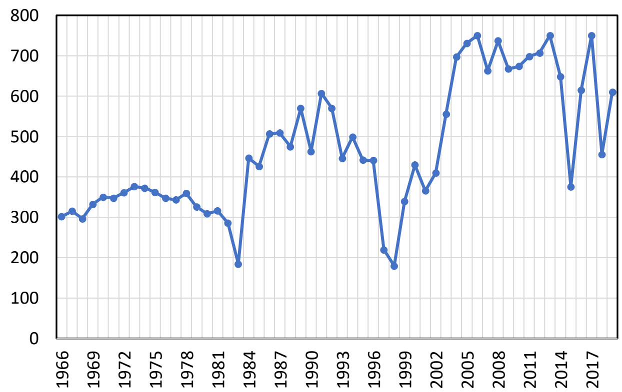


Figure 30. Punjab yield (kg/ha) 1966-2019

Haryana

Yields in Haryana increased from 265 kg/ha in 1966 to 450 kg/ha in 1992 followed by a fluctuating decline to reach a low level of 195 kg/ha in 2001. Yields increased to 568 kg/ha in 2004 before *Bt*-cotton was introduced. The average yield was 586 kg/ha in 9 years from 2009 to 2017 with an average of 88.10% area under *Bt*-cotton.

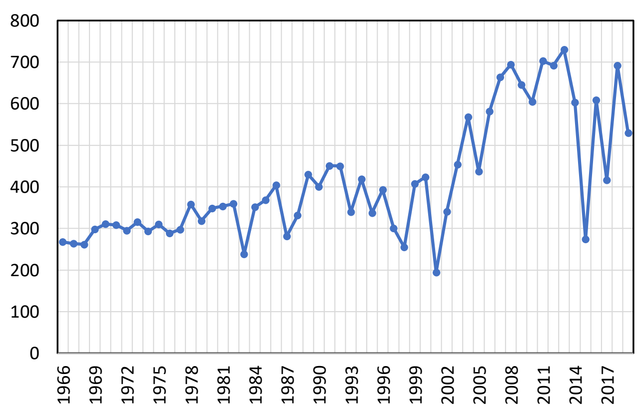


Figure 31. Haryana yield (kg/ha) 1966-2019

Rajasthan

Yields increased steadily from 125 kg/ha in 1966 to 386 kg/ha in 1989, followed by a stagnant phase for 7 years until 1996 and a subsequent dip to 94 kg/ha in 2001. Later, yields increased to 351 kg/ha in 2003 before *Bt*-cotton was introduced. The average yield was 363 kg/ha in 2006 when the *Bt*-cotton area was 1.43% and 345 kg/ha in 2009 when the *Bt*-cotton area was 63.06%. Yield was 557 kg/ha with 63.61% area under *Bt*-cotton in 2013 and 461 kg/ha with 79.46% area under *Bt*-cotton in 2015. Yields increased to a record level of 630 kg/ha in 2019. Yield trends do not follow a trend that is consistent with the adoption trends of *Bt*-cotton in Rajasthan.

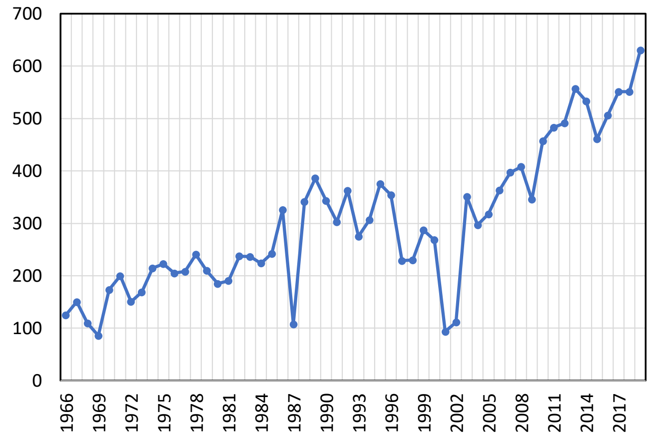


Figure 32. Rajasthan yield (kg/ha) 1966-2019

Gujarat

Yields increased from 140 kg/ha in 1966 to 400 kg/ha in 1998. However, yields declined during the subsequent 4 years due to drought. Yields followed an increasing trend from 165 kg/ha in 2001 to 604 kg/ha in 2005 when the area under *Bt*-cotton was 7.82%. When the area under *Bt*-cotton increased above 61.60% in 2008, yields declined to 507 kg/ha and 551 kg/ha in 2009.

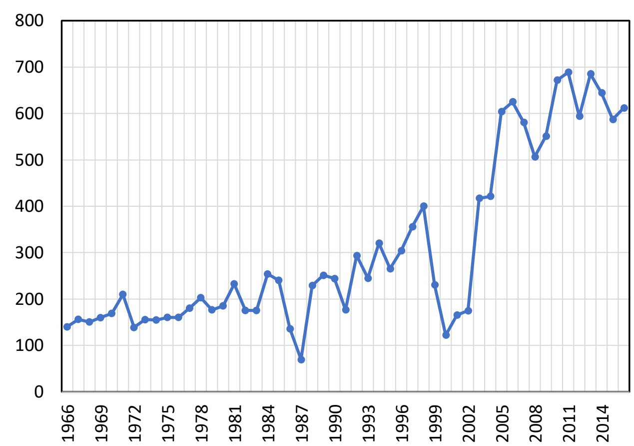


Figure 33. Gujarat yield (kg/ha) 1966-2019

Madhya Pradesh

During the 36 years period from 1966 to 2002, cotton yields in Madhya Pradesh were low at 58 kg/ha to 167 Kg/ha. Yields increased from 124 kg/ha in 2001 to 238 kg/ha in 2009 with 99.34% of the area under *Bt*-cotton. Yields increased subsequently but had little to do with *Bt*-

cotton. Thus, according to data of the State Department of Agriculture, Madhya Pradesh, yields of 238 kg/ha with about 50.0% irrigation appears pathetic and less than even the poorest of African countries neither have irrigation nor cultivate either *Bt*-cotton or hybrid cotton. Surprisingly, yields doubled suddenly from 238 kg/ha in 2009 to 523 kg/ha in 2010 and continued to be high in subsequent years. The factors that influenced the sudden jump in yields within a single year are not clear as yet.

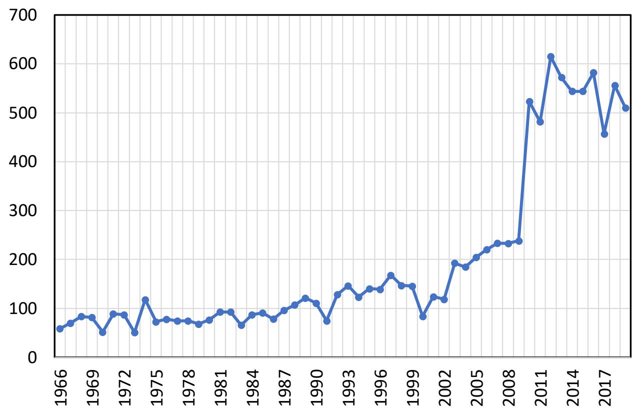


Figure 34. Madhya Pradesh yield (kg/ha) 1966-2019

Maharashtra

Yields increased slowly with cyclic fluctuations from a low 69.9 kg/ha in 1966 to 187 kg/ha in 2005. Data showed that with more than 88.0% area under *Bt* cotton during 11 years from 2007 to 2017, the state average yield was low at 325 Kg/ha. Yields were as low as 265 kg/ha in 2017 with 89.9% area under *Bt*-cotton. The average yields of 325 kg/ha is equivalent to the average yields of resource poor African countries where neither *Bt*-cotton nor hybrids are cultivated.

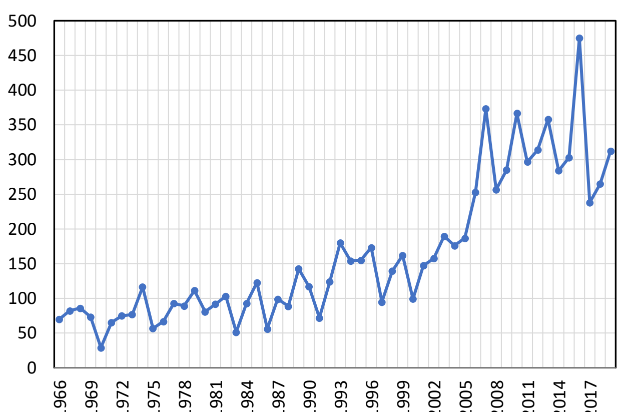


Figure 35. Maharashtra yield (kg/ha) 1966-2019

Andhra Pradesh

Cotton yields in Andhra Pradesh were 75 kg/ha in 1966 but increased to 362 kg/ha in 1983. Yields fluctuated in a range of 153 kg/ha to 314 kg/ha from 1984 to 2002. *Bt*-cotton was introduced in 2002. Cotton yields increased from 288 kg/ha in 2001 to 384 kg/ha with just 0.60% area under *Bt*-cotton in 2003. Yields declined to 381 kg/ha in 2006 and 374 kg/ha in 2009 when the area under *Bt*-cotton increased to 67.59% in 2006 and 85.41% in 2009. Thus, yields did not appear to be directly correlated with *Bt*-cotton.

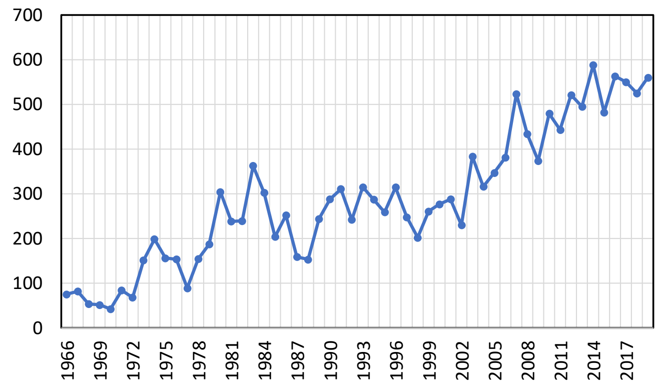


Figure 36. Andhra Pradesh yield (kg/ha) 1966-2019

Telangana

Telangana was bifurcated from Andhra Pradesh as a new state in 2014. Yields were in a range of 351 kg/ha to 466 Kg/ha.

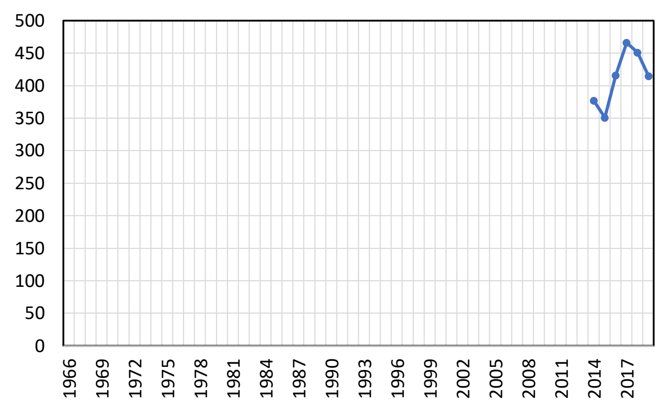


Figure 37. Telangana yield (kg/ha) 1966-2019

Karnataka

Yields increased from 48.7 kg/ha in 1966 to 232 kg/ha in 1988, after which yields stagnated for 16 years during 1989 to 2005 at an average of 217 Kg/ha. Yields were 263 kg/ha in 2000 before *Bt*-cotton was introduced and continued to be low at an average of 202.72 kg/ha within a range of 143 to 276 kg/ha from 2002 to 2006 after *Bt* cotton was introduced in 2002. Yields increased to 481 kg/ha in 2013 with 85.05% of the area under *Bt* cotton; but declined to 337 kg/ha in 2016 and 381 kg/ha in 2017 when the area under *Bt*-cotton was 90.0%.

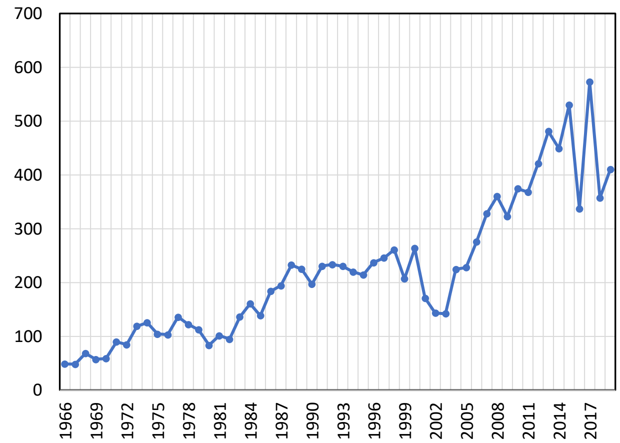


Figure 38. Karnataka yield (kg/ha) 1966-2019

Tamil Nadu

Cotton yields in Tamil Nadu were less than 200 kg/ha before 1975 but increased to slightly higher average yield of 281 kg/ha during the 33 years period from 1976 to 2009. Yields averaged at 312 kg/ha from 1999 to 2001 before *Bt*-cotton. The yields averaged at 284.92 kg/ha over 8 years from 2002 to 2009 after *Bt* cotton was introduced in 2002. Yields increased subsequently but did not correlate directly with increase in the *Bt*-cotton area.

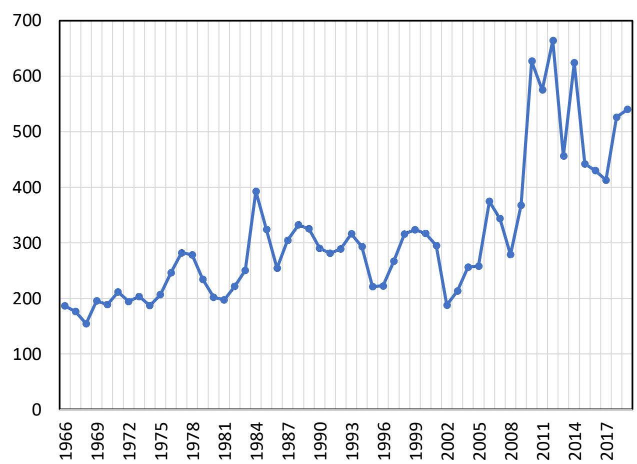


Figure 39. Tamil Nadu yield (kg/ha) 1966-2019

Orissa

Cotton yields in Orissa were low and the area was also negligible until 1993. Yields stabilized at above 400 kg/ha after 2003.

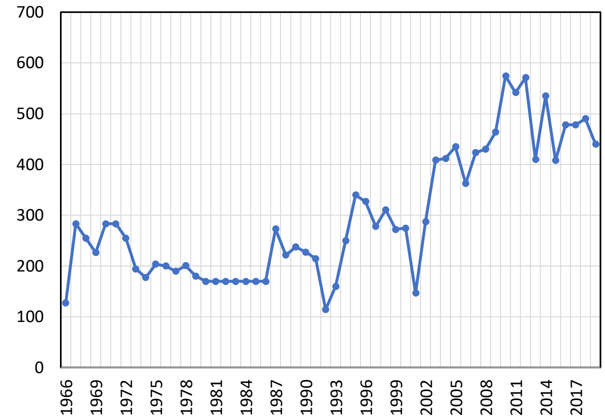


Figure 40. Orissa yield (kg/ha) 1966-2019

Cost of Cultivation & Net Returns

National

Cultivation costs didn't change much from 1996 to 2002 but picked up an increasing trend from US$508/ha in 2003 to US$1232/ha in 2011. Costs remained at almost the same levels from 2011 to 2016. The market value of the farm produce was generally higher than the cultivation cost, except on three occasions — 2001, 2014 and 2015, — which resulted in negative returns. Net returns ranged from - US$ 62/ha to - US$ 130/ha from 1996 to 2006 followed by an increase to a range from US$ 160/ha to US$ 257/ha from 2007 to 2016, with exceptions of 2010 (when returns were US$ 542), 2012 (when returns decreased to US$ 42/ha) and in 2014 and 2015, when returns were negative.

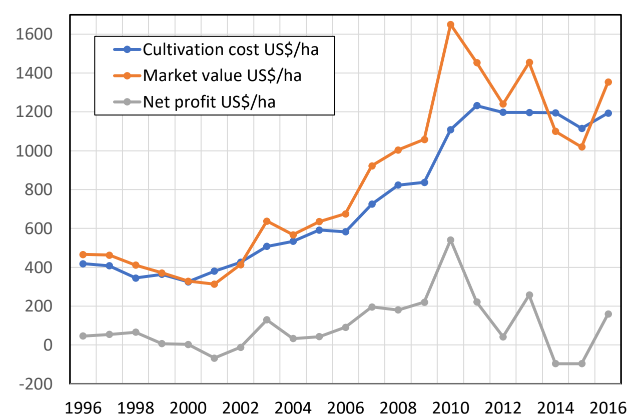


Figure 41. National: Cost of cultivation, market value and net returns 1996 to 2016

Punjab

Cultivation costs increased nearly 300% from US$ 367/ha in 1998 to US$ 1392 in 2011 after which costs declined. The market value of lint and by-products was less than the cultivation costs during 1996 to 2002 and also in 2015, which resulted in financial losses to farmers. Net returns ranged from US$ 0/ha to US$ -160/ha from 1996 to 2002 but increased later to US$ 63/ha to US$ 575/ha except in 2015, when the returns were negative at US$ -378/ha.

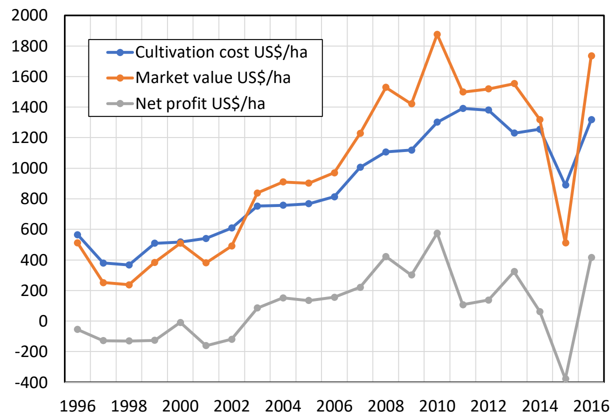


Figure 42. Punjab: Cost of cultivation, market value and net returns 1996 to 2016

Haryana

Cultivation costs ranged from US$ 309/ha to US$ 453/ha from 1996 to 2002, but increased later to US$ 1301/ha in 2011, followed by a decline in the subsequent period. Market prices of the farm produce were very remunerative in 2004, from 2007 to 2013 and in 2016 as a result of which the net returns were high at US$ 106/ha to US$ 595/ha. The net returns were negative in 1997, 2005, 2014 and 2015.

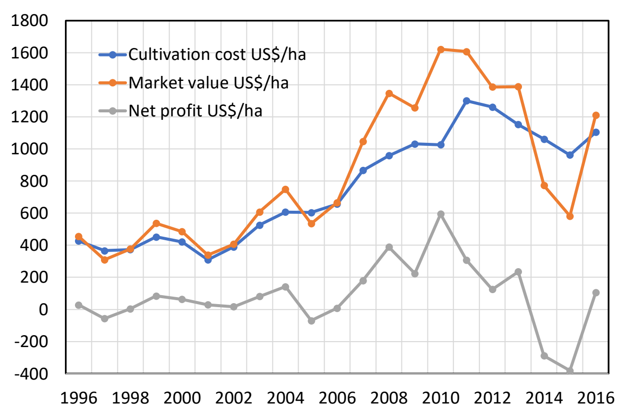


Figure 43. Haryana: Cost of cultivation, market value and net returns 1996 to 2016

Rajasthan

Cultivation costs ranged from US$ 275/ha to US$ 410/ha from 1996 to 2005. Costs increased 2.9-fold from US$ 397/ha in 2005 to US$ 1171/ha in 2011, after which costs changed only marginally from US$ 1079/ha to US$ 1225/ha. The market value of farm produce was higher than the cultivation costs because of which farmers always had positive net returns. The net returns averaged US$ 137/ha from 1996 to 2005 and increased 6.7-fold from US$ 173/ha in 2005 to US$ 1163/ha in 2010. Net returns declined to US$ 443/ha in 2016 with lowest returns of US$ 252/ha in 2014 and US$ 241/ha in 2015.

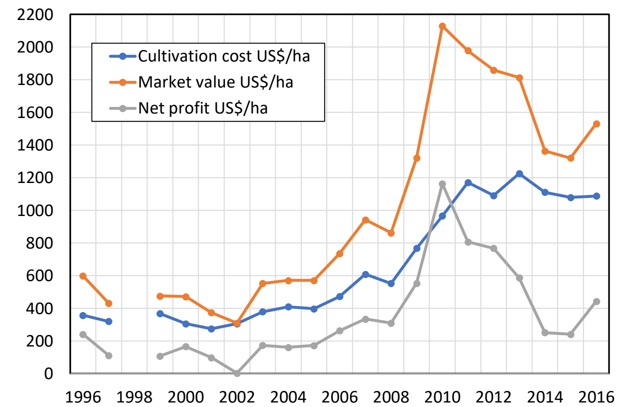


Figure 44. Rajasthan: Cost of cultivation, market value and net returns 1996 to 2016

Gujarat

Cultivation costs in Gujarat ranged between US$ 234/ha to US$ 421/ha from 1996 to 2002. Costs increased by 3.8-fold from US$ 320/ha in 2002 to US$ 1218/ha in 2011, followed by range of US$ 1047/ha to US$ 1198/ha from 2012 to 2016. Market value of the farm produce was higher than production costs almost all through 1996 to 2016 except for 2000 and 2001. Net returns ranged from US$ 39/ha to US$ 434/ha from 1996 to 2016 except in 1999, 2000, 2001 and 2012 when net returns were either nil or marginal or negative and in 2010 when the returns were at a record high of US$ 1081/ha.

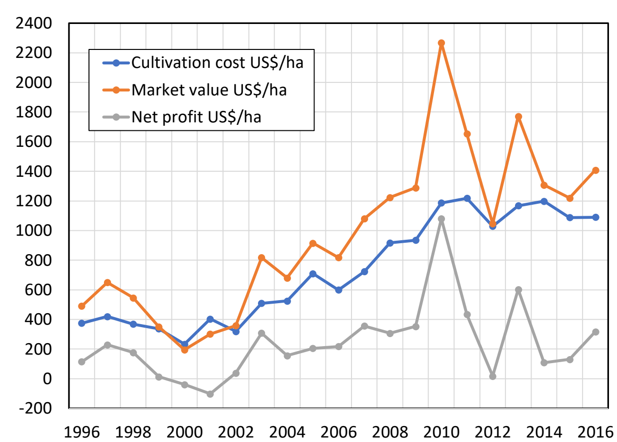


Figure 45. Gujarat: Cost of cultivation, market value and net returns 1996 to 2016

Madhya Pradesh

Cultivation costs increased 4.8-fold in 5-years from US$ 162/ha in 2000 to US$ 787/ha in 2005 followed by a relatively horizontal trend in a range of US$ 577/ha to US$ 882/ha from 2005 to 2013. Costs were in a range of US$ 1233/ha to US$ 1262/ha from 2014 to 2016. Market value of farm produce was higher than cultivation cost during 1996, 2000 and from 2005 to 2013. Net returns were US$ 185/ha in 2005 and increased from US$ 100/ha in 2007 to US$ 559/ha in 2010 followed by a decline to US$ 259/ ha in 2013 to end up in negative returns of US$ -277/ha to US$ 429/ha from 2014 to 2016.

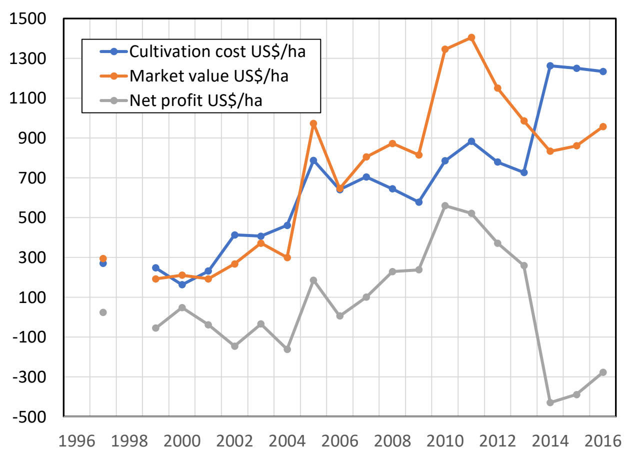


Figure 46. Madhya Pradesh: Cost of cultivation, market value and net returns 1996 to 2016

Maharashtra

Cultivation costs increased 4.3-fold from 312/ha in 2000 to 1335/ha in 2012 after which there was a marginal decline until 2016. There was hardly any margin between the market value of the farm produce and cultivation costs because of which the net returns were either nil or negative as in the years 2000 to 2002; 2004 to 2006; 2011 to 2012 and 2014 to 2015. Net returns were low at US$ 51/ ha to US$ 236/ha in years when the market value of farm produce was higher than production costs.

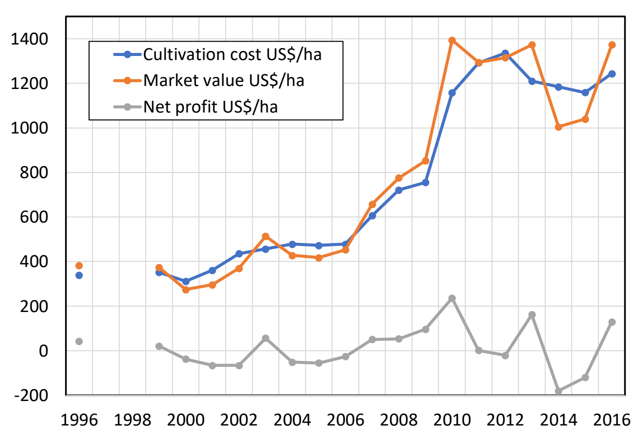


Figure 47. Maharashtra: Cost of cultivation, market value and net returns 1996 to 2016

Andhra Pradesh

Cultivation costs increased 3.3-fold from US$ 417/ha in 1999 to US$ 1380/ha in 2013 followed by a decline from 2014 to 2016. From 1999 to 2004; 2006 to 2011 and in 2016, the market values of farm produce were higher but only marginally so than the corresponding cultivation costs as a result of which the net returns were relatively low at US$ 19/ha to US$ 290/ha. Net returns were negative at US$ -29/ha to US$ -226/ha in 1996, 2005 and the period from 2012 to 2015.

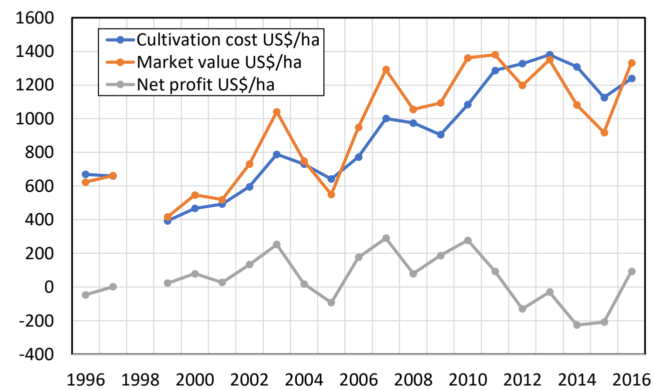


Figure 48. Andhra Pradesh: Cost of cultivation, market value and net returns 1996 to 2016

Karnataka

Cultivation cost increased constantly from US$ 215/ha in 1997 to reach US$ 523/ha in 2009 and to 5.3-fold higher levels of US$ 1149/ha in 2016. From 1996 to 2006, the market values of farm produce were mostly either less than cultivation costs or only marginally higher than cultivation costs, thus resulting in low net returns or financial losses in some years. From 2007 to 2016 the net returns ranged from US$ 70/ha to US$ 522/ha, except in 2014 and 2015 when the net returns were negative.

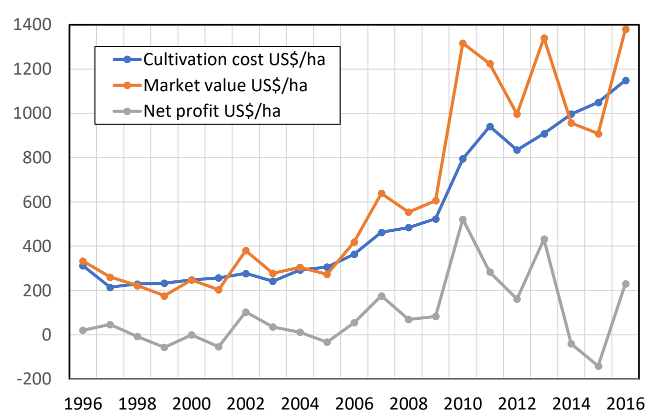


Figure 49. Karnataka: Cost of cultivation, market value and net returns 1996 to 2016

Tamil Nadu

Cultivation costs did not change much from 1996 to 2007 but increased later from US$ 668/ha in 2007 to reach US$ 1530/ha in 2016. The market value of farm produce was lower than cultivation costs from 1996 to 2005; 2011 to 2013 and in 2016, thus resulting in negative net returns. Out of the 20 years period under study, the market value was higher than cultivation costs only in seven years (2006 to 2010 and 2014 to 2015) thereby leading to net returns of US$ 38/ha to US$ 508/h.

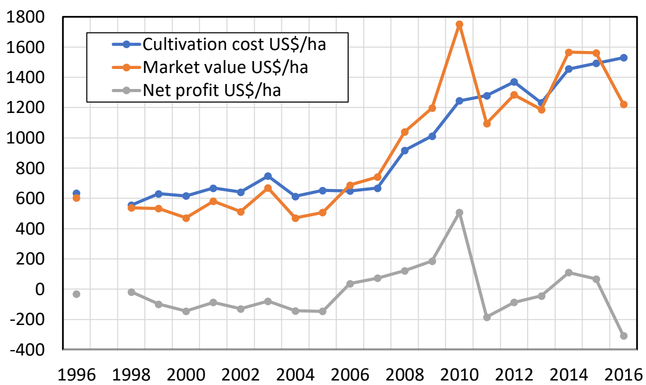


Figure 50. Tamil Nadu: Cost of cultivation, market value and net returns 1996 to 2016

Production Cost (US$) per 100 of Kg Seed-Cotton

National

The cost of producing 100 of kg seed-cotton declined from US$ 61 in 1996 to US$ 37 in 2006, after which the cost increased to US$ 73 in 2012 and US$ 66 in 2016.

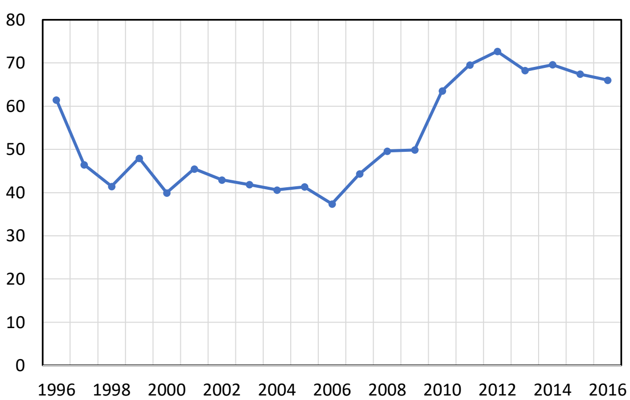


Figure 51. National: Production Cost (US$) per 100 kg seed-cotton

Punjab

The cost of producing 100 of kg seed-cotton declined from US$ 77 in 1997 to US$ 36 in 2006, after which the cost increased to US$ 78 in 2010 and US$ 114 in 2015.

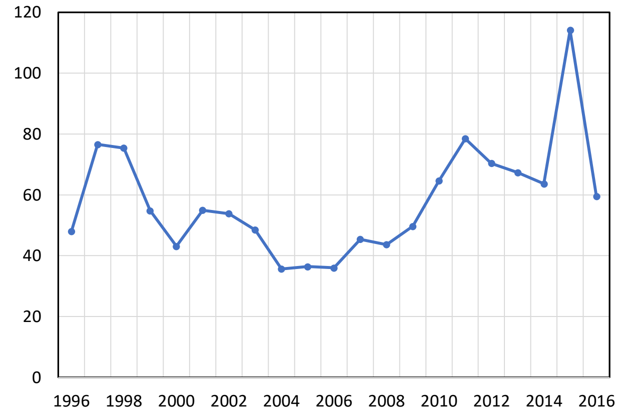


Figure 52. Punjab: Production Cost (US$) per 100 kg seed-cotton

Haryana

The cost of producing 100 of kg seed-cotton declined from US$ 57 in 1997 to US$ 32 in 1999, after which the cost increased to US$ 108 in 2015.

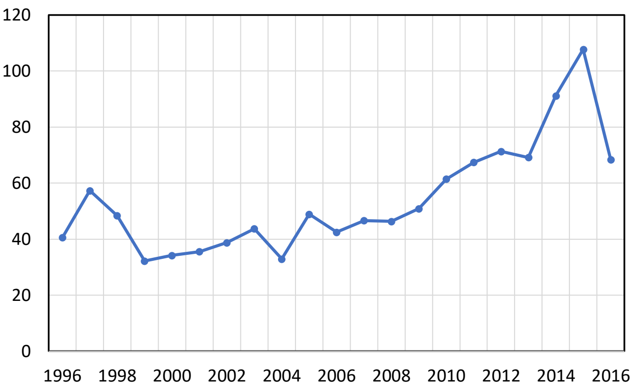


Figure 53. Haryana: Production Cost (US$) per 100 kg seed-cotton

Rajasthan

The cost of producing 100 of kg seed-cotton was between US$ 26 to US$36 from 1996 to 2007, except for one year (2002) when the cost was US$ 49. The cost increased continuously from US$ 27 in 2006 to US$ 69 in 2016.

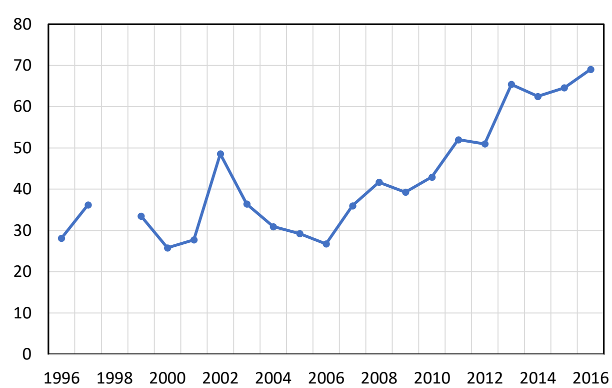


Figure 54. Rajasthan: Production Cost (US$) per 100 kg seed-cotton

Gujarat

The cost of producing 100 of kg seed-cotton was US$ 33 to US$ 43 from 1996 to 2007, except for two years in 2000 and 2001, when it was US$ 61 and US$ 55, respectively. Production cost increased to more than US$ 50 after 2010 to reach US$ 82 in 2012.

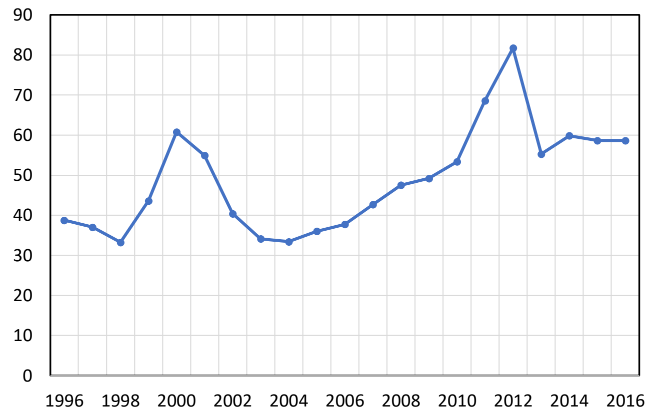


Figure 55. Gujarat: Production Cost (US$) per 100 kg seed-cotton

Madhya Pradesh

The cost of producing 100 of kg seed-cotton ranged from US$ 50 to US$ 62 from 1999 to 2013, except in 1997, 2005, 2008 and 2009, when it was less than US$ 50. Production cost increased to US$ 91 in 2014 before declining to US$ 79 in 2016.

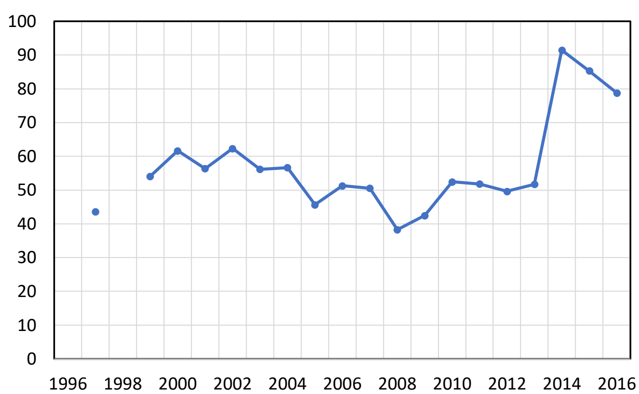


Figure 56. Madhya Pradesh: Production Cost (US$) per 100 kg seed-cotton

Maharashtra

The cost of producing 100 of kg seed-cotton was less than US$ 50 from 1996 to 2007, after which it increased to US$ 83 in 2011 and declined to US$ 67 in 2013 and 2016.

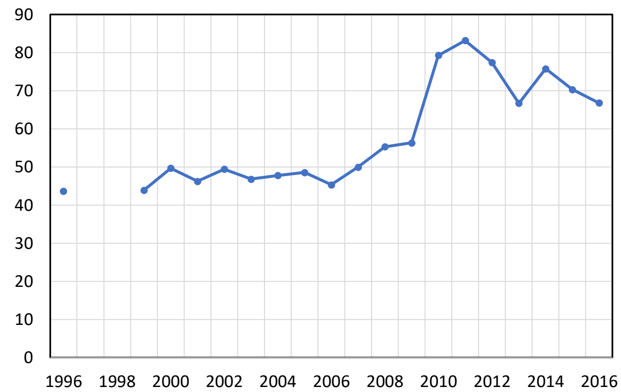


Figure 57. Maharashtra: Production Cost (US$) per 100 kg seed-cotton

Andhra Pradesh

The cost of producing 100 of kg seed-cotton was within a range of US$ 35 to US$ 55 from 1996 to 2009 but increased to a higher range of US$ 68 to US$ 77 from 2010 to 2016.

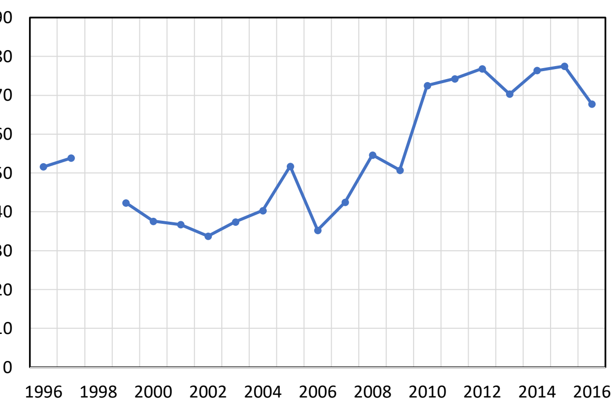


Figure 58. Andhra Pradesh: Production Cost (US$) per 100 kg seed-cotton

Karnataka

The cost of producing 100 of kg seed-cotton ranged from US$ 38 to US$ 55 from 1996 to 2009, after which production cost increased to a higher range of US$ 61 to US$ 83 from 2010 to 2016.

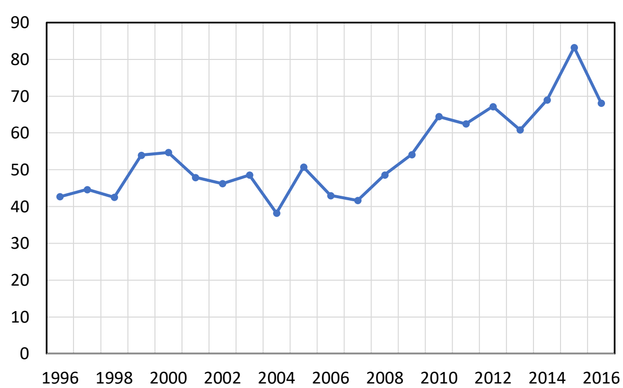


Figure 59. Karnataka: Production Cost (US$) per 100 kg seed-cotton

Tamil Nadu

The cost of producing 100 kg of seed-cotton was within a range of US$ 43 to US$ 65 from 1996 to 2015, except in 2011, 2012, 2013 and 2016, when it was in a higher range of US$ 84 to US$ 104.

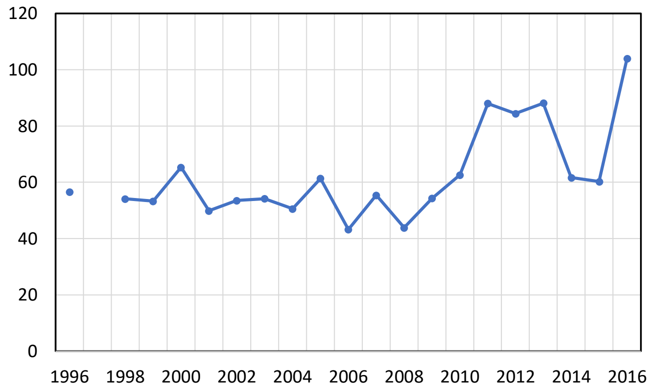


Figure 60. Tamil Nadu: Production Cost (US$) per 100 kg seed-cotton

Cost of Inputs

Four major inputs — seed, labour, fertilisers and insecticides — are considered in the data presented here because they constitute the major components of input costs in India. Inputs such as irrigation, machinery and land rent are also important but are not common to all farmers. It is pertinent to mention here that probably due to the high seed costs of *Bt*-cotton hybrids, coupled with high expectations, cotton farmers across the country invested more on all production processes including timely deployment of human labour, fertilisers and pesticides to ensure better production from *Bt*-cotton hybrids. Data show that the costs of seeds, fertilisers, insecticides and labour increased at a higher growth rate after the introduction of *Bt*-cotton in India.

National

Hiring labourers constitutes the major share of cultivation costs of cotton in India. Generally, 25% to 35% of the total cost of cultivation goes to labourers. From 1996 to 2002, the cost of seeds increased by 60% and the cost of insecticides, fertilisers and labourers increased by only 10% to 20%. However, compared to 2002, the cost of seeds in 2011 increased by 340%, insecticides by only 70%, fertilisers by 240% and labour by 280%.

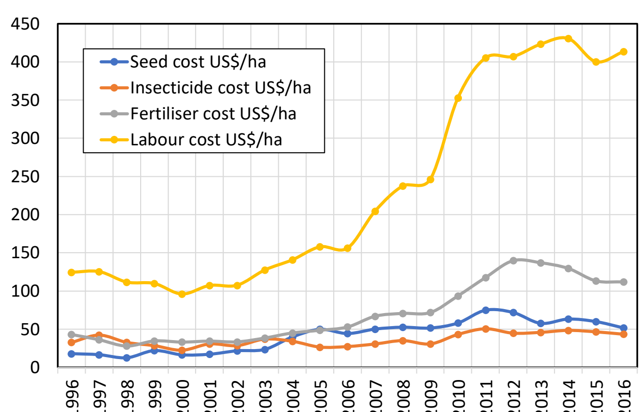


Figure 61. National: Cost of inputs, seeds, insecticides, fertilisers and labour 1996 to 2016

Punjab

Compared to 1996, seed costs increased by 150% in 2002 but compared to 2002, seed costs in 2011 increased by 680%. However, the cost of insecticides in 2011 decreased by 20% compared to 2002. Compared to 1996, the costs of fertilisers and labourers in 2002 did not increase, but compared to 2002, the costs of fertilisers and labourers increased by 260% and 230% respectively in 2011.

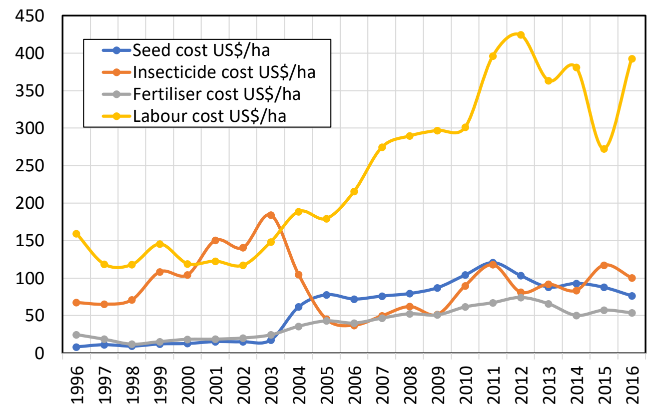


Figure 62. Punjab: Cost of inputs, seeds, insecticides, fertilisers and labour 1996 to 2016

Haryana

From 1996 to 2002, the cost of seeds and labour increased by 70% and 36% respectively and the cost of insecticides and fertilisers decreased by 30% and 40% respectively. However, compared to 2002, seed costs in 2011 increased by 1070%; insecticide costs by 20%; fertilisers by 190% and labour by 250%.

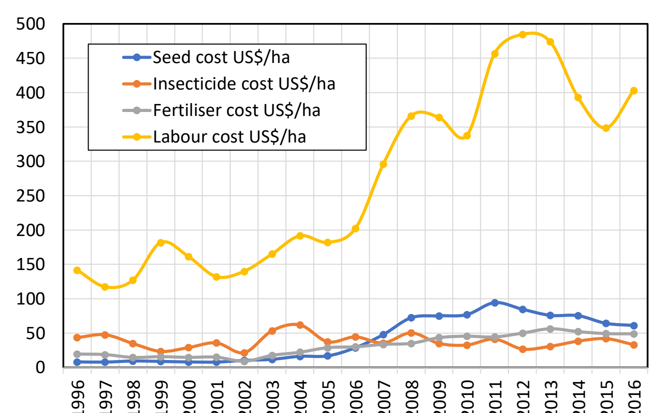


Figure 63. Haryana: Cost of inputs, seeds, insecticides, fertilisers and labour 1996 to 2016

Rajasthan

From 1996 to 2002, insecticide costs decreased by 10% but costs of fertilisers and labour increased by 10% to 50%. However, compared to 2002, the cost of seeds in 2011 increased by 790%; cost of insecticides by 90%; cost of fertilisers by 240% and cost of labour by 340%.

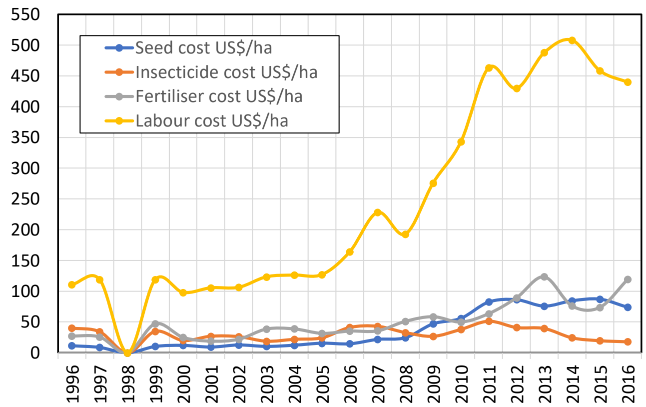


Figure 64. Rajasthan: Cost of inputs, seeds, insecticides, fertilisers and labour 1996 to 2016

Gujarat

While costs of seeds, insecticides, fertilisers and labour did not increase much from 1996 to 2002, compared to 2002, costs of these inputs in 2011 increased by 100% for insecticides and between 250% and 330% for seeds, fertilisers and labour.

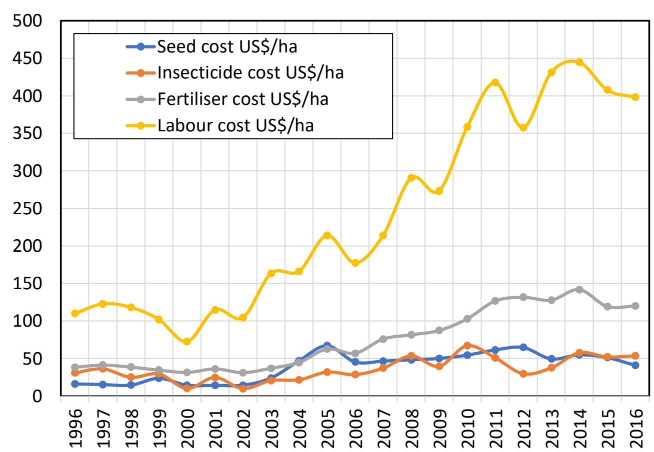


Figure 65. Gujarat: Cost of inputs, seeds, insecticides, fertilisers and labour 1996 to 2016

Madhya Pradesh

Compared to 1997, the cost of seeds in 2016 increased only by 150%, but other inputs such as insecticides increased by 1620%, fertilisers by 1030% and labour by 890%.

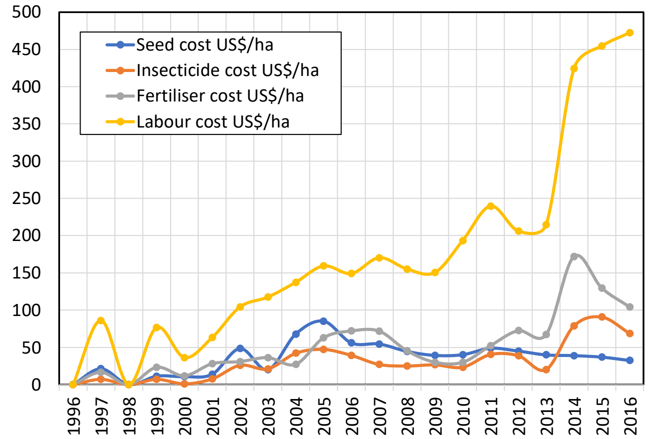


Figure 66. Madhya Pradesh: Cost of inputs, seeds, insecticides, fertilisers and labour

Maharashtra

From 1996 to 2002, the cost of seeds, insecticides, fertilisers and labour increased only by 10% to 60%. From 2002 to 2011, the cost of these inputs increased by 230% to 350%.

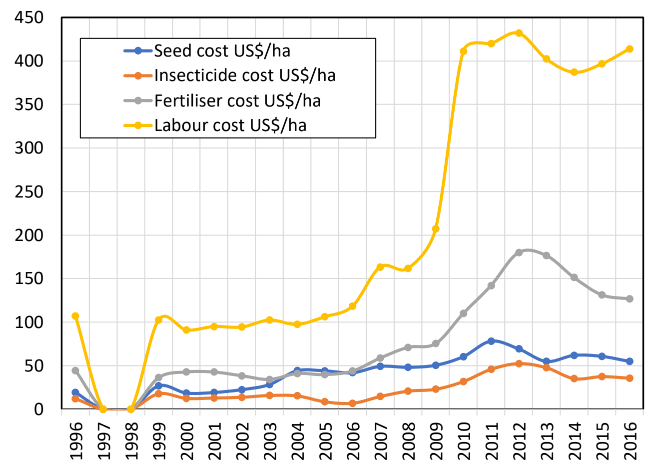


Figure 67. Maharashtra: Cost of inputs, seeds, insecticides, fertilisers and labour

Andhra Pradesh

From 1996 to 2002, the cost of seeds and insecticides increased by 160% and 30% respectively, whereas cost on fertilisers and labour decreased by 10% to 12%. However, compared to 2002, the cost of seeds increased by 570%, insecticides by 30%, fertilisers by 210% and labour by 220%.

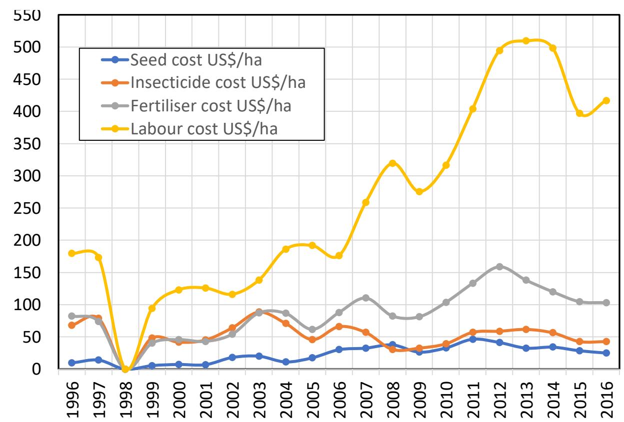


Figure 68. Andhra Pradesh: Cost of inputs, seeds, insecticides, fertilisers and labour

Karnataka

Cost of fertilisers decreased from 1996 to 2002, but the cost of other inputs such as seeds, insecticides and labour did not increase much. However, compared to 2002, the cost of seeds in 2011 increased by 510%, fertilisers by 350% and labour by 310%.

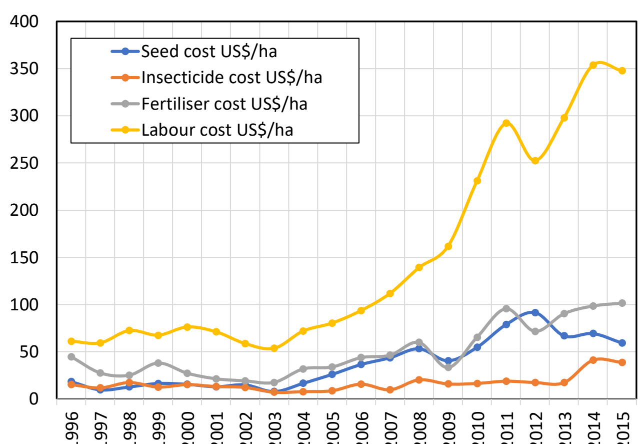


Figure 69. Karnataka: Cost of inputs, seeds, insecticides, fertilisers and labour

Tamil Nadu

The cost of insecticides decreased from 1996 to 2002 but the cost of seeds increased by 210%. Cost of fertilisers and insecticides did not increase much during this period. However, compared to 2002, the cost of seeds in 2011 increased by 380%; fertilisers by 280%; labour by 130% and cost of insecticides by 70%.

Fertilisers

It is common knowledge that precision-mode-need-based use of chemical fertilisers such as nitrogen, phosphorus, potassium increases yields in crops including cotton. Fertiliser usage in cotton in India started to increase significantly after the introduction of *Bt*-cotton. Application of fertiliser quantities in cotton more than doubled between 2002 to 2011. *Bt*-cotton seeds were expensive and farmers treated the crop with extra care by increasing critical inputs such as fertilisers and pesticides to harness full value of the money spent on seeds. Subsidies on urea (nitrogenous fertiliser) also led to its higher use compared to phosphorus and potassium fertilisers. In the initial years of increased use, the crop responded well, and yields increased immediately, followed by stage where yields plateaued irrespective of the fertiliser quantities applied. Further profits were not commensurate with the high rates of fertiliser application as the law of diminishing returns set in.

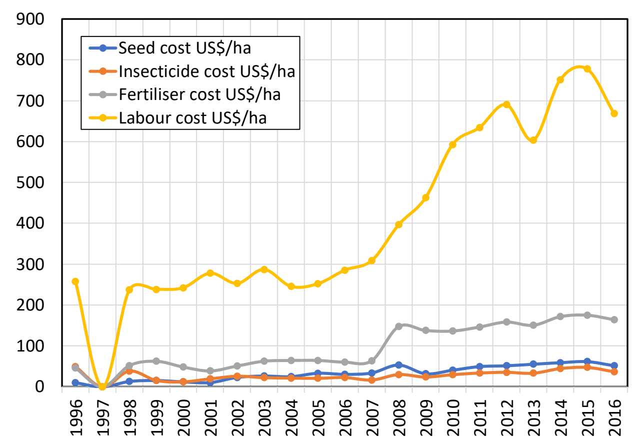


Figure 70. Tamil Nadu: Cost of inputs, seeds, insecticides, fertilisers and labour 1996-2019

National

Fertiliser use was less than 100 kg/ha until 2003 but increased continuously thereafter reach 222 kg/ha in 2011, after which usage declined to 187 kg/ha in 2016.

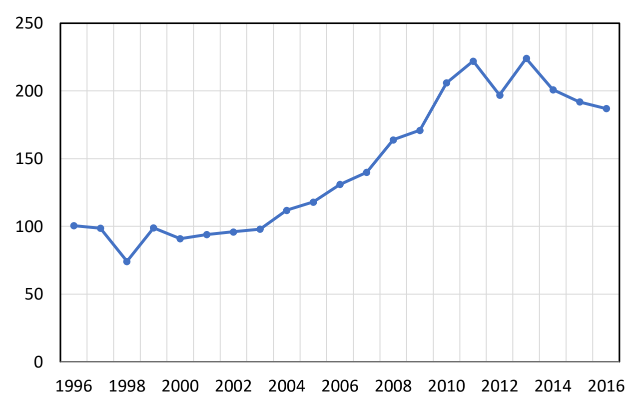


Figure 71. National: Fertiliser usage in cotton kg/ha 1996-2019

Punjab

The average annual fertiliser use was 76 kg/ha for 8 years from 1996 to 2003. Fertiliser use increased from 91 kg/ha in 2003 to 160 kg/ha in 2006, followed by an increase to 231 kg/ha in 2011. Usage declined later to 161 kg/ha in 2014 and 181 kg/ha in 2016.

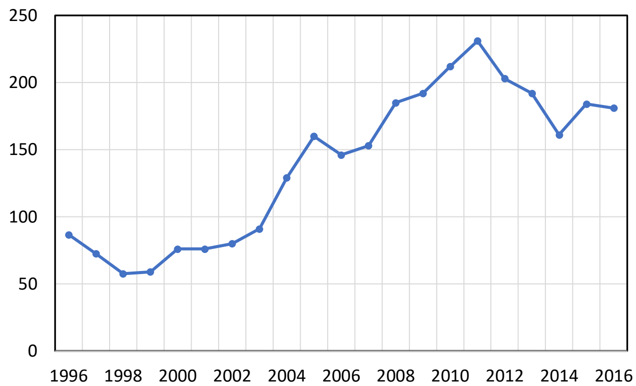


Figure 72. Punjab: Fertiliser usage in cotton kg/ha 1996-2019

Haryana

Fertiliser usage declined from 81 kg/ha in 1996 to 40 kg/ha in 2002, after which usage increased to 107 kg/ha in 2006 and 156 kg/ha in 2009. Excessive usage of fertilisers, especially nitrogenous fertilisers, were found to aggravate infestation of whiteflies and usage started declining after 2010 to reach 126 kg/ha in 2016.

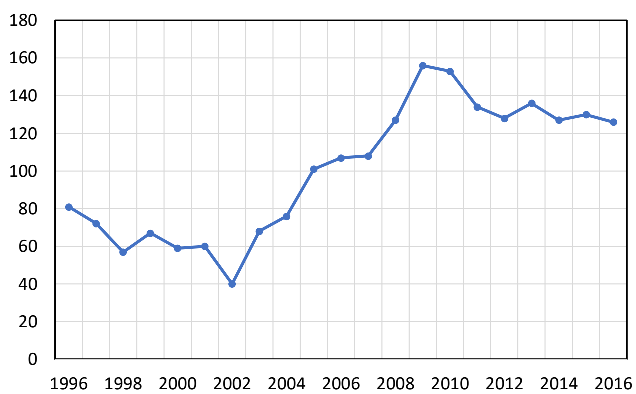


Figure 73. Haryana: Fertiliser usage in cotton kg/ha 1996-2019

Rajasthan

Fertiliser usage in Rajasthan followed haphazard patterns without any decipherable trends.

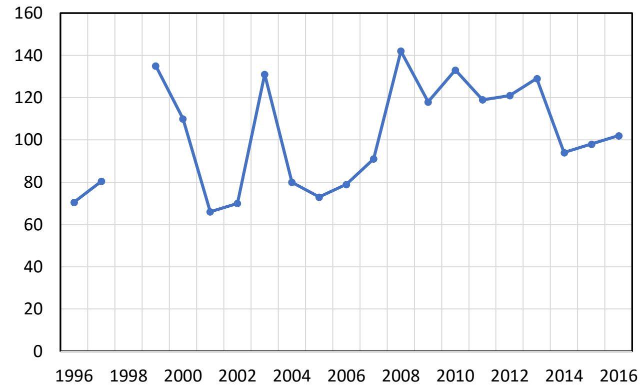


Figure 74. Rajasthan: Fertiliser usage in cotton kg/ha 1996-2019

Gujarat

Fertiliser usage in Gujarat was less than 100 kg/ha from 1996 to 2003. Usage increased from 66 kg/ha in 2002 to 103 kg/ha in 2004 and 205 kg/ha in 2011 after which it declined to 189 kg/ha in 2016.

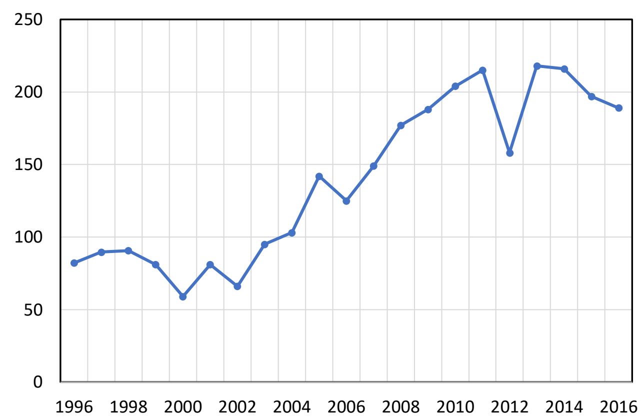


Figure 75. Gujarat: Fertiliser usage in cotton kg/ha 1996-2019

Madhya Pradesh

Across the years, fertiliser usage fluctuated immensely in the state. Usage was high at 143 kg/ha in 2005, 173 kg/ha in 2006, 157 kg/ha in 2007, 166 kg/ha in 2014 and 145 kg/ha in 2015. Fertiliser use was less than 100 kg/ha in rest of the years except in 2002, when it was 109 kg/ha, and in 2016, when it was 128 kg/ha.

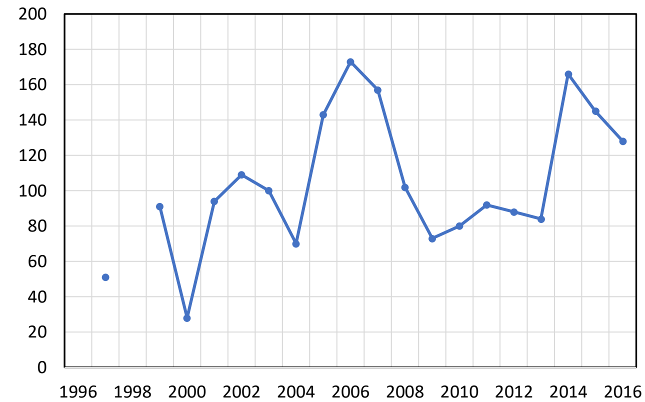


Figure 76. Madhya Pradesh: Fertiliser usage in cotton kg/ha 1996-2019

Maharashtra

The annual average fertiliser usage in Maharashtra was 99 kg/ha from 1996 to 2006. Usage increased from 90 kg/ha in 2005 to 155 kg/ha in 2009 and to a record high of 273 kg/ha in 2011 followed by a decline to 191 kg/ha in 2016.

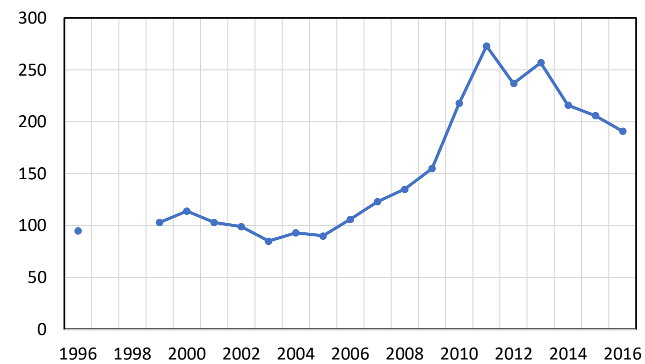


Figure 77. Maharashtra: Fertiliser usage in cotton kg/ha 1996-2019

Andhra Pradesh

Fertiliser usage was more than 200 kg/ha in 2004, 2006 and from 2008 to 2016. Fertiliser usage in the state was generally at higher levels than most other states.

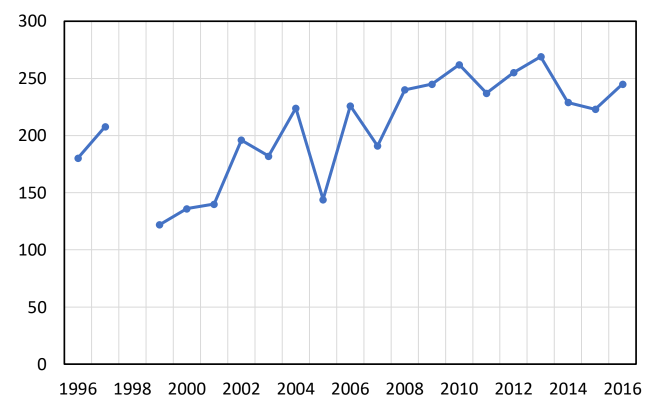


Figure 78. Andhra Pradesh: Fertiliser usage in cotton kg/ha 1996-2019

Karnataka

The annual fertiliser usage declined from 96 kg/ha in 1996 to 37 kg/ha in 2003, after which it increased to 164 kg/ha in 2011 and 170 kg/ha in 2013, followed by a decline to 139 kg/ha in 2016.

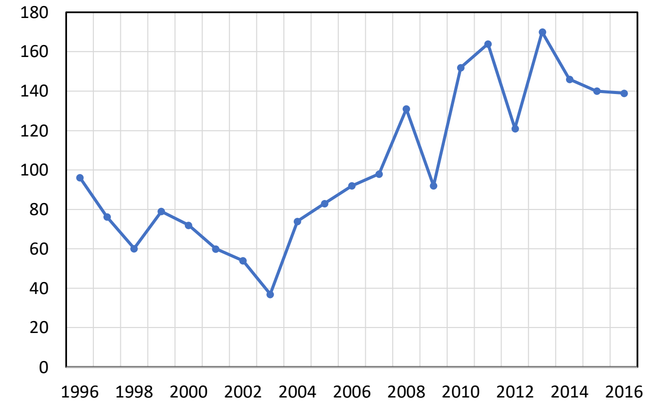


Figure 79. Karnataka: Fertiliser usage in cotton kg/ha 1996-2019

Tamil Nadu

Fertiliser usage increased from 130 kg/ha in 2001 to 204 kg/ha in 2003. Usage levels were almost constant at 195 kg/ha to 210 kg/ha from 2003 to 2006. Fertiliser usage increased to very high levels of 308 kg/ha to 361 kg/ha during 2008 to 2010 and declined to 173 kg/ha in 2013 before rising back to 266 kg/ha in 2015.

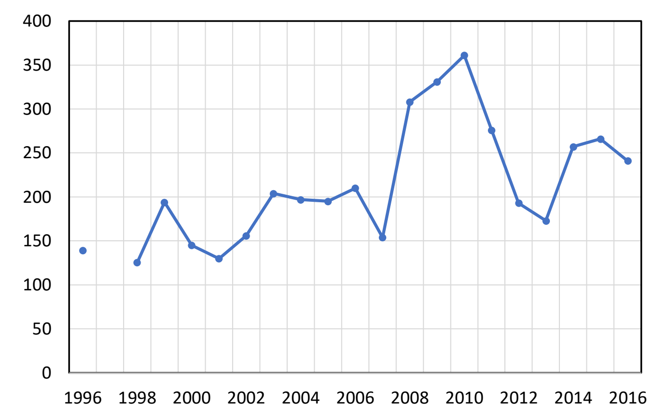


Figure 80. Tamil Nadu: Fertiliser usage in cotton kg/ha 1996-2019

Insecticides

India uses about 3% of the total pesticides used in the world. About 67.0% of the pesticide is used in agriculture and horticulture in the country. Insecticide market in cotton was about US$ 268 million in 2016. Currently, a total of 65 pesticides have been approved by the Central Insecticide Board (CIB) for use on cotton in India. After conducting a review of 66 pesticides during 2015-2017, the Government of India in January 2018 banned the sale and use of 11 highly hazardous pesticides (HHPs) and passed phasing-out orders on 6 more HHPs.

The national average insecticide usage on cotton during 1996 to 2004 was 10,664 mt which reduced to 6202 mt from 2005 to 2012. The average insecticide usage increased again to 9643 mt during 2013 to 2018. Insecticide usage ranged from 10,004 mt to 13,176 mt at 1.0 to 1.5 kg per hectare during 1996 to 2001. The introduction of *Bt*-cotton in 2002 resulted in a significant decline in insecticide use in cotton to 4,623 metric tonnes at 0.51 kg/ha in 2005.

Insecticide usage for bollworm control increased from 6412 metric tonnes (mt) in 1996 to 9864 mt in 2001 and declined thereafter to 458 mt in 2011, mainly due to the impact of *Bt*-cotton on bollworm control. Pink bollworm developed resistance to *Bt*-cotton in 2009, so insecticide usage increased to 1962 mt in 2018. Insecticide usage for sucking pest control declined from 4487 mt in 1999 to 2374 mt in 2006 but increased steadily thereafter to 9701 mt in 2014 before declining to 8201 mt in 2018.

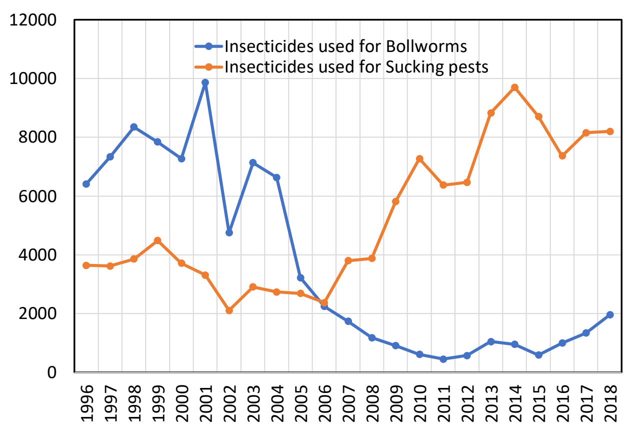


Figure 81. Insecticide quantities (Mt) used for the management of sucking pests and bollworms on cotton

Insecticide usage increased from 1.1 kg/ha in 1996 to 1.51 kg/ha in 2001, and later declined to 0.51 kg/ha in 2006, mainly due to *Bt*-cotton because of which insecticide usage for bollworm control declined significantly during 2002 to 2006. Due to higher infestation of sap-sucking pests, insecticide use increased gradually to 0.83 kg/ha in 2013 and remained at similar levels until 2018.

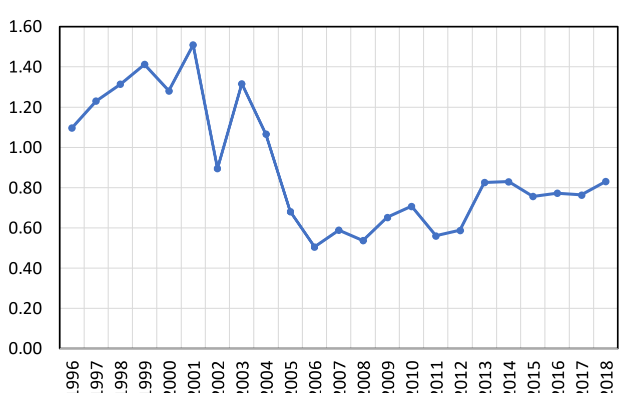


Figure 82. Average quantity (kg/ha) of insecticide used on cotton

The average value of insecticide usage on cotton during 1996 to 2004 was US$ 123 M which decreased to an average of US$ 117 M from 2005 to 2012, after which it increased to an average of US$ 194 M during 2013 to 2018. The value of insecticide usage for bollworm control increased from US$ 75 M in 1996 to US$ 103 M in 2004 before declining to 14 M in 2011 followed by an increase to US$ 63 M in 2018. The value of insecticides used for sucking pest control was low at US$ 26 M to US$ 45 M during 1996 to 2006. Insecticide use increased steadily thereafter to reach US$ 206 M to US$ 223 M from 2013 to 2018.

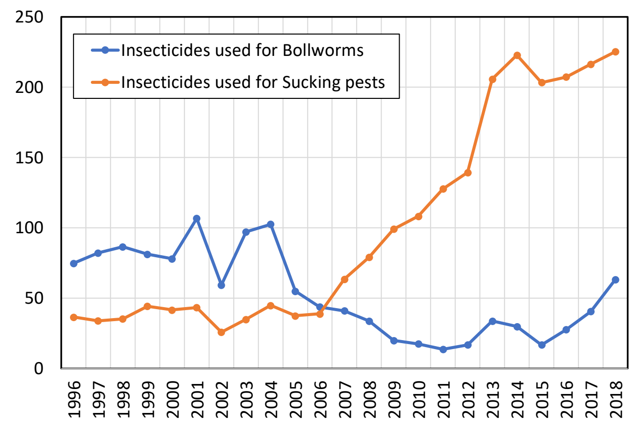


Figure 83. Value of (million US$) insecticides used on cotton

Out of the total insecticides used in agriculture in India, the share of insecticides used for cotton pest management declined from 39.9% in 1997 to a historical low of 14.7% in 2006. However, a large number (734) of new *Bt*-cotton hybrid cultivars were approved during 2006 to 2011, most of which were susceptible to sucking pests, thereby resulting in an increase in insecticide usage to 0.83 kg/ha in 2013. The share of insecticides in cotton increased to 19.6% in 2018.

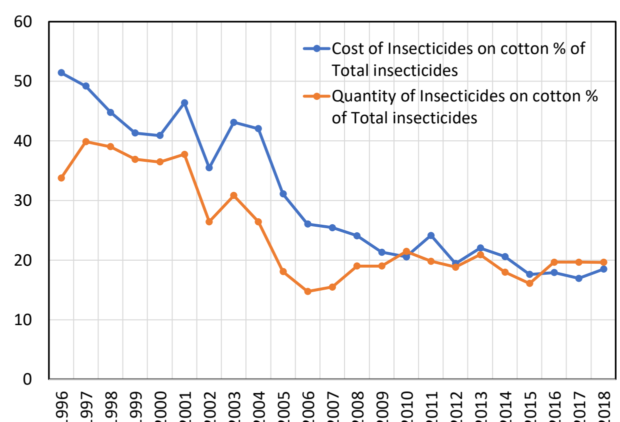


Figure 84. Share of insecticides used on cotton as % of total used in agriculture 1996 to 2018

In terms of value and volume, the proportion of insecticides used for bollworm control v/s sucking pests was 70:30 from 1996 to 2004, which became 20:80 from 2009 to 2018 for value and 10:90 for volume. In 1997, cotton consumed 49% of the total value and 40% of the total volume of insecticides used in india. By 2018, insecticide usage share of cotton declined to 18% of value and 20% of volume of the total insecticides used in the country.

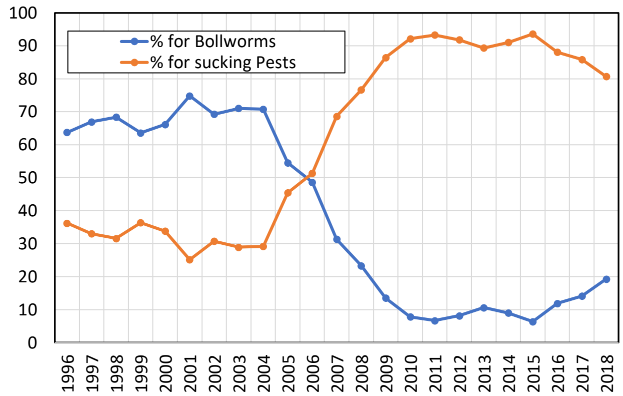
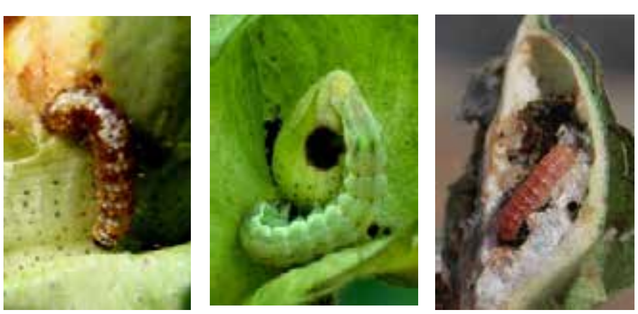


Figure 85. Relative proportion of insecticide quantities used for bollworm control vs sucking pests, 1996 to 2018

Adoption of *Bt*-Cotton

Bt-cotton is a product of genetic modification (GM) that was designed to express insecticidal toxin genes derived from the soil bacterium *Bacillus thuringiensis* mainly intended to kill the three main species of bollworms: American bollworm, *Helicoverpa armigera*; pink bollworm, *Pectinophora gossypiella;* and spotted bollworm, *Earias vittella*. *Bt*-cotton technology was introduced in India as a single *cry1Ac* gene in 2002 and a combination of *cry1Ac+cry2Ab* genes in 2006. *Bt*-cotton functions like an insecticide that kills lepidopteran larvae including bollworms and does nothing else. In India, unlike elsewhere in the world, the *Bt* technology was restricted only in hybrids and not in open-pollinated straight-varieties. *Bt*-cotton was approved for commercial cultivation in 2002 in Central and South India and in 2006 in north India.



Spotted bollworm, American bollworm and pink bollworm

National

Until 2003, the adoption rate of *Bt*-cotton was less than 1.2% but increased from 5.6% in 2004 to 91.4% in 2011 after which it ranged between 83.0% to 93.7%.

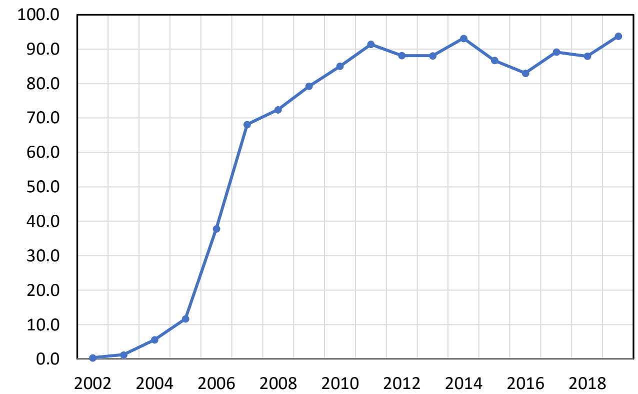


Figure 86. National: Adoption rate (%) of *Bt*-cotton

Punjab

Adoption of *Bt*-cotton has been very high in Punjab. *Bt*-cotton area was above 90% from 2007 to 2019.

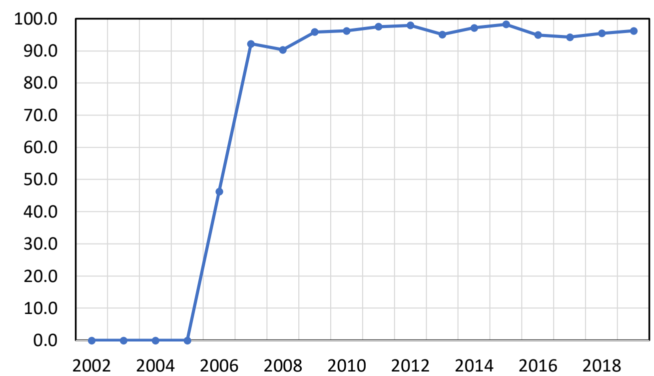


Figure 87. Punjab: Adoption rate (%) of *Bt*-cotton

Haryana

Bt-cotton was introduced in 2006. The area under *Bt*-cotton increased rapidly from 7.9% in 2006 to 57.8% in

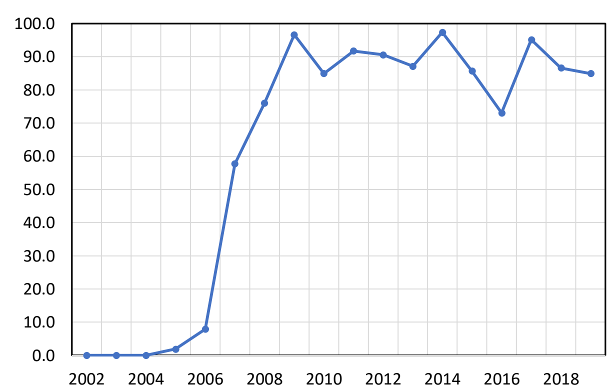


Figure 88. Haryana: Adoption rate (%) of *Bt*-cotton

2007 and to 96.6% in 2009. From 2010 to 2019, *Bt*-cotton area remained above 85%, except in 2016 when the area declined to 73.1% and farmers switched to the local Desi varieties, which are resistant to the dreaded cotton leaf curl virus that had inflicted severe damage in 2015 in north India.

Rajasthan

Bt-cotton was introduced in 2016. Adoption rate increased from 10.3% in 2007 to 85.1% in 2011, after which it fluctuated in a range between 63.6% and 85.0%. the cotton leaf curl virus is a major factor that influences farmer preferences for the local Desi species *Gossypium arboretum,* which is almost immune to the disease.

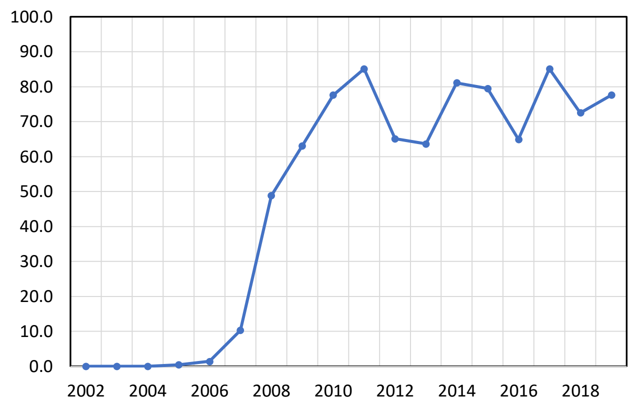


Figure 89. Rajasthan: Adoption rate (%) of *Bt*-cotton

Gujarat

Until 2005, the area under *Bt*-cotton did not exceed 7.8%. However, speculations were rife that the area under unapproved brands and fake brands of *Bt*-cotton occupied an area that may have been equivalent to the area under approved brands or possibly even double of that. Area under *Bt*-cotton quickly jumped to 53.7% in 2007 and to 90.4% in 2011. *Bt*-cotton occupied 97.8% of Gujarat's cotton acreage in 2014 and remained at 79.3% to 96.4% in the subsequent period.

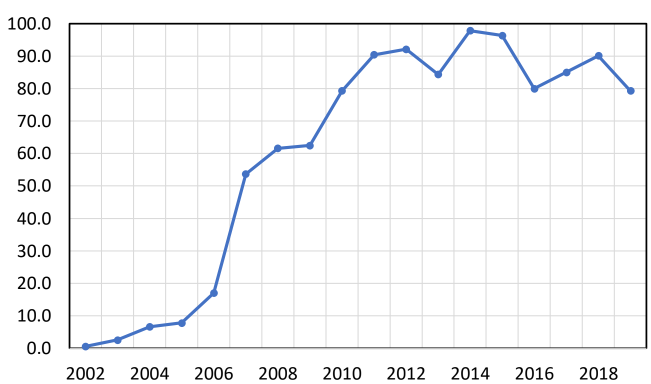


Figure 90. Gujarat: Adoption rate (%) of *Bt*-cotton

Madhya Pradesh

The area under *Bt*-cotton increased very rapidly from 2.3% in 2003 to 99.3% in 2010 after which the area ranged from 80% to 95%.

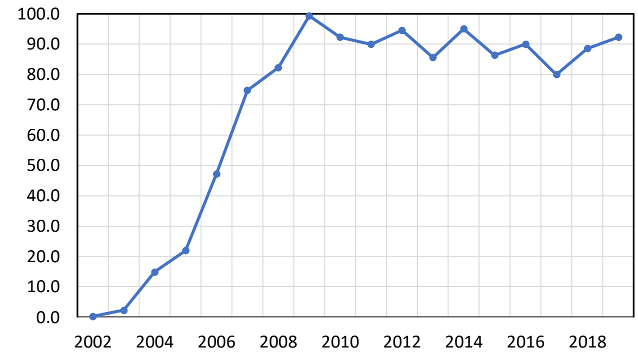


Figure 91. Madhya Pradesh: Adoption rate (%) of *Bt*-cotton

Maharashtra

The area under *Bt*-cotton was less than 0.6% until 2003 but increased rapidly from 5.7% in 2004 to 80.0% in 2007, after which it remained high at 82% to 95% until 2019.

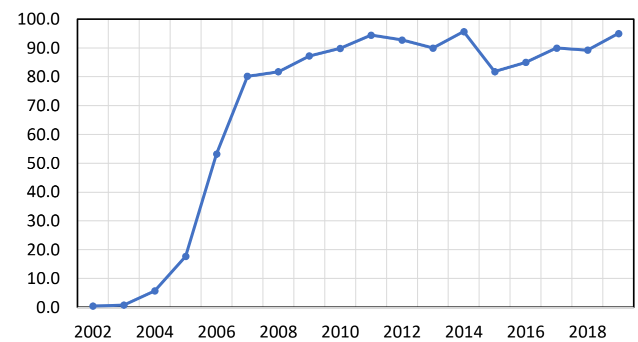


Figure 92. Maharashtra: Adoption rate (%) of *Bt*-cotton

Andhra Pradesh

The area under *Bt*-cotton was 0.5% to 0.6% until 2003 and increased to 8.7% in 2005. Area increased rapidly to reach

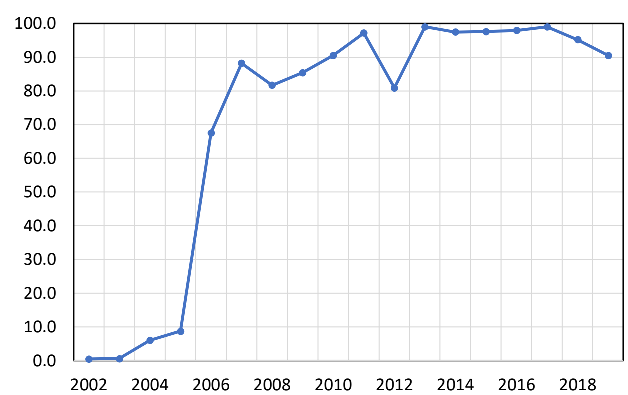


Figure 93. Andhra Pradesh: Adoption rate (%) of *Bt*-cotton

68% in 2006 and 88% in 2007 after which it remained high to reach a near saturation point of 98% to 99% from 2013 to 2017.

Telangana

Adoption of *Bt*-cotton in Telangana ranged from 93.7% to 99.0% from 2014 to 2019.

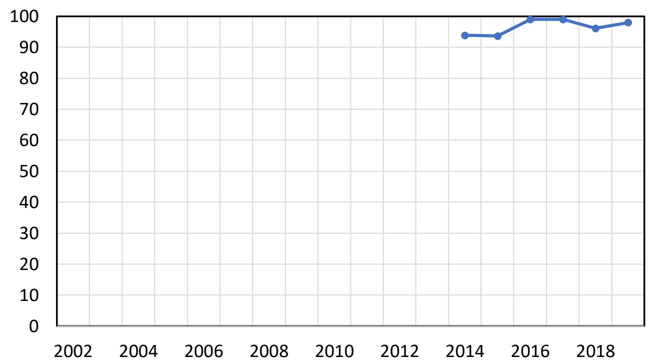


Figure 94. Telangana: Adoption rate (%) of *Bt*-cotton

Karnataka

Adoption of *Bt*-cotton was slow in the state with negligible area until 2003 and less than 7.0% until 2005. However, area under *Bt*-cotton increased to 92.8% in 2012 after which it declined to a range of 65% to 80% until 2019, with the exceptions of 2013 and 2017, when the area was 85% and 90% respectively.

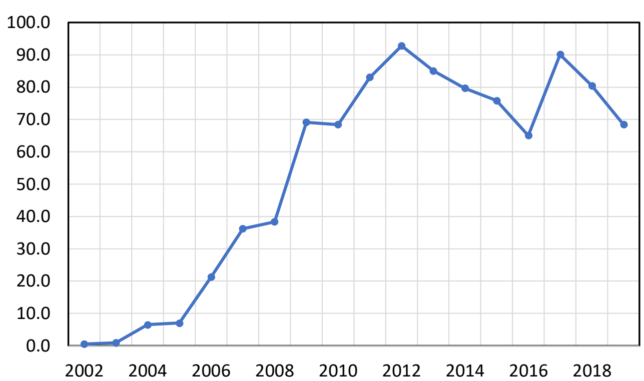


Figure 95. Karnataka: Adoption rate (%) of *Bt*-cotton

Tamil Nadu

Adoption of *Bt*-cotton increased from 12.1% in 2005 to 60.6% in 2007 but slipped down to less than 10.4% in 2008 and 2009, before increasing again to 96.1% in 2012. The area under *Bt*-cotton declined to 50.8% in 2019.

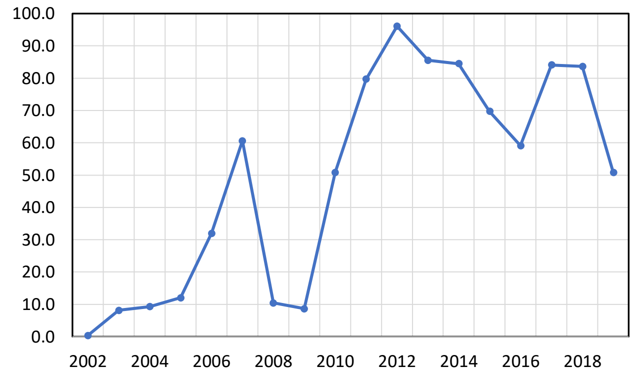


Figure 96. Tamil Nadu: Adoption rate (%) of *Bt*-cotton

Discussion

The long-term trends of data sourced from authentic Government data portals have been shown here in a graphical form for an easy comprehension of trends. Data on area and production, yields, cost of production, cost of inputs, cost cultivation, net returns, insecticide usage, fertiliser usage and impact of *Bt*-cotton have been presented here. It is important to explain the trends to be able to identify key factors that influenced them.

Area and Production

Historically the changes in cotton area and production have been either driven by market prices or production costs or influenced by yields that were impacted by insect pests or diseases. Several factors influenced the changes in cotton acreage in India over the past few decades. Area declined to a historical low of 6.46 million ha in the three-decade period from 1954 to 1984, mainly due to low yields, the problems of jassids, *Spodoptera litura* and the pink bollworm. The increase in area from 1995 to 2001 was due to higher cotton prices and the introduction of newer insecticide molecules such as spinosad, indoxacarb, emamectin benzoate, imidacloprid etc., which assisted in better management of the insecticide resistant whiteflies and bollworms. The significant increase in area after 2007 can be attributed primarily to two factors: *Bt* cotton and high domestic cotton prices due to increased Indian exports after 2005.

It is widely believed that *Bt* cotton played a part in the sudden increase of India's contribution to global cotton production, from 14% in 2002 to 24.83% in 2014. However, the increased levels of production were partly due to increase in area and partly due to yields that may have been protected from bollworm damage.

Since 2010, cotton has been cultivated in 11 million to 12 million ha (ha) in the country. An additional area of about 4.0 million ha were added to cotton within eight years after 2002 when *Bt*-cotton was introduced. Large tracts of cotton were added in the central Indian region in Gujarat, Maharashtra and Telangana. Interestingly the additional area did not encroach the land under essential foods such as rice, wheat, oilseeds and pulses. Maharashtra, Gujarat and Telangana have the largest area under cotton in India. The three states occupy 70.0% of India's cotton area. Over the past 20 years, the area increased by 25% in Maharashtra, 60% in Gujarat and at least 100% in AP + Telangana. Cotton area in rest of the country was more or less the same. In recent times, cotton area increased to a high decadal average value of 11.93 M ha from 2009 to 2019 with the highest high record of 12.85 M ha in 2014.

Drought from 1999 to 2002

Most studies erroneously consider 1999 to 2002 as pre-*Bt* era to compare this period with post-2003 as *Bt*-era. Perusal of data shows that cotton yields were low, prior to the introduction of *Bt*-cotton, from 1999 to 2002, primarily because of the continuous deficit-rainfall and drought in the cotton growing regions. A 'severe drought' was declared in 2002 with a rainfall deficit of -19.2% and the preceding three years suffered rainfall deficits between -4.0 to -8.3%. However, the subsequent period from 2003 and 2018 received normal rainfall in the rainfed cotton growing states, except for one year (2009) which received deficit rains in some of the cotton growing districts in the rainfed regions. However, despite normal rainfall, the national annual rate of yield increase slowed down substantially to an average annual growth rate of 3.84%. Therefore, it is inappropriate to consider 1999 to 2002 as 'the pre-*Bt* era'. Despite significantly less use of fertilisers, there are times when each of the states obtained high yields in years prior to 1999.

Yields

Cotton yields in India increased primarily from 2002 to 2006 and did not increase thereafter. Data showed that from 2002 to 2006, yields doubled in north India and Gujarat and increased partly in Maharashtra, whereas yields in other states did not increase significantly during this period. Interestingly, yields had doubled in north India even before *Bt*-cotton was introduced. Yields in Gujarat had doubled when the area under *Bt*-cotton was just about 7.8% in 2005 and did not increase significantly thereafter irrespective of the increase in the area under *Bt*-cotton. Similarly, yields (CAB data) in Maharashtra increased from 158 kg/ha in 2002 to 311 kg/ha in 2004 when the *Bt* area was just 5.7% after which yields averaged at 335 kg/ha from 2007 to 2019 even with more than 80% area under *Bt*-cotton. Government official data indicates that cotton yields increased in all the cotton growing states over 4-5 years (2002 to 2005) to recover from a 3- to 4-year drought period from 1999-2002, before *Bt*-cotton became popular. Yield enhancement after 2003 in India is correlated to the increase in fertiliser usage. Other factors such as increase in the area under hybrid cotton, new pesticides and irrigation appear to have played a significant role in plant protection and yield enhancement. Yield trends in Madhya Pradesh, Andhra Pradesh, Karnataka, Tamil Nadu and Orissa do not correlate with the adoption rate of *Bt*-cotton especially from 2003 and 2004 and also from 2005 to 2019. Therefore, the role of *Bt*-cotton in the narrative of India's increasing cotton yields from 2002 to 2006 appears dubious.

About half of India's cotton production came from north India plus Gujarat in 2003 and 2004 despite their share of the area being only 40% of the country. India's yields from 2003 to 2006 were influenced largely by the increase in yields mainly in Gujarat. Gujarat underwent significant policy and infrastructural changes following the severe 2-3 years of drought leading up to the year 2000, thereafter clocking an impressive growth rate of about 10.0% for several years in the farm sector due to good monsoons for four consecutive years after 2001, as well as significant policy changes related to water and electricity, including:

- Improved quality of power supply,
- Metered use in new agro-wells,
- Promoting micro-irrigation, and
- Decentralised water harvesting (Kumar *et.al*, 2010) such as check dam constructions.

A critical analysis shows that while *Bt*-cotton protected the crop from bollworm damage, several factors such as new hybrid cultivars, significant increase in fertiliser usage, investments, and inclusion of irrigated-fertile lands for *Bt*-cotton in Gujarat may have played a crucial role in sustaining higher yields after 2004. From 2000 to 2008, nearly, 500,000 irrigation structures, comprising of 176,270 check dams, 55,917 bori bandhs, 240,199 farm ponds and were built in the Saurashtra and Kutch regions of Gujarat, wherein 0.64 million ha of cotton area was added due to irrigation. Compared to 2000-2002 period, yields doubled in Gujarat when the area under *Bt*-cotton was 2.6% in 2003, 6.6% in 2004 and 7.8% in 2005; but remained stagnant at a 12-year (2006 to 2017) average of 630 kg (Ag-min data) to 686 kg/ha (CAB data) at the 2005/06 levels despite high adoption rates of *Bt*-cotton that exceeded 50% of the area after 2007 and averaged more than 90% of the area after 2011. The increased average yield of cotton to 625 kg/ha in 2006-07 (data: Ag Min) could be due to the replacement of rainfed cotton by irrigated cotton and greater use of high yielding varieties of cotton (Kumar *et.al*, 2010). Moreover, fertiliser use in Gujarat also increased consistently over the four-year period, from 66 kg/ha in 2002 to 142 kg/ha in 2005 which combined with good monsoon resulted in yield enhancement (Kranthi, 2017).

The yield in 2003 in the three states of Gujarat, Punjab and Andhra Pradesh was about 50% higher than the highest yield in the preceding decade. Interestingly, though *Bt*-cotton wasn't introduced as yet in the state, the yields in Punjab had also already increased by 50% over the previous decade best record yield to reach 551 (Tex Min) and

697 kg/ha (Ag Min) in 2004. Concomitantly, productivity almost doubled within three years from 2002 to 2004 in Haryana and Rajasthan. Therefore *Bt*-cotton cannot be a factor in the yield increase in north India prior to 2005. Increase in yields from rest of India could have also been influenced by the same set of factors that contributed to yield enhancement in north India. Because *Bt*-cotton was introduced in 2006 in north India, inclusion of the 2002-2006 yield data of north India into the national data leads to misinterpretation of the national trends with reference to the impact of *Bt*-cotton from 2002 to 2006.

It is interesting that while the area under approved *Bt*-cotton hybrids did not increase beyond 1.2% of India's total cotton area in 2003, the national average yield of seed cotton increased spectacularly from an average of 186 kg/ha in 2001 to 307 kg/ha in 2003 according to the Ministry of Agriculture, and from 308 kg/ha in 2001 to 399 kg/ha in 2003 as per the Textile Ministry. If it is assumed that without *Bt*-cotton, the national average yields in 2003 would have been similar to the year 2000, and that the 1.2% area under *Bt*-cotton was solely responsible for the spectacular increase in yields in 2003, then it must be presumed that the yields in the 1.2% *Bt*-cotton should be about an inconceivable 10,000 kg/ha to justify the national cotton production achieved in 2003!

Scientific studies conducted in India subsequent to the introduction of *Bt*-cotton showed that the yields in non-*Bt* cotton were 3.3% to 7.1% less than *Bt*-cotton (Gaurav *et.al* 2012; Qayyum *et.al*, 2006; Pemsl et al 2004; Bennet *et.al*, 2005) and 22.2 to 28.6% less than *Bt*-cotton (Stone, 2011; Kathage and Qaim, 2012; Subramanian *et.al*, 2010; Sadasivappa *et.al*, 2009; Patil *et.al*, 2007; Gandhi *et.al*, 2006; Morse *et.al*, 2005; Naik, 2001). Many researchers erroneously credit this sudden growth to the introduction of *Bt*-cotton in India in 2002. Much of the confusion arose because of the inclusion of the yield data of 2002 to 2006 in north India which didn't have *Bt*-cotton before 2006. It is inconceivable to infer that the big yield jump from 2002-2004 may have happened due to a mere 6.2% area under *Bt*-cotton in India in 2004. Intriguingly, the subsequent increase in '*Bt*-cotton adoption' from 15.4% in 2005 to more than 92.0% in 2011 and thereafter did not result in any perceptible changes in yields. Therefore, it is difficult to find a positive correlation between yield trends and the adoption of *Bt*-cotton. Fertiliser use increased from 96 kg/ha in 2002 to 222 kg/ha in 2011. Investment increased almost threefold from US$ 426/ha in 2002 to US$ 1232 in 2011.

How did yields increase from 2002 to 2004?

Irrigation projects in Gujarat and Andhra Pradesh, increase in fertilisers, and new varieties caused high yields while new insecticides and the small area under *Bt*-cotton protected crops from insect damage. The construction of more than 30,000 check-dams and 35,000 farm ponds in Gujarat and commissioning of new canal irrigation projects in Telangana region from 2000 to 2003 helped cotton immensely. New fertile lands of 750,000 ha in Gujarat and about 200,000 ha in Andhra Pradesh were brought under cotton cultivation from 2002 to 2006. Neonicotinoid insecticides were widely used as seed treatment to protect the crop against sucking pests up to 60 days after sowing and also as foliar sprays for effective control. At least until 2004, bollworms were controlled effectively in more than 94.4% of the cotton area under non-*Bt*-cotton with insecticides such as spinosad, indoxacarb, novaluron and emamectin benzoate belonging to four new insecticide chemistries, while *Bt*-cotton controlled bollworms in the 5.6% of the area in 2004. Fertiliser usage increased significantly in Punjab, Haryana, Gujarat and Andhra Pradesh. New leaf-curl virus resistant varieties RS-875, RS-2013 and high yielding sap-sucking pest resistant varieties RS-810, LH-1556, H-1098, F-1378, were grown in north India. New varieties such as NH-545, JK-4, G-Cot-16 gave high yields in central India. New varieties such as Surabhi, Sumangala and Narasimha contributed to high yields in south India. Introduction of new high yielding sucking pest resistant non-*Bt* hybrids such as LHH-144, Ankur-651, Ankur-9, Bunny, Mallika, RCH-2, CICR-Omshankar and Ajeet-11 also contributed to high yields.

Cost of seeds, fertilisers, insecticides and labour

Cultivation costs increased significantly after the introduction of *Bt*-cotton in India. These costs were mainly associated with inputs such as seeds, fertilisers, insecticides and labour. Needless to mention, a higher investment on technological inputs would result in higher yields. Because these investments which resulted in high yields were concomitant with the adoption rate of *Bt*-cotton, there was a general misunderstanding that higher adoption of *Bt*-cotton caused higher yields. A closer look at published papers shows that the yields of *Bt*-cotton in India were 3.3% to 28.6% higher compared to non-*Bt*-cotton, which however could not be attributed to *Bt* technology alone, because of the simultaneous large-scale adoption of several other yield-influencing technologies. For example, Gruère and Sun (2012) clearly showed a 19% overall contribution of *Bt* to cotton yields, but found this inseparable from changes in fertiliser, hybrids, labour, pesticides, and irrigation. *Bt* hybrid seed costs 4-5 times more than non-*Bt* hybrids and about 10 times more than non-GM varieties. Farmers achieved high yields of *Bt* cotton partly because they lavished the expensive GM seeds with care and attention (Gilbert, 2013). Kathage and Qaim (2012) reported that *Bt* fields received 23-26% more irrigation, 13-25% more fertiliser, and 11-18% more labour. Similarly, Dev and Rao (2007) reported that *Bt* fields received 28% more human labour and 21% more machine labour, 83% more irrigation, and 27% more manure. Other than *Bt*-cotton, a few important technologies were introduced simultaneously during the same period. These technologies and other inputs are likely to have contributed to yield enhancement especially from 2002 to 2004 (Gruere and Sun, 2012; Kranthi, 2011, 14).

While crediting the *Bt* technology for such gains, some of these studies followed a simplistic assumption that *Bt* technology was the main and probably the only game-changer in India. However, several studies (Gilbert, 2013; Dev and Rao, 2007; Gruere and Sengupta, 2011; Kuruganti, 2009; Gruere and Sun, 2012; Kranthi, 2011, 2014; Stone, 2012) suggested that the increase in yields could be due to other factors as well. Kranthi (2017) suggests that the 150% increase in fertiliser usage contributed more to the yields than bollworm protection by *Bt*-cotton. Stone (2012) surmises the predicament to state that 'the Indian case has been a poor laboratory for isolating the impacts of *Bt* seeds, and the time for valid comparisons is past because non-*Bt* cotton seed had virtually disappeared'.

Prior to the introduction of *Bt*-cotton in India, cotton hybrid seeds were 3-5 times more expensive than the cotton variety seeds. However, *Bt*-cotton hybrids were 5 times more expensive than conventional hybrid seed, due to technology fee and other commercial considerations (Stone, 2012; Ramasami, 2012). Thus *Bt*-cotton hybrid seeds were at least 8 to 10 times costlier compared to seeds of open pollinated straight varieties. Conservative estimates showed that on an average, the additional expenditure on seeds was at least US$ 21 per hectare and the Indian farmers may have spent a total additional amount of US$ 2.6 billion to US$ 3.6 billion on *Bt*-cotton seeds from 2002 to 2019.

The labour requirement in hybrid cotton is more as compared to varieties due to the additional processes required in hybrid cotton fields. Hybrids are input intensive and are sown at wide spacing of 90 x 60 cm or wider. The sowing process needs more labour for making a grid in the fields and dibbling the hybrid seeds manually. Sowing of varietal seeds is not labour-intensive because the seeds are sown in rows using seed drills. Weeds are more in the vacant spaces in hybrid fields due to wider spacing. Fertiliser application in a grid pattern such as in the hybrid-cotton fields requires more labour compared to application in rows of varieties. Hybrid plants are much taller than varieties and produce multiple flushes which need more labour for picking. Hybrid crop thus needs more human labour for sowing, weeding, spraying, fertiliser application and harvesting. On average, a total of about 100-110 man-days are required currently for one-hectare cultivation to include all operations such as sowing, weeding and harvesting (Kranthi, 2014).

According to the Ministry of Agriculture (https://cacp.dacnet.nic.in), expenditure on insecticides increased constantly over the years even after the introduction of *Bt*-cotton, from US$ 23 per hectare in 2000 to an average of US$ 46 per hectare from 2010 to 2016. In north India, the expenditure on insecticides doubled in 10 years after the introduction of *Bt*-cotton in 2005, while over a period of 14 years from 2002 to 2015, it increased by 4-5 times in Andhra Pradesh and Tamil Nadu, about 6.5 times in Gujarat, Maharashtra and Karnataka and 3 times in Madhya Pradesh. Though insecticide usage in cotton decreased in the first few years immediately after the introduction of *Bt*-cotton in India, it has increased back to almost the same levels as that of the pre-*Bt* era mainly because of the rapid proliferation of a plethora of cotton-hybrids, which were susceptible to sap-sucking insect pests. *Bt*-cotton adoption in India resulted in 50% to 60% reduction of insecticides from 2002 to 2007 and assisted in protecting yields. Insecticide use increased after 2007. *Bt*-cotton was able to reduce insecticide use on bollworms by more than 90% but insecticide usage increased for sucking pests. Majority of the *Bt*-hybrids are susceptible to sap-sucking insects such as whiteflies, mealybugs, jassids, thrips, mirid bugs and aphids and susceptible to diseases such as cotton leaf curl virus disease, leaf streak virus, *Alternaria* etc., and are serving as hot-spots by supporting pest and disease populations.

Yield trends correlate tightly with fertiliser usage

It is commonly known in agricultural sciences that application of chemical fertilisers lead to increase in yields, especially when it is precision based. State-wide analysis shows that the trends in cotton yields correlate with fertiliser usage. While yield increase and adoption rate of *Bt*-cotton did not correlate, fertiliser usage and yields were tightly correlated (Kranthi, 2017, Kranthi and Stone, 2020). Kranthi (2017) showed that not only did fertiliser use increase by 2.2 times, but the expenditure on fertilisers in cotton increased by 5.3 times from 2002 to 2013. Fertiliser usage started to increase significantly after the introduction of *Bt*-cotton, from 96 kg/ha in 2002 to 192 to 224 kg/ha from 2010 to 2015. Fertiliser usage increased from 0.84 million tonnes in 2002 to 2.57 million tonnes by 2011-12, with highest increases of 5.8 times in Gujarat, 4.3 times in Maharashtra, 4.2 times in Karnataka and 2.5 times in Andhra Pradesh. The expenditure on cotton fertilisers at current prices, increased by 5.5 times, and at constant prices by 2.3 times from 1999 to 2013. Expenditure on fertilisers declined from 2013 to 2015.

From 2002-2011, the average annual usage of fertilisers per hectare increased by 250% in Karnataka, 150% in Maharashtra, 140% in Gujarat and 110% in Punjab and Haryana (Srivastava *et.al*, 2016; Kranthi, 2017). Hybrid vigour is harnessed with increased levels of fertilisers and irrigation. Thus, cotton hybrids respond to fertiliser application resulting in higher yields. The increase in hybrid cotton area from 45% in 2006 to 95% in 2011 seems to have been one of the main factors that triggered the increase in fertiliser usage by 120% on cotton in India. Interestingly while crediting *Bt*-cotton for the yield increase in India, many authors (James, 2014; Brookes and Barfoot, 2012; Ramasundaram *et.al*, 2014; Kathage and Qaim, 2012; Herring and Rao, 2012; Ashok *et.al*, 2012; Gruere and Sun, 2012; Bennett, *et.al*, 2006; Gandhi and Namoodri, 2006; Naik *et.al*, 2005; Narayanamoorthy and Kalamar, 2006; Qaim, 2003, 2009;Qaim and Zilberman, 2003; Qaim *et.al*, 2006; Sadashivappa and Qaim, 2009; Subramanian and Qaim, 2009, 2010; Ramasamy *et.al*, 2012) ignored the fact that from 2003 to 2011, fertiliser usage increased at an average annual growth rate of 10.84% compared to the poor annual average growth rate of 0.89% from 1996 to 2002 — prior to the introduction of *Bt*-cotton in India.

Changes in the cropping systems, pest dynamics and insecticides

Historically, until India gained independence in 1947, the native Desi cotton species *Gossypium arboreum* and *G. herbaceum* were cultivated on India in more than 97.5% of the cotton acreage. The majority of the Desi cotton varieties were resistant to drought and most insect pests and diseases. However, because many Desi varieties were of longer duration spanning 7-8 months of the crop, damage due to insect pests was observed, but insecticides were rarely used. Before 1980, the pink bollworm, *Pectinophora gossypiella* (Saunders), Jassids, *Amrasca devastans* (Distant) and the cotton leafworm *Spodoptera litura* (Fabricius) were the major insect pests of cotton in India. The main insecticides that were used on cotton in India from 1950-1980 were BHC, DDT, endosulfan, carbaryl, carbofuran, parathion, dimethoate, monocrotophos, acephate, triazophos, metasystox chlorpyriphos and quinalphos.

In the mid 1970s, Spodoptera litura had developed resistance to the conventional insecticide groups such as organophosphates and carbamates. Synthetic pyrethroids were introduced in 1981. Excessive use of these insecticides is believed to have caused *H. armigera* and whiteflies to emerge as major pests by mid 1980s. During the mid 1990s, chloronicotinyl insecticides such as imidacloprid, acetamiprid and thiomethoxam were introduced as seed-treatment and foliar sprays for sucking pest control. These insecticides were found to be very effective as seed treatment in protecting seedlings against sap-sucking insects for the first two months, and as foliar sprays for 15-20 days. Cotton yields started increasing due to the effective protection of the vegetative stage of the crop from sucking pest infestation. During the late 1990s, new chemicals such as rynaxypyr, novaluron, spinosad, indoxacarb, emamectin benzoate, and lufenuron were introduced to control the American bollworm, *Helicoverpa armigera* and the cotton leaf worm, *Spodoptera litura*. However, with the introduction of *Bt*-cotton in 2002, the demand for these insecticides declined but insecticide use to control sucking pests increased.

The increase in insecticide usage in cotton farms was primarily because of the constantly increasing infestation levels of sap-sucking insects such as the whiteflies, leaf hoppers, thrips and mealy bugs that were prompted by the introduction of a large number of *Bt*-cotton hybrids which were susceptible to sap-sucking insects. Additionally, increase in insecticide usage on the susceptible *Bt*-cotton hybrids led to insecticide resistance in sap-sucking insect pests (Peshin 2014, Preetha, 2014), which has also further contributed to the progressive increase in insecticide usage.

Three main factors may have contributed to the enhanced infestation of sap-sucking pests. The first being increased usage of fertilisers, especially urea, mainly in Gujarat, Karnataka and Maharashtra wherein fertiliser usage increased by 138% to 246%. The second factor could be the rapid, indiscriminate introduction of >1000 commercial *Bt*-cotton hybrids, most of which were highly susceptible to sucking pests and were not tested rigorously for agronomic suitability in various agro-eco zones where they were supposed to be cultivated. The third factor could be the increase of the total area of hybrid cotton (*Bt* + non-*Bt*) from 45% in 2006 to >95% in 2013, which replaced almost all the public sector varieties that were resistant to sap-sucking insects.

Emergence of American bollworm as a major pest in India

The American bollworm *Helicoverpa armigera* was not a major pest of cotton in India prior to 1978. It was a major pest of vegetables, pulses and oilseeds. Two factors are believed to have triggered the emergence of *H. armigera* as the major pest of cotton. Introduction of the synthetic pyrethroid group of insecticides into India in 1981 was the first factor. Introduction and proliferation of *G. hirsutum* hybrids in mid 1970s was the second factor. Synthetic pyrethroids were introduced to control pink bollworm and the cotton leafworm and became very popular very soon because of their broad-spectrum action on insects. Increase in the area under *G. hirsutum* hybrid-cotton coupled with indiscriminate use of pyrethroids during the 1980s are believed to have altered the ecosystems and replaced the pink bollworm and the leaf worm with the American bollworm *Helicoverpa armigera* (Hubner) and the whitefly *Bemisia tabaci* (Gennadius). By early 1990s, *H. armigera* and *B. tabaci* showed high levels of resistance to insecticides to almost, all the insecticides that were recommended for their control. Efforts were intensified to develop and implement Integrated Pest Management (IPM) and Insecticide Resistance Management (IRM) strategies primarily to combat the American bollworm and the whitefly. *Bt*-cotton has thus far been very effective in controlling the American bollworm.

Introduction of Bt-cotton

Cotton was genetically modified to express crystal toxins of a soil bacterium called *Bacillus thuringiensis* (*Bt)* to develop *Bt*-cotton. The crystal toxins expressed in *Bt*-

cotton plants are toxic as stomach poisons to bollworm larvae. *Bt*-cotton in India is available only in the form of hybrid *Bt*-cotton. Prior to the introduction of *Bt*-cotton, the American bollworm *Helicoverpa armigera* had become resistant to almost all the recommended insecticides. *Bt* cotton was approved for commercial cultivation in central and south India in 2002 and in north India in 2006. *Bt*-cotton with a single gene *cry1Ac* was approved in 2002 and *Bt*-cotton with two genes *cry1Ac+cry2Ab*, was approved in 2006. Six *Bt*-cotton genetic events developed by five companies have been approved for commercial cultivation in India. From 2002 to 2006, a total number of 62 new *Bt*-cotton hybrids were approved. From 2007 to 2012, a total number of 1,034 new *Bt*-cotton hybrids were approved. As the number of companies increased to more than 50, the number of approvals of *Bt*-cotton hybrids also increased. Currently it is estimated that more than 3,000 *Bt*-cotton hybrids have been released in India thus far. The area under *Bt* cotton increased from 29,307 ha (0.38%) in 2002 to 10.12 million ha in 2010 which was 90% of India's cotton acreage. Currently *Bt*-cotton is grown in 11 to 12 million ha in the country.

The two main economic benefits that are expected from *Bt*-cotton are enhanced yield and fibre qualities due to prevention of bollworm damage and reduction in the usage of insecticides for bollworm control. A closer look at published papers and Government data shows that cotton yield trends do not correlate with the adoption rate of *Bt*-cotton and the initial trends of insecticide reduction from 2005 to 2008 could not be sustained after 2009.

The problem of pink bollworm resistance to *Bt*-cotton

From 1980 to 2010, there were hardly any major reports of economic damage caused by the pink bollworm *Pectinophora gossypiella* in India. The two major factors that caused a decline in pink bollworm from 1980 to 2006 were the release of short and medium duration varieties (150-180 days) and use of synthetic pyrethroids that controlled the pest very effectively. Introduction of *Bt*-cotton in 2002 kept the pink bollworm under check. The main factors that brought the pest back are the cultivation of cotton for a long duration of 210-240 days and development of pink bollworm resistance to *Bt*-cotton.

In the six years after *Bt*-cotton was introduced, the pink bollworm *Pectinophora gossipella* developed resistance to *Bt*-cotton in 2008 in India (Dhuruva and Gujar, 2009; Naik *et.al*, 2018) and ever since, the efficacy of *Bt*-cotton has been limited to the major pest called the American bollworm, *Helicoverpa armigera* while extending its control efficacy on the relatively less important pest, the spotted bollworm *Earias vittella*. The pink bollworm *Pectinophora gossypiella* resistance to Cry1Ac based *Bt*-cotton was reported by Monsanto and ICAR-IARI New Delhi in 2010. Pink bollworm started appearing on Bollgard-II® in seriously damaging proportions after 2014, especially in Gujarat and was confirmed by ICAR-CICR, Nagpur in 2014 to have developed resistance to Bollgard-II® containing Cry1Ac+Cry2Ab. *Bt*-resistant pink bollworm can reach menacing proportions if the cotton duration is not curtailed from the current 210 to 240 days to a shorter duration of 150 to 160 days. Farmers have started using insecticides (pyrethroids) for pink bollworm control, mostly in Gujarat. Indiscriminate use of pyrethroids and organophosphate mixtures are likely to trigger resurgence of the most dreaded American bollworm *Helicoverpa armigera* and whitefly outbreaks in the near immediate future. Farmers do not follow the 'refuge strategy' of growing 20% area of non-*Bt* cultivars in the vicinity of *Bt*-cotton fields. Multinational companies are reported to have been working on the deployment of new transgenic cotton with several new genes (Vip3A, Cry2Ae, Cry1Ab, Cry1F and undisclosed genes) in India in the near immediate future, but none of these appear as potent as the existing combination of Cry1Ac+Cry2Ab and none effective on the *Bt*-resistant pink bollworms.

Impact of *Bt*-cotton on yields

Data show that adoption trends of *Bt*-cotton in India were not correlated with yield trends. Yields increased spectacularly from 2002 to 2006 when the area under *Bt*-cotton was negligible, and yields did not increase after 2007 even when the area under *Bt*-cotton high and occupied more than 80% of India's cotton acreage. According to the data of Ministry of Agriculture, yields stagnated at 466 kg/ha from 2008 to 2018 after having reached 467 kg/ha in 2007 with 68.13% area under *Bt*-cotton. Similarly, data from the Textile Ministry show that yields stagnated at 521 kg/ha from 2008 to 2018 after reaching 554 kg/ha in 2007 with 68.13% area under *Bt*-cotton. Yields in India have been stagnating despite the area being almost saturated with *Bt*-cotton hybrids. Data show that the yields in India had increased to a record 463 kg/ha lint in 2004 with area under public sector non-*Bt* varieties and non-*Bt* hybrids was 94.4%, even before *Bt* cotton became popular with a meagre 5.6% share in India's cotton acreage. Recent estimates of the Cotton Advisory Board (CAB) show that yields were 507 kg/ha in 2017 when the area under private sector *Bt* cotton hybrids was 93.13%. Therefore, the relationship of *Bt*-adoption with yield trends appears spurious.

Interestingly, except India, other *Bt*-cotton adopting countries including China, USA, Brazil, Australia, Mexico and Burkina Faso did not credit *Bt*-cotton with yield enhancement in their countries. *Bt*-cotton is a plant protection technology and not a yield enhancing technology. *Bt*-cotton is only designed to kill only bollworms. It would be wrong to credit an insecticidal technology such as *Bt*-cotton for higher yields. *Bt*-cotton works like an insecticide; the Cry1Ac and Cry2Ab proteins present in the *Bt*-cotton varieties/hybrids in India are specifically toxic only to larvae of leaf eating Lepidopteran insects and are non-toxic to non-Lepidopteran insects such as the sap-sucking insect species such as jassids, aphids, whiteflies, thrips, mealybugs, mirid bugs etc., that damage the crop. Yields of non-*Bt*-cotton and *Bt*-cotton would be the same in the absence of bollworm infestation or if bollworms are controlled effectively with insecticides on non-*Bt*-cotton. Thus, the extent of crop protection benefits due to *Bt*-cotton depend on the levels of bollworm infestation. In the absence of bollworm infestation, cultivation of *Bt*-cotton does not provide any advantages whatsoever.

Data (http://www.aiccip.cicr.org.in/main_aiccip_reports.html) showed that bollworm infestation was either moderate or low over the past 15-16 years and new insecticides were effective in controlling bollworms. *Bt*-cotton is meant to control the two main species of bollworms, namely, the American bollworm, *Helicoverpa armigera* and the pink bollworm, *Pectinophora gossypiella*. *Bt*-cotton in India now controls the American bollworm and the relatively less important spotted bollworm because the pink bollworm has developed resistance to *Bt*-cotton.

New technologies beyond *Bt*-cotton

The seed industry believes that *'even more advanced GM traits'* are imperative to increase yields in India. However, this argument lacks supporting evidence. Firstly, data show that yields stagnated, and insecticide use increased in India after introducing new GM *Bt*-cotton technologies in 2006 and after 2008. It is pertinent to mention here that the introduction of Bollgard-II (Cry1Ac + Cry2Ab) in 2006, followed by the approval of four more new additional *Bt*-cotton events in 2006 and 2008 from four different technology providers, and the approval of more than 3000 new *Bt*-cotton hybrids after 2006, do not seem to have had any additional impact after 2007 on either the yields or reduction in insecticide usage in India. If anything, the data indicate that subsequent to 2007, yields stagnated and there was an unambiguous increase in expenditures on insecticides, seeds and fertiliser quantities applied.

Secondly, there are no GM traits available anywhere in the world that can increase yields or help to increase cotton yields. The two technologies that are being used in other countries and which India doesn't have are the 'three-gene based *Bt*-cotton' and 'herbicide tolerant HT-cotton'. The three-gene based *Bt*-cotton neither kills the '*Bt*-resistant pink bollworms of India' nor any other insects that are not killed by the two-gene *Bt*-cotton. HT cotton only facilitates weed control with herbicide spray. There is no evidence anywhere to show that the introduction of these technologies can help India to increase yields or reduce pesticide usage.

Reasons for low yields and high pestilence

India's cotton crop is characterised by its unique long season (180 to 240 days), low harvest index (0.2 to 0.3) and low ginning out-turn (32% to 34%), which cause low yields. The reasons for higher pestilence and low yields could be linked with the long duration *Bt*-cotton hybrids that are kept longer in the field for multiple pickings and thereby become vulnerable to insect pests, diseases and environmental stress. Hybrid cotton extends for long durations and needs supplemental irrigation. Therefore, hybrids are suitable only for 34% to 40% of cotton area in India, for the irrigated regions, but are being grown in more than 94% of India's cotton area, which resulted in low yields despite increased inputs. Harvest index is the relative proportion of harvested seed-cotton versus the total plant biomass. Indian hybrid cotton crop produces an average of 3 to 4 monopodial (vegetative) branches that produce more of wasteful biomass and are less productive thus resulting in low harvest index. Shedding of reproductive fruiting parts is common in bushy hybrids which also results in low harvest index. A long season also results in poor quality fibre and low ginning% especially in late-formed bolls.

India depends on hybrid cotton for high yields and harvests about 500 kg/ha as national average yield. Hybrids are planted at a low density of 1-3 plants per metre row at 11,000 to 16,000 plants per hectare with an expectation of 40 to 100 bolls per plant which takes a long duration of 180 to 240 days. Indian cotton has a low harvest index of 0.2 to 0.3 and a poor ginning% of 32% to 34%. The long duration leads to a long window of boll-formation that receives monsoon only for a few initial bolls while majority of the bolls that form later starve of water and nutrients thus resulting in poor yields. Long duration also leads to long vulnerability of the crop to drought, insect pests and diseases resulting in high pesticide usage and crop damage.

Countries such as Australia, Brazil, China, Mexico, Turkey and USA depend on open pollinated varieties for high yields and harvest 1000 to 2450 kg/ha as national average yield. Varieties are planted in high density of 8-12 plants per metre row at more than 110,000 plants per hectare with an expectation of 8-12 bolls per plant which takes a short duration of 140 to 160 days. Harvest index is high at 0.4 to 0.5. and ginning% is at 38% to 40%. The short-season crop has a short window of boll formation that captures monsoon and receives water and nutrients for almost all the bolls thereby resulting in good quality bolls and high yields. Short duration escapes most insect pests and diseases resulting in a healthy crop that requires less pesticides.

Hybrids versus Varieties

Many Indian academicians and Indian seed industries believe that hybrid cotton is superior to varieties in providing high yields. The fact is that all the top 16 countries of the world have been using open-pollinated varieties (not hybrids) to harvest 1000 to 2450 kg/ha, compared to India's embarrassingly low yield of 500 kg/ha despite being saturated with hybrid cotton. The usage of fertilisers and water is also less in these countries compared to India. India is the only country that believes in the concept of hybrids for high yields. China, Uzbekistan and Pakistan have plenty of manpower to produce hybrids — but they decided against it. Pakistan grows only open pollinated varieties, not hybrids, but, in the past 5 years at least, harvested 15%-50% more than the comparable adjacent areas in north India which grow only hybrids. The agro-ecology in north India and Pakistan are very similar. Indian seed companies also acknowledge the fact that the right kind of varieties can provide high yields under high density planting but are concerned about IPR being misused by others if they sell varieties.

Getting stuck with hybrid cotton — and a presumption that only biotech-cotton-hybrids can provide answers — will not help India increase its yields any further. If hybrid cotton could provide high yields, Maharashtra's cotton lint yields of 330kg/ha with very high fertiliser use and saturation with *Bt*-cotton-hybrids wouldn't have been less than rainfed sub-Saharan Africa's 350kg/ha, wherein non-*Bt* varieties are grown with negligible fertiliser use and no irrigation. Maharashtra is saturated with the two-gene *Bt*-cotton hybrids and fertiliser use at 273kg/ha is higher than the world average. In contrast, sub-Saharan African countries barely have any technologies such as *Bt*-cotton or hybrids, chemical fertilisers, pesticides, irrigation or improved varieties. In India, though the area under hybrid *Bt*-cotton increased steadily from 38% in 2006 to 95% as of now, the yields didn't increase after 2006. There is ample evidence that hybrids are not suited for the 60% of India's rainfed areas at least. Indian cotton situation could have been different probably if Indian farmers were also presented with a proper choice of *Bt*-varieties suitable for rainfed conditions in addition to *Bt*-hybrids for irrigated regions.

The Challenges

The major challenges for Indian cotton are low yields, yield stagnation, high fertiliser usage, degraded soils, *Bt*-resistant pink bollworms, whiteflies, leaf curl virus, impending threat of *Bt*-resistance in *H. armigera*, increased usage of insecticides and high cost of cultivation. The usage of spurious *Bt*- and HT-seeds presents risks and uncertainties. As mentioned before, *Bt*-hybrids are kept longer in the field for multiple pickings and thereby become vulnerable to insect pests, diseases and environmental stress. Majority of the *Bt*-cotton hybrids are susceptible to sap-sucking insects such as whiteflies, mealybugs, jassids, thrips, mirid bugs and aphids and susceptible to diseases such as cotton leaf curl virus disease, leaf streak virus, *Alternaria* etc., and are serving as hot-spots by supporting pest and disease populations. The cotton leaf curl virus disease and whiteflies are re-emerging as major problems in north India due to the indiscriminate release of susceptible hybrids in the north. Insecticide usage is increasing each year because of sucking pests' developing resistance to imidacloprid and other neonicotinoid insecticides. There is a need to develop sucking pest resistant cultivars. The number of *Bt*-hybrids is huge and confusing. Restricting the number to a few highly productive cultivars can make a positive difference to crop management and yields. Package of practices for each cultivar need to be well defined. Farmers do not follow the 'refuge strategy' of growing 20% area of non-*Bt* cultivars in the vicinity of *Bt*-cotton fields. While the '*Bt*-cotton-resistant' pink bollworms are causing severe economic losses to *Bt*-cotton, the American bollworms are developing resistance to *Bt*-cotton and could soon start causing economic damage, thus leading to unsustainability of the technology.

Biotech cotton helped India fight the American bollworm effectively to protect the crop from damage that also led to about 90.0% reduction in insecticides meant to be used for American bollworm control -and the argument rests there. It would not be appropriate to credit *Bt*-cotton for yield enhancement that may have happened due to improved cutivars, higher usage of fertilisers, irrigation and improved agronomy. The major challenges now for India are low yields, low harvest index (the proportion of harvestable bolls versus the total plant biomass), *Bt*-resistant pink bollworms, insecticide-resistant whiteflies, leaf curl virus, indiscriminate insecticide use and unsustainable fertiliser use. There are no biotech-cotton solutions available anywhere in the world right now that can solve any of these problems. These challenges are interlinked — and are also linked to long duration hybrid cotton. India's cotton duration is the longest in the world, which presents a management nightmare requiring significantly more fertilisers and water. India uses higher levels of 250g of nitrogen (N) fertiliser to produce 1 kg cotton lint, compared to lesser levels of 36 to 152g N per kg lint, used by Australia, Brazil, China, Turkey, South Africa, Mexico and USA that provide 2-4 times higher yields than India.

Strategies to Increase Cotton Yields in India

Is it possible to increase cotton yields in India? Of course, it is possible to enhance the national average cotton yields of India to reach the world average possibly in 4 to 5 years. It is also possible to design a practical roadmap to double farmers' income. However, this requires a paradigm shift in a few recalcitrant concepts that have plagued the country for a long time and have been holding the country back from breaking yield barriers. One of the concepts is that 'hybrids are better than varieties for high yields'. This notion is false because the top-16 high yielding countries all depend on varieties for high yields and obtain 2-5 times higher yields than India. Indeed, hybrids can give high yields with irrigation and high agrochemical inputs, but India hasn't succeeded in getting respectable national average yields despite saturating the country with hybrids. Therefore, this concept needs to be seriously reconsidered. Other notions for high yields include long-duration cotton; increasing the number of bolls per plant; big-statured plants; big bolls; etc. Interestingly, the top-yielding countries such as Australia, Brazil, China, Mexico, Turkey and USA think exactly the reverse of these concepts and have succeeded in retaining their global leadership of high yields. One simple step that can have the greatest impact to enforce a shift in these major intractable concepts is to plan the crop for mechanical picking. This would not only increase yields significantly but also reduce the cost of picking, which constitutes a major share of labour costs. Mechanical picking requires plants with a compact architecture and synchronous boll opening. It needs plants that are machine planted with uniform distribution of 10 plants in a metre row with rows separated at 80cm at least. Machine picking also requires good boll retention and strict canopy management. Because of their vigour, hybrids will be difficult for canopy management, and because of high seed cost would not be suited for high density planting — and thus would be least suited for machine picking.

India needs to move towards open-pollinated varieties at least for the rainfed regions which constitute 65% of the cotton acreage. Yields can only increase with improved varieties, better agronomic management practices and good weather. India needs varieties that are resistant to sucking pests, zero-monopodial, compact architecture, early maturing and indeterminate growth habit suitable for a short-season. Genetics and agronomy should be synchronised to ensure that the short boll formation window fits completely within the monsoon window. This will ensure that the bolls get adequate water and nutrients that can guarantee good boll retention for high yields. Risk mitigation is possible with varieties that are endowed with the capacity to compensate and rejuvenate, just in case the first flush gets negative affected due to biotic or a-biotic stress.

Strategies are proposed here as a set of guidelines to enhance yields through production strategies that are economically viable and ecologically sustainable. These are based on the established best global practices that helped countries to increase their yields. While a few of the global best practices have been validated through on-farm experiments in India, more needs to be done to validate the rest.

The 10 strategies are as follows:

1. **Varieties with zero-monopodia**
   The most crucial factor for high yields in India is a variety with eight main attributes such as short duration (140-160 days), compact architecture with zero-monopodia, early maturation, synchronous boll opening, high harvest index, resistance to sap-sucking insects, high ginning% (>40%) and compensatory growth habit. Attempts were made over the past 10 years to develop such varieties suited for high-density planting in India.

2. **High-density planting systems (HDPS) & 'Short-dense-early' pattern**
   High density is defined by a spacing of 10 cm between plants in a row, with variable row spacing at 38 to 100 cm. All the countries that have yields higher than 1000 kg/ha are known to have been following the high-density approach. Plant density is kept at more than 110,000 plants per hectare. Interception of light is an important factor for high yields. Therefore, compact-architecture varieties are more suited for high density planting. In high density planting, at least 8 plants are kept per meter of row length. Fewer plants than this would produce more bolls on outer positions and delay maturity.

3. **Sub-soiling to break hard-pans**
   Though not taken seriously, degraded soil with a hard-pan is a major problem in many regions in the country. Hard-pan results in poor root penetration and low yields. Land Preparation must be done by **s**ub-soiling at a depth of 40-45 cm to break the hard-pan and sub-soil layer to improve water and root penetration. Avoid compaction due to tillage machinery to retain porosity and soil structure for internal drainage which is a limiting factor in heavy clay soil.

4. **Precision planting**
   Under many conditions, early sowing helps the crop to establish itself and escape several insect pests. Seeds must be planted at uniform spacing of 10-12 cm between plants with precision in drilled or hill drop pattern at a depth of 3-5 cm with precision planters. Row spacing may be kept 60cm or 75cm or 90cm depending on type of variety, soil, water source and weather. This will optimise emergence, save seed and ensure uniform germination. Planting on ridges or raised beds using BBF (broad-bed furrow) planters improves drainage, warms soil and discourages seedling pathogens. North-south oriented row direction could ensure effective penetration of solar radiation to plants in a row especially during squaring, flowering and boll formation. Use systemic pesticides for seed treatment to protect the seed and seedlings from insects, nematodes and pathogens. Plant mapping and scouting for early season pests/symptoms of pest damage improves decision making to ensure higher boll retention.

5. **Water management**
   Cotton is extremely sensitive to excess moisture and water stagnation could reduce yields in heavy textured soils. Drainage of excessive water is crucial for a

good crop. Ridges and furrows enable effective drainage and moisture conservation especially in rain-dependent regions. Wherever irrigation is available, drip irrigation or furrow irrigation may be followed. Ideally adequate amount of water and nutrients should be made available in a precise manner based on the crop requirements during flowering and fruiting period to obtain high yields. Avoid water stress from squaring, flowering and early boll window. Adequate soil moisture during this critical phase helps plants establish the desired structure and helps in the retention of fruiting forms. Do not provide heavy irrigation after the first open boll. Moist soil at first open boll is sufficient to provide adequate moisture required to mature the crop. Excess moisture delays harvest and complicates pest management.

6. **Stale weed-seed bed system**
Weed management in the early stages of seedling growth is very crucial for high yields. Application of contact herbicides three weeks prior to planting enables the preparation of a stale seedbed while ensuring that no green vegetation is left on the field. Application of post-emergence herbicides on young weeds and/or application of pre-emergence herbicides such as pendimethalin 1.0 kg a.i./ha just before sowing helps cotton seedlings to retain their initial vigour in the absence of weed competition. Fields must be kept free of weeds through subsequent interculture and weeding at least for the first 2-3 months of the crop to prevent weed competition.

7. **Conservation tillage, cover crops, crop residue recycling & mulching**
zero-till or strip till systems, deploy cover crops to protect the emerging cotton seedlings. Legume crops such as soybean, cowpea, groundnut, sesbania and sunnhemp or melon and pumpkin are sown in alternate rows of cotton as cover crops. Green manure cover crops such as sesbania or sunnhemp fix atmospheric nitrogen, prevent soil erosion and act as mulches. These crops may be sown 15-20 days after the cotton crop to avoid competition. Green manure crops may be mowed and tilled into the soil after they attain 30-40 days age to act as effective green manure and organic mulch. The use of mulches is negligible in India. Cover crops, green manure crops, organic straw mulch and plastic mulches must be explored in India to conserve soil moisture and to improve plant stand establishment, biomass, lint yield and earliness. In China, plastic mulches are used extensively to cover almost all cotton fields across the country in 3.0 to 4.0 million ha, especially in the arid and semi-arid regions of northern China and coastal saline-alkali areas. Drip irrigation in mechanised plastic mulching and training plant architecture in high density planting played a major role in enhancing yields in majority of the areas in China and in also in some parts of India. In addition, intercropping with legume crops such as red-gram, black-gram, green-gram, cowpea etc., not only fix nitrogen but also encourage establishment of predators and parasitoids of insect pests.

Currently, crop residues are burnt in India resulting in loss of biomass and environmental pollution. Cotton stalks from one hectare when shredded and incorporated back into the soil, provide 20-25 kg nitrogen and 70-80 kg phosphorus per hectare apart from killing diapausing pink bollworms.

8. **Canopy management, square and boll retention**
Plant training practices such as removal of vegetative branches, old leaves, empty branches, early fruiting branches, apical points of vegetative and fruiting branches and removal of growth-tip (topping), are done for canopy management mainly to facilitate nutrients to be redirected to fruiting parts. Plant growth regulators (PGRs) are used for canopy management to prevent excessive vegetative growth and allow adequate transfer of nutrients to bolls. Low rate multiple applications of PGRs are less risky. Under Indian conditions it may be appropriate to resort to topping at 90-100 days and use a PGR such as mepiquat chloride to prevent a bushy lateral growth of fruiting branches. It helps to maintain an open canopy, limits vegetative carbon sink and stimulates the development of bolls on lower branches, instead of inefficient boll set on the upper branches which gets most affected due to moisture stress in the late stages of the crop. However, care must be taken to ensure that PGR application should be done only when the soil moisture and nutrition levels are adequate.

Efforts must be made to retain first 70% to 80% of the position bolls by taking remedial measures based on regular plant monitoring for square and boll retention with reference to nutrient deficiencies, moisture stress, waterlogging, diseases and insect pests to ensure timely interventions of water, fertilisers, crop protection measures and application of plant growth regulators (PGR) if necessary.

9. **Nutrient management**
The cotton crop needs nitrogen levels of 85% during the critical stage of flowering and early boll formation. Soil nutrient status is determined by plant analysis and soil testing to diagnose nutrient deficiency and provide corrective measures to provide a balanced nutrition for the crop. Synchronising nutrient availability with plant nutrient demand at critical stages, saves fertilisers, improves nutrient use efficiency and results in high yields. Application of fertilisers in two or three splits at planting, squaring or flowering stage and after topping helps in providing nutrients when

the plant needs them most. Band placement of fertilisers, especially neem-coated urea ensures controlled release with minimum nutrient loss. Drip-fertigation can be used for precision nutrient delivery. Application of Farmyard Manure (FYM) @ 5 to 10 t/ha or compost after the first rain. Seed treatment with Azotobacter and PSB (phosphate solubilising bacteria) @ 25 g per kg of seed helps in nutrient uptake. Nitrogen should be applied in splits, with full dose of phosphorus and potash at planting or early vegetative phase. Excessive application of nitrogen makes the crop susceptible to insects and diseases, induces rank vegetative growth, results in boll shedding, delays fruiting and crop maturity and reduces lint yield and profit.

10. Pest and disease management

IPM is most effective when oriented with host plant resistance that can be supplemented by naturally occurring biological control. Varieties that are resistant to sap sucking pests provide robust foundation for integrated pest management. Coupled with appropriate seed treatment these varieties can tolerate sap-sucking pests and diseases so that there would not be any need for pesticide applications early in the season. In the absence of disruptive pesticides, naturally occurring biological control gets strengthened and plays a significant role in sustainable pest control. Early planting of short season varieties enables the crop to escape several species of insect pests. Avoidance of excessive nitrogen is crucial for crop health. Other technologies such as inter-crops, trap crops, botanical pesticides, augmented biological control, pheromones and cultural control practices also can assist in effective control of insect pests and pathogens in an eco-friendly and sustainable manner. Choice of insecticides must be based on principles of insect resistance management (IRM) to minimise resistance risk and International Organisation for Biological Control (IOBC) rating for selectivity to beneficial and bio-control insects.

Proof of Concept

Nationwide R&D projects on development of zero-vegetative-branch-short-season-varieties, HDPS and extra-long-staple Desi cotton were initiated in India in 2009. The projects resulted in new varieties and novel agronomic management. The results provided proofs of concepts that India can achieve a break-through in yields through short-season varieties under high density planting coupled with canopy management as is followed in the top cotton producing countries of the world. In the past few years, scientists of CICR and eleven State Agricultural Universities published scientific papers to show that both Desi-cotton and HDPS with non-*Bt* varieties gave significantly higher yields, premium fibre quality and high net-returns under rainfed and irrigated systems. The teams conducted more than 5000 field demonstrations across India on these systems. However, lack of *Bt* in the upland-cotton varieties (not Desi) served as a mental block in adoption.

The solutions to India's cotton challenges are now just around the corner. The Vasantrao Naik Marathwada Krishi Vidyapeeth (VNMKV), Parbhani developed some outstanding long-staple-short-season Desi cotton varieties such as PA08, PA-528, PA-812 and PA-740 recently (Kranthi 2016). Indian institutions and a few seed companies have recently developed a few short-season compact-architecture cotton varieties such as Subiksha (non-*Bt*), SIMA-Shakti-*Bt*, SRI-1-*Bt* and five other varieties from CICR which were developed in 2017. High yields with high density systems have been demonstrated extensively. Hopefully seeds of all these varieties will be demonstrated under high density planting soon to farmers to present an alternative approach to obtain high yields without additional fertilisers or water. These varieties have a high harvest index and can potentially escape pink bollworm infestation due to the short seasonal cycle. There is tremendous hope for Indian cotton to change for the better and double its yields, provided Indian researchers have the will and wherewithal to catalyse the change.

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