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Hybrid Bt cotton is failing in India: cautions for Africa

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Abstract

This paper reviews the ongoing failure of hybrid transgenic Bt (*Bacillus thuringiensis*) cotton unique to India. The underlying cause for this failure is the high cost of hybrid seed that imposes a suboptimal long-season low plant density system that limits yield potential and has associated elevated levels of late-season pests. Indian hybrid Bt cotton production is further complicated by the development of resistance to Bt toxins in the key pest, the native pink bollworm (*Pectinophora gossypiella* Saunders, PBW), resulting in increased insecticide use that induces ecological disruption and outbreaks of highly destructive secondary pests. Rainfed cotton production uncertainty is further exacerbated by the variable monsoon rains. While hybrid cotton produces fertile seed, the resulting plant phenotypes are highly variable preventing farmers from replanting saved seed, forcing them to buy seed yearly (i.e., market capture), and effectively protecting industry Intellectual Property Rights (IPRs). The lessons gained from the ongoing market failure of hybrid Bt cotton in India are of utmost importance to its proposed introduction to Africa where, similar to India, cotton is grown mainly in poor rainfed smallholder family farms, and hence similar private–corporate conflicts of interest will occur. Holistic field agroecological studies and weather-driven mechanistic analyses are suggested to help foresee ecological and economic challenges in cotton production in Africa.

High-density short-season (HD-SS) non-hybrid non-genetically modified irrigated and rainfed cottons are viable alternatives for India that can potentially produce double the yields of the current low-density hybrid system.

Keywords Hybrid cotton, Insecticides, HD-SS cotton, Bt toxin, Economics, Suicides, Secondary pest outbreaks

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Introduction

Cotton production in India is a weather-driven agroecological problem embedded in the economic, political, and social milieu of India. Native diploid "Desi" cottons (*Gossypium arboreum* L. and *G. herbaceum* L.) have been cultivated in India for more than five thousand years, with new world cotton *G. hirsutum* L. introduced in the 1790s to increase production for the industrial revolution in England [1]. Hybrid cotton (primarily *G. hirsutum*) is unique to India, and was first developed in the mid-1950s ostensibly to increase yield and quality through heterosis, with releases of commercial varieties beginning in the 1980s with genetically modified (GM) Bt hybrid cotton introduced beginning in 2002 [2] (see Fig. 1A). In sharp contrast to India, fertile non-hybrid, pure line GM and non-GM cotton varieties are the mainstay globally, with only China cultivating F2 hybrid cottons as a small

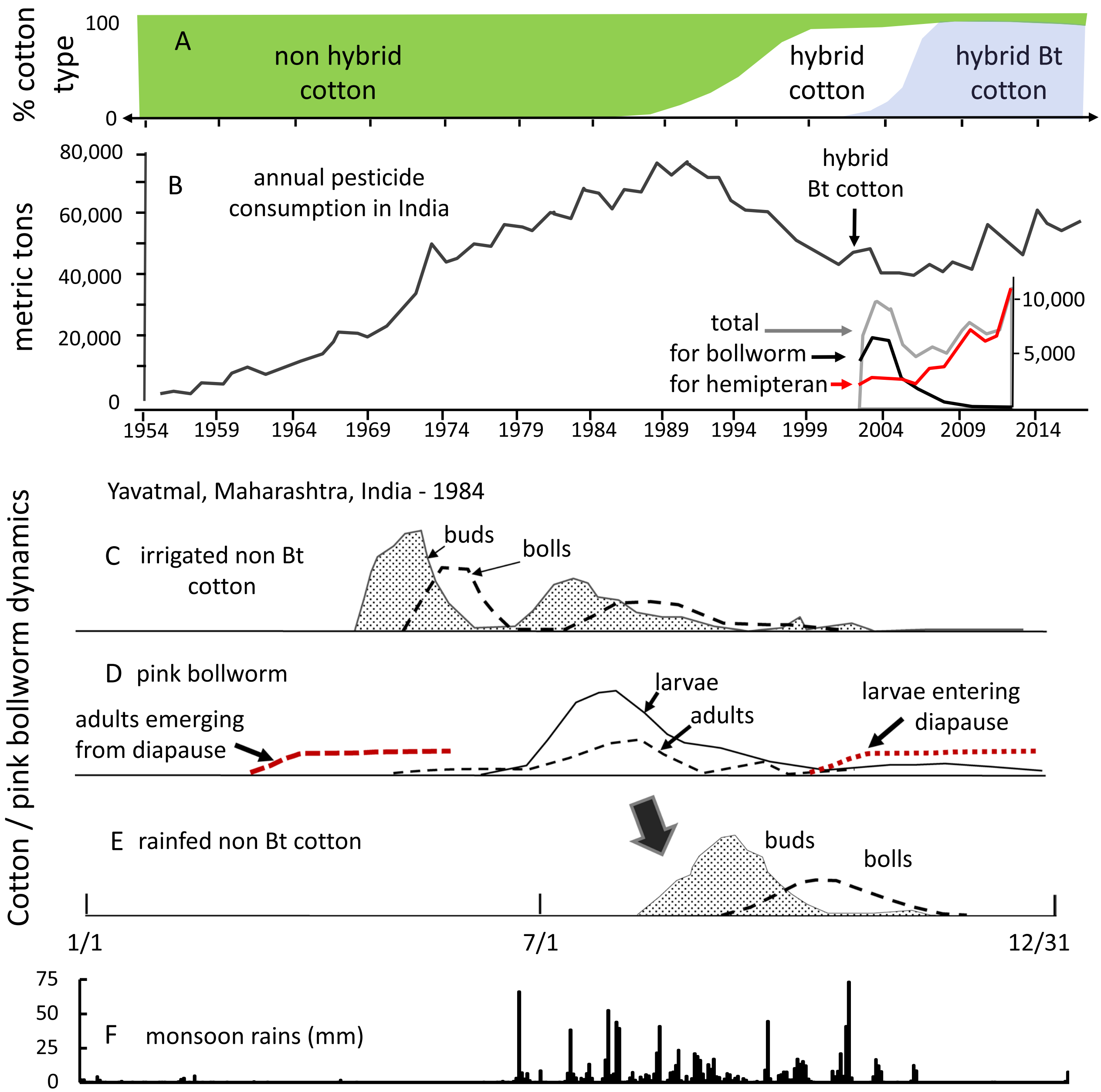

Fig. 1 The Indian cotton system. **A** Changes in the types of cotton grown during 1954–2017, **B** national pesticide use (97% active ingredient) during 1955 to 2017 [8, 9] with the inset in B showing the relative changes in total insecticide applied for bollworm and hemipteran control during 2002 to 2013 [10], **C** the simulated relative dynamics of irrigated non-Bt cottons, **D** relative dynamics of pink bollworm, **E** relative dynamics of rainfed non-Bt cotton with the large bold arrow indicating infestation inoculum from irrigated cotton, and **F** daily precipitation (mm) in 1984. Panels C, D, and E are modified from physiologically based demographic models as driven by daily weather dynamics for the 1984 season (see [3, 4])

proportion of its production. An obvious question is why does hybrid cotton dominate the market in India?

In this overview paper, we analyze the underlying major issues in hybrid Bt cotton production in India that underlie its ongoing failure. Essential background to the agroecological problems of cotton production in India (see [3, 4]) was the accelerating pattern of heavy insecticide use after 1954 (see Fig. 1B). Absent control, the phenology and dynamics of long-season irrigated non-Bt non-hybrid cotton and PBW are illustrated from physiologically based demographic simulations as driven by daily weather data (Fig. 1C and D, respectively), while that of long-season rainfed non-Bt non-hybrid cotton is illustrated in Fig. 1E [3, 4]. A key factor in cotton production is the spring emergence of PBW adults from overwintering diapause (dormant) larvae which is well timed to infest irrigated cotton leading to increasing populations over the season. In contrast, rainfed cotton germinates with mid-summer monsoon rains (Fig. 1E and F) and largely escapes this source of infestation (red dashed line, Fig. 1D). However, PBW infestations in rainfed cotton may also originate from irrigated cotton (large bold arrow, Fig. 1E) engendering insecticide use in both systems that fosters regional outbreaks of secondary pests such as the so-called "American" bollworm (*Helicoverpa armigera* Hübner, ABW) that is more damaging than PBW, and outbreaks of hemipteran whitefly, mealybug, and other secondary pests [3, 4].

To control PBW and insecticide-induced outbreaks of ABW, hybrid Bt cotton was introduced in 2002 engendering a two-decade controversy concerning its economic benefit. Factious debate and critique occurred because prior analyses: (i) were not holistic, (ii) were conducted early in the implementation phase of Bt cotton before resistance in PBW to Bt toxin(s) developed, (iii) disregarded agroecological problems associated with insecticide use in long-season cotton, and (iv) failed to recognize the impact of the high prices and market capture properties of hybrid and hybrid Bt cotton seed that affected agronomic practices, yield, profit, indebtedness, and farmer suicides [3, 4]. Further, prior analyses did not explore why yields in India are among the lowest globally (Fig. 2), or consider more viable alternative high-yielding non-hybrid short-season (SS), high-density (HD) cottons [5] (see Additional file 1).

Herein we analyze the interplay of insecticide use, the hybrid and Bt technologies, and the role of IPRs in the ongoing market failure of hybrid Bt cotton in India, and strongly caution against the proposed introduction of hybrid cotton to Africa [6] where, similar to India, most cotton is rainfed and grown by small farmers, with more than two million poor rural families depending on cotton cultivation [7].

Ecological disruption by insecticides

Worldwide, insecticide use in cotton (and other crops) to control key pests disrupts natural controls (i.e., parasitoids and predators) releasing outbreaks of highly damaging secondary pests normally kept in check at low levels [11]. We note, however, the key pest PBW does not have effective natural enemies in India sufficient to provide economic control, and starting in the mid-1950s chlorinated hydrocarbon insecticides (OCs) were used to control it (see Fig. 1B). As OCs were banned globally, they were increasingly replaced in India by more toxic organophosphate and later classes of insecticides.

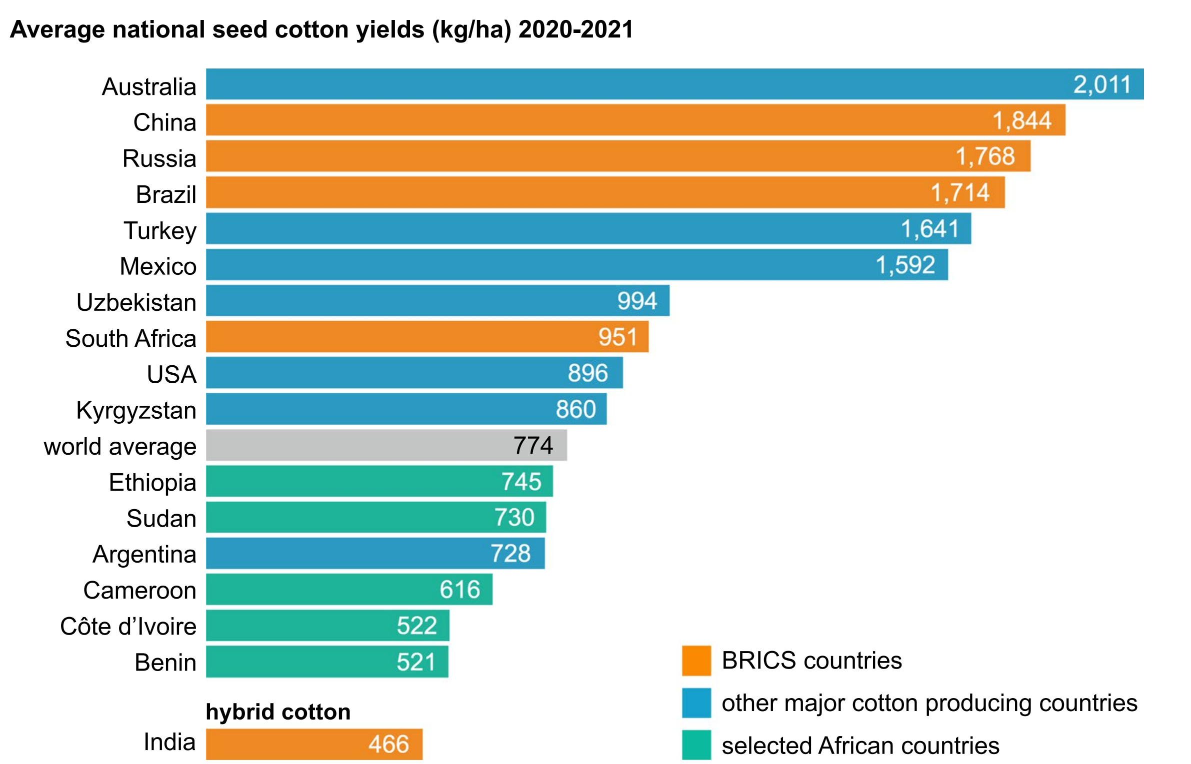

Fig. 2 Average national yields ha^{-1} in the major cotton-producing countries [21]. Modified chart generated using Datawrapper (https://app.datawrapper.de/)

Insecticide use peaked in 1989–1992 (Fig. 1B) [8, 9], and then declined as more toxic insecticides requiring lower dosages were introduced, and when insecticide subsidies were abolished [12]. 36–50% of insecticides in India were applied to cotton [9], and predictably, outbreaks of highly damaging ABW and hemipteran pests followed [3, 4]. To control PBW and insecticide-induced ABW outbreaks, hybrid Bt cotton was introduced beginning in 2002, and because of its initial effectiveness in controlling both pests, rapid adoption occurred (Fig. 1A) resulting in a further decline in insecticide use that reached a nadir during 2006–2008 (Fig. 1B).

Hybrid Bt cotton and insecticide use

Agricultural economists began to study the benefits of hybrid Bt cotton in India early in the implementation phase before the development of resistance to Bt toxins in PBW in 2008. Resistance increased quickly in PBW [13] because the recommended refuges of non-Bt cotton designed to conserve susceptibility were not widely implemented due to small farm size [12–15]. As a result, insecticide use to control resistant PBW increased, and by 2012 when hybrid Bt cotton adoption was > 90%, insecticide use surpassed pre-Bt 2002 levels (Fig. 1B), but now targeted induced hemipteran pests (e.g., whiteflies, jassids, mealybugs) that are unaffected by Bt toxin(s) [13] (see inset Fig. 1B). Hence, despite early projections based on industry data positing an ~ 80% increase in yield [16], the hybrid Bt cotton technology in India began to unravel.

The data from India indicate the benefits from hybrid Bt cotton were limited to the early years of adoption and were geographically variable with meager benefits documented after 2008 in the major cotton-producing regions of India. In 2020, Kranthi & Stone [17] graphically summarized eighteen years of national and state data on hybrid Bt cotton in India, and concluded the meager yield increases were due to increased use of fertilizer, with Bt permitting a temporary decline in insecticide use. In response to Kranthi & Stone [17], agricultural economist Qaim [18] based on 2002–2004 and 2006–2008 panel data from > 500 farms, asserted that … "Bt cotton has increased yields through better pest control …", though not included in the analysis were stagnating yields, increasing Bt resistance in PBW and the associated post-2008 increases in insecticide use and outbreaks of hemipteran pests. Also in response, Plewis [19] based on an analysis of hybrid Bt cotton and insecticide use on farmer profits and yield in the northern states of Haryana, Punjab, and Rajasthan, surmised "…the widely held (and evidence-based) belief [is] that Bt … cotton has benefited Indian farmers", but recognized the benefits were not evenly distributed across India with positive effects only in Rajasthan. Analysis of 1999–2014 statewide Indian Ministry of Agriculture data [10, 20] from Andhra Pradesh, Gujarat, Karnataka, Maharashtra, and Madhya Pradesh in central and southern India where most cotton is rainfed showed average yields increased with kg fertilizer ha^{-1}, percent of irrigated land, and average June–December monsoon rainfall, and though not significant, yields decreased with kg insecticide ha^{-1} [3]. Furthermore, adjusted farmer suicides corrected for area of cotton cultivation across the states were negatively correlated with yield and net revenues [3].

Global cotton yields

A key question ignored in prior analyses [3, 4, 16–18] is why average national seed cotton yields (kg ha^{-1}) in India based on > 90% hybrids are among the lowest globally (Fig. 2, [21]). Although India is the second largest producer of cotton with ~ 40% of the global cultivated area, average 2020/2021 national yield ha^{-1} was far below the global average, and below those of other economically aligned BRICS nations and of some African countries having far less developed scientific infrastructure. N.B. 67% of Indian cotton is rainfed [22].

While the total national production is impressive, the economic impact of low yields on farmers is a better metric of the failure of Bt hybrid cotton in India. For example, in the major cotton-growing state of Maharashtra where ~ 67% of cotton is rainfed, average state yield plateaued at ~ 320 kg ha^{-1} after 2007 when hybrid Bt cotton adoption was > 80% and input costs ranged from 24 to 30% of revenues with labor averaging ~ 58% of the total input costs, fertilizer ~ 22%, insecticides ~ 6.7%, and seed costs ~ 13.7% [10]. Assuming parallel increases in prices and costs over time and a high 2022 price of \$2.60 kg^{-1} of cotton, the average net annual income from cotton corrected for average input costs is ~ \$832 × 0.73 = \$607 ha^{-1}, or ~ \$1.66 per day. In India, > 80% of the millions of cotton farms are < 1.5 hectares, with the poorest 50% averaging 0.28 hectares [23] yielding an average income from cotton of ~ \$0.47 per day, or 4.57 times lower than the 2022 individual extreme poverty threshold of \$2.15 per day [24].

The role of intellectual property rights (IPRs) in hybrid Bt cotton market failure

In developed countries, large farms are the norm, and IPRs enforcement against replanting of fertile pure-line transgenic seed is by legal means. However, in India, the millions of small farms make legal recourse impractical. Conveniently, the hybrid technology provides mechanisms for both value capture and IPR protection because although seed from hybrid cotton is fertile, the resulting plant phenotypes are highly variable, discouraging seed saving for replanting [3]. Inured to unavailability of agricultural extension advice, widescale input industry marketing, and the observed high early efficacy of the Bt constructs against ABW and PBW, farmers rapidly adopted hybrid Bt seed despite its high price. In 2020, the price of hybrid Bt seed was ~ \$31.50 ha^{-1} at the recommended low planting density of ~ 20,000 plants ha^{-1} [21]. (N.B. Hybrid and Bt hybrid cotton are approximately the same price [21].) Comparatively, the same quantity of pure-line Bt and herbicide-tolerant seed in the USA is ~ \$26–36 ha^{-1}. Market capture in India was reinforced by the decreasing availability of non-Bt non-hybrid pure line seed that costs ~ \$7–8 ha^{-1} at the recommended seeding rate (Fig. 1A).

Globally, field trials to determine the optimal planting density for cotton varieties are standard practice, and higher planting densities are the norm in most countries. In India, the recommended low plant density system requires a long season to maximize the density-related potential yield, has associated increased levels of late-season pests and associated control costs, and is sub-optimal for yield [3]. So why are low planting densities recommended in India and are there better alternatives?

Alternatives and prices

High-density (HD, say > 150,000 plants ha^{-1}) short-season (SS) pure-line non-hybrid, non-Bt rainfed *G. hirsutum* varieties and native Desi varieties have been developed in India by the Central Institute for Cotton Research (CICR), Nagpur, Maharashtra (and elsewhere) that can potentially produce more than double the yield compared to the current low-density hybrid Bt rainfed cotton system [5] (see Additional file 1). Although the 7.5-fold higher seeding rate for non-hybrid HD-SS cotton would increase seed costs to ~ \$56 ha^{-1} (i.e., \$7.5 × 7.5), this would be offset by higher yields, avoidance of spring PBW infestations (Fig. 1C vs. 1E), reduced buildup of late-season pests (i.e., PBW, ABW, and others), lower pest control costs and pest damage, synchronized maturity for harvesting, seed saving for replanting, increased profit [3], and the facilitation of organic production [25]. Of course, high-yielding hybrid HD-SS Bt varieties have also been developed [26], but at current hybrid seed prices, the 7.5-fold seeding rates would cost ~ \$236 ha^{-1} (i.e., \$31.50 × 7.5) without commensurate increases in yield, and the hybrid technology would prevent seed saving for replanting. Due to its pest avoidance properties, the wide-scale planting of non-hybrid HD-SS rainfed cotton (Fig. 1E) would render the Bt technology largely irrelevant as demonstrated in irrigated desert cotton in California where HD-SS pure-line non-hybrid varieties combined with early harvesting and plowing disrupted overwintering in PBW, saving the cotton industry from the ravages of this invasive pest (see [27, 28] and Additional file 1).

Moreover, rainfed HD-SS varieties are better suited agronomically to the limited period of monsoon rains, ameliorating but not eliminating the *gamble of the monsoon* on yield [3]. Currently, many rainfed cotton farmers assume additional debt to develop tube wells for irrigation for long-season cotton and to augment uncertain monsoon rains, only to rapidly deplete groundwater levels below well depth, exacerbating indebtedness and bankruptcy [3, 29]. This practice also forecloses future uses for the groundwater under ongoing climate change on a wide geographic scale [30].

Discussion

Pure-line HD-SS cottons were not widely promoted in India [26] due to apparent commercial and government agency artifice [3]. The decades-long, perplexing—and globally unique—concentration on hybrid cotton by India's agricultural research system in the face of persisting low average national yield can better be understood using the critical framework outlined by Raina ([31], page 278; also see history in Raina [32]): "Patronage or decision-making in the ICAR [Indian Council on Agricultural Research] is, for the most part, vested in bureaucratic nodes, marking the dichotomy in the organization between scientific and administrative or financial decision-making. … The nodes in the ICAR rely on bureaucratic decision-making not validated by evaluations or assessments using scientific expertise. It is argued that stringent evaluation can replace bureaucratic authority with scientific expertise and authority, thereby bringing more accountability to the system of patronage of science."

The dominant time-place limited econometric analysis paradigm attempted to provide scientific expertise but overlooked alternatives to the hybrid Bt cotton technology (e.g., [16, 18, 19]), overvalued panel data on current production practices used to estimate factors contributing to yield and profit, and lacked well defined agro-ecological background on ecological disruption and agronomic factors. Agricultural economists failed to recognize the inherent obsolescence of the Bt construct under Indian conditions as resistance to Bt toxins quickly evolved in PBW increasing costs, economic distress and systematic dispossession of resource-poor households, and appropriation of their meager resources by other economic actors (see [15]). Econometric research narrowly focused on the benefits of the Bt cotton technology proved a *red herring* cloaking the root agronomic problem: the system limiting effects of high hybrid seed costs. Moreover, ecologically based mechanistic analyses of interacting time-varying system components (i.e., system modeling) were dismissed. As a result, Indian farmers became trapped on pesticide (cf. [11]) and biotechnology [3, 4] treadmills as they sought to solve agronomic and insecticide-induced pest problems using an inappropriate hybrid Bt cotton technology, the costs of which imposed suboptimal planting densities resulting in low stagnating yields, increased indebtedness, and foreclosures with thousands of farmers seeking relief in suicide [3, 4]. Indian cotton farmers have been paying a premium for a hybrid technology that is a value-capture mechanism protecting seed industry IPRs and profits—the economic plight of poor farmers appears to have been viewed as collateral damage. Hence, simply because econometric analyses of time and place-specific panel data on current production practices suggest positive gains, they may not yield the best solution(s) for farmers. Agricultural economists should heed Nobel Laureate Friedrich von Hayek's admonition in his 1974 Nobel Prize in Economics address titled *The Pretense of Knowledge*: "…We have indeed … little cause for pride: as a profession we have made a mess of things" [33].

Currently, based on the claimed grand success of hybrid Bt cotton (see [34]), development of hybrid GM crops is ongoing in India which is a major center of biodiversity of Desi cottons, mustard, and brinjal. Transgene introgression to landraces of these species could occur as found by Quist and Chapela [35] in maize landraces in Mexico; findings that triggered aggressive backlash from the seed industry, and academic and government supporters leading to the journal Nature withdrawing support for the article. However, transgene introgressions to wild and landraces (and weedy species) are now well documented [36], and in Mesoamerica, 35% of 224 wild relatives of important crops such as maize, common bean, cotton, potato, squash, and others risk extinction under global change – a risk factor is transgene introgression [37]. Introgressions of transgene for cry (Bt) and cp4-epsps (tolerance to the herbicide glyphosate) have been found in native wild *G. hirsutum* cotton in Mexico, with the cp4-epsps introgression in wild plants altering their extrafloral nectar inducibility and their symbiotic association with ant species resulting in increased herbivore damage [38]. Herbicide-tolerant Bt (HT-Bt) hybrid cottons are under development in India with illegal planting occurring [39]. The widescale adoption of the HT technology in India would add other layers of ecological complexity and costs and affect the environment and human health.

Klátyik et al. [40] reviewed the available 2010 to 2023 literature on terrestrial ecotoxicity and concluded that the high use of glyphosate-based herbicides (GBHs) has had unintended side effects on many terrestrial organisms and their ecosystems, and cannot be considered ecologically sustainable. Furthermore, in the USA, non-Hodgkin's lymphomas are reported linked to GBHs, with legal settlement costs to industry of $10 billion [41]. In 2017, world eminent toxicologist John E. Casida [42] cautioned: "The classification of glyphosate, malathion, and diazinon as probable human carcinogens leads to the need for replacements."

In sum, before hybrid (Bt and HT) cotton is introduced to Africa (e.g., [6]), holistic agroecological (e.g., [43, 44]) and weather-driven mechanistic model analyses should be conducted to identify and fill important information gaps, and to provide insights about alternatives (e.g., [5]). Such analyses would serve as a basis for sound econometric analyses of a well-defined problem (cf. [45]) required to inform the development of sound agricultural policy, and to better estimate and make widely known the benefits and risks for African farmers of hybrid GM cotton. Heeding von Hayek's admonition, we sought to deconstruct the underpinning agroecology of the tragedy of hybrid and GM technology applications in Indian cotton. As technology analyst Vaclav Smil [46] asserts, not all innovations produce desirable outcomes, and some produce effects contrary to the best interests of society—hybrid HT-Bt cotton in India should be added to this list, and we caution against its uncritical introduction to Africa.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12302-023-00804-6.

Additional file 1. Supplementary Information: High-density short-season cotton is not a new technology.

Acknowledgements

We dedicate this paper to the memory and environmental ethics of entomologist Professor Robert van den Bosch on the 100th anniversary of his birth (31 March 1922) and premature death on 19 November 1978. His clarion call that we must all continue to fight abominations against humanity and nature is even more relevant today. If not, Albert Schweitzer's opening quote in Rachael Carson's *Silent Spring* (1962) [47] will come true: *"Man has lost the capacity to foresee and to forestall. He will end by destroying the earth"*. And in Robert van den Bosch's (1978) [11] final epilogue words: "… *and as a final bit of irony, it will be insects that polish the bones of the very last of us to fall"*. Special thanks are due to reviewers for adding clarity to our arguments. The International Cotton Advisory Committee, Washington DC, USA provided 2021 national yield data, and Mrs. Aruna Rodrigues, Sunray Harvesters, India, motivated our analysis.

Author contributions

All authors contributed equally.

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Availability of data and materials

The cotton data for the Indian states of Andhra Pradesh, Gujarat, Karnataka, Maharashtra, and Madhya Pradesh for years 1999–2014 [3] used in the current study are available open access on Zenodo at https://doi.org/10.5281/zenodo.8325340.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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