# Supplementary Material:

# Deconstructing Indian Cotton: Weather, Yields and Suicides

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**Author notes:** APG and LP designed and did the analysis, and all authors contributed to writing the paper.

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## History of Bt cotton in India

Native diploid Desi cottons (varieties of *Gossypium arboreum* L. and *Gossypium herbaceum* L) have been grown in India for more than 5000 years without synthetic inputs (i.e., functionally whether or not certified *organically*) [1]. Although cotton was domesticated as well in Africa and America, for all but the past 180 years India has been the center of world cotton innovation both in agricultural practices and in textile manufacturing technologies. The rest of the world, from China and Japan to Africa, Middle East, Europe and Americas sought to imitate the productivity and quality of India's cotton cloth, and was inspired by Indian cotton production techniques. India was the largest cotton-producing political entity. The millions of small scale farmers over millennia were under pressure to produce for home consumption, central government taxes, and to have the equivalent of a bank account; cotton cloth that could be stored and sold when households needed cash. Cotton was the target of innovation, selection and adaptation by farmers. Their efforts adapted cotton production systems, and altered the ecological niches of all the other species – crop-associated agrobiodiversity – found in cotton fields and nearby. This altered the evolutionary selection pressures on these communities of species, which then co-evolved under the influence of the goals of the human managers of cotton [2].

Agronomic changes have altered the ecology and economics of cotton production as it became the raw material for the world's largest manufacturing industry – cotton textiles – for the first half of the Industrial Revolution. This tied small scale cotton farmers in India to a global ecological system with cosmopolitan pests and a global economic system where the price farmers receive is determined by production and policies negotiated in other countries and dominated by industrial sectors linked through textiles. Many farmers abandoned farming to become textile factory workers [1], but the ones left on the farm faced higher stakes and risks, usually with information asymmetry maintained by weak connectivity, poor or biased sources of information, little exposure to scientific concepts shared by others in the global cotton system, and over-burdened extension systems that cannot well interpret the claims of local inputs dealers. This is the historical perspective for our analysis of cotton in India.

## Econometric analyses of cotton production in India

> *Politically, anti-transgenic NGOs have interests in failure of Bt technology, precisely the inverse of farmers' interests in getting the agro-economics right. Could there be intentional deception in field studies, or less egregious cherry-picking of respondents? The answer is clearly yes...*
>
> Herring (2008) (see also Herring 2012) [3,4]

Numerous economic studies worldwide have found high benefits for Bt cotton (e.g., [5]). Technology oriented economic analyses based on survey data disregard underlying agro-ecological principles of yield formation and interactions with the social environment and produce statistical relationships of little help in the evaluation of multiple causes and effects in complex agricultural systems (e.g. [6]). In particular, econometric analyses tell us nothing about the origins of the problem being evaluated, or alternatives to the current production system and, most important, provide little insight into what is firstly a biological problem with economics superimposed. These studies do not question whether the technology was needed in the first place. Some economic studies of Bt cotton adoption in India were based on inappropriate trial plot data that biased the results [7-9], did not control for important inputs such as fertilizer and water [10] [10], used industry data to predict unrealistic estimates of yield gains [11], and ignored important agronomic aspects of the systems (e.g., irrigated vs. rainfed, density considerations, varieties, pest dynamics) and the effects of weather. For example, historically, pink bollworm was the key pest in long season irrigated cotton, and after the introduction of insecticides in the 1970s, ecological disruption occurred that induced outbreaks of formerly minor secondary pests, namely bollworms and hemipteran pests. This scenario has occurred in other areas of the world (see text). The inescapable fact is that Bt cotton was introduced to India to solve an insecticide induced bollworm problem. Economist using field studies fail to comprehend this root issue.

For example, Bennett et al. [12] analyzed commercial field data from Maharashtra during 2002 and 2003 where farmers grew both Bt and conventional cotton varieties. They found that average yields were 45% higher in Bt fields in 2002 and 63% in 2003. Glover [13] examined the evidence base for Bennett et al. and related papers (e.g., [14-16]), and found the performance and impact highly variable, socio-economically differentiated and contingent on a range of agronomic, socio-economic and institutional factors, and further questioned the assumptions and interpretations. Glover [13] found a high degree of variation in productivity and profits in both *Bt* cotton and conventional cotton that could have other social and economic explanations, and further the studies had a ‘placement bias’ of irrigation and ‘good growing conditions’ for producing long season cotton.

A comparison of Bt and non-Bt farms in three major cotton growing districts in Karnataka state during 2005 and 2006 [17] showed that yield-contributing factors were significantly different between the two groups; that the influence of pesticide inputs on yields was positive in Bt farms but negative or non-significant in non-Bt farms; that only 5% of the 16% yield gain was attributable to the Bt technology itself whereas the contribution of all other inputs was negative, and that farm structural differences between the two groups overwhelmingly determined yield differences. Adding the insights gained from our study, Bennett et al. [12], Hugar et al. [17] and others did not measure the economic benefits of Bt cotton, but rather the benefit relative to the failed insecticide technology which induces more pests in insecticide treated cotton relative to Bt cotton. Furthermore, studies conducted in ecologically disturbed environments are known to bias the results against untreated checks [18]. They did not ask whether the Bt technology was useful in the first place!

In contrast, Pemsl et al. [19] critiqued mainstay econometric methods as being situation dependent, provide assessment of the static productivity of pest control agents (and other inputs), are less suitable for capturing the interaction between control decisions and dynamic ecosystem reactions, and reflect the influence of institutional settings and the context in which the data were collected. Under ecological disruption in China, Pemsl et al. [20] found that productivity effects of Bt varieties and pesticide use depended on the action of natural control agents, and that the profitability of damage control measures increased with the severity of ecosystem disruption. The findings raised doubt as to whether the high benefits of Bt cotton varieties claimed by previous studies based on cross sectional comparisons are realistic.

The panel data studies have been extended to other areas of the problem. For example, Qaim [5] used panel data to argue that Bt cotton adoption enhanced farmer nutrition, but the analysis did not look at changes in nutrition over time for adopters and non-adopters; did not check if the adopters were better off at the start failing to check for self-selection and endogeneity; the impact pathway was unsound; the definition of food insecurity as calorie consumption and not the change was inappropriate; the use of year 2008 as a dummy variable is suspect; if all non-adopters had adopted Bt cotton, 16% of the farmers would still be food insecure (Table 5 in Qaim [5]); and average farm size > 5ha in the study is not small by Indian standards. In Andhra Pradesh and Maharashtra, more that 80% of cotton farms are less than 2ha with 75 and 53% respectively being <1ha [21,22]. In Gujarat, 43% of the farms are <1ha.

In our study we used biological models of the cotton/pink bollworm system to examine irrigated and rainfed cotton in finer detail finding conflict between the two systems as PBW from irrigated fields infest rainfed cotton potentially causing large infestations in both systems. Below we outline the biological and mathematical details of the model used in our analysis, and the rationale for restricting the study to cotton and pink bollworm in India.

## A WEATHER DRIVEN MODELS OF COTTON AND ITS PESTS USED IN THE STUDY

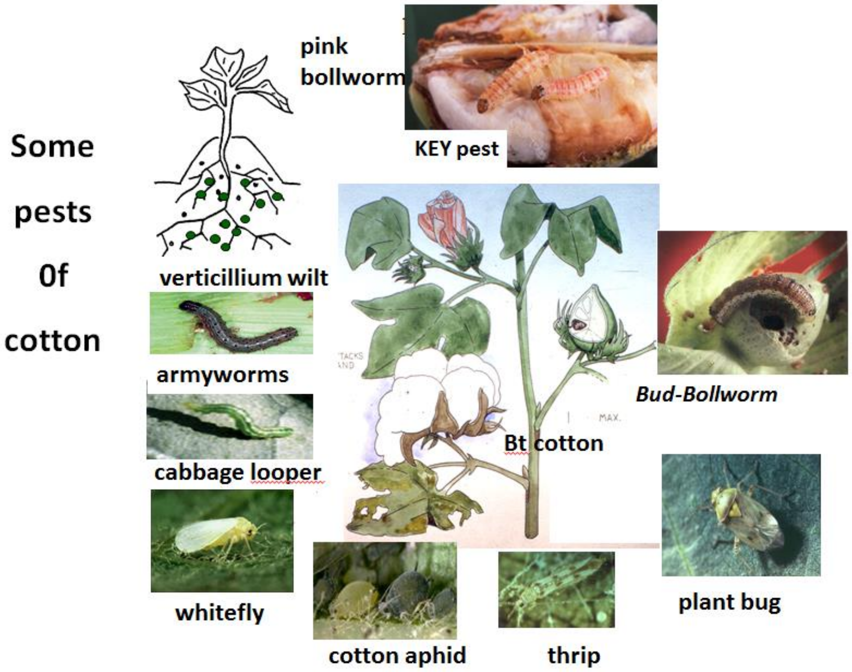


**Figure S1.** A typical array of cotton pests in North America with ecological homologues in other areas. Pink bollworm is a common stenophagous key pest of cotton pest in frost free areas worldwide, with the other species being polyphagous secondary pests easily induced by insecticide use.

**Biology** - Cotton worldwide is attacked by similar complexes of herbivorous ecological homologues (e.g., California; Fig. S1a). In India (as in southern California and Egypt) the key pest of cotton is the cosmopolitan stenophagous semi-tropical pink bollworm (*Pectinophora gossypiella* Saunders (hereafter PBW)); while many of the other species are secondary pests that may be induced to damaging levels by ecological disruption (see below). In India these species historically include generalist such as jassids (*Amrasca biguttula* Ishida), spotted bollworm (*Earias vitella* Fabricius) and defoliators such as *Spodoptera litura* (Fabricius). The bollworm (*Helicoverpa armigera* (Hübner), whitefly (*Bemisia tabaci* (Gennadius)), mites and other species were uncommon in cotton prior to the introduction of insecticides (see text). Of the induced pests, bollworm is by far the most destructive though many of the other species can cause significant crop loss under ecological disruption. Our focus for India before the introduction of insecticides is on pink bollworm for reasons outlined above and in the text.

The linkage of the dry matter dynamics of cotton and pink bollworm are illustrated in fig. S2a. Note the effects of diapause induction as a function of temperature and photoperiod on pink bollworm dynamics allows the pest to bridge seasons. In contrast to other pests, pink bollworm attacks the standing crop and does not affect cotton growth dynamics.

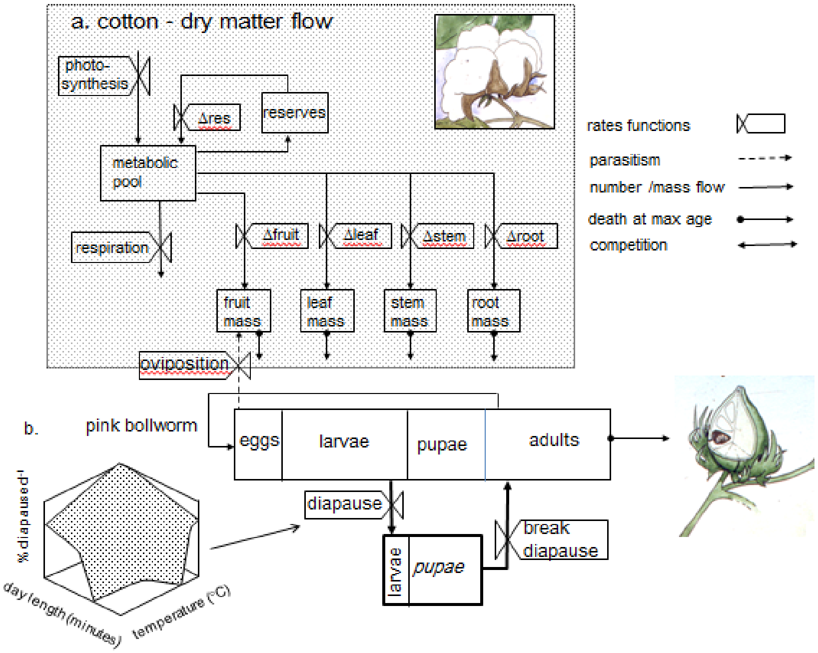


**Figure S2a.** Dry matter flow dynamics in a linked cotton-PBW system: (a) energy flow within cotton and to pink bollworm, and (b) the diapause model for pink bollworm (see text) [25,26]. The mathematics of the models has been reviewed in considerable detail in [24,27] (see below).

**The model –**

A plant-herbivore (and higher tropic levels) model may be viewed as *ns* {*n* = 1, ns} linked *functional* age/mass structured population models [24]. The plant is a canopy model consisting of five linked demographic models: mass of leaves {*n* = 1}, stem {2} and root {3}, and for fruit mass and numbers {4, 5}. These models {1-5} are linked by photosynthate production and allocation with the ratio of production to demand controlling all vital rates. The age structured number dynamics of herbivore are modeled using a similar model {6} linked to the model of the plant sub unit they attack. In the case of PBW {4, 5}, it uses cotton bud and maturing fruit as hosts for its progeny.

Each *functional* populations, be it plants or sub units or herbivores/natural enemies may be modeled using a time-invariant distributed-maturation time age-structure model (eqn. A1; see [28-30] for related model forms). We use the notation of DiCola et al. ([30], p. 523-524) to describe the Manetsch [28] distributed maturation time model used in our analysis. This model is characterized by the assumption

$$v_i(t) = v(t) = \frac{k}{del(t)}\Delta a \qquad i=0,1,\ \ldots,k \tag{A1.1}$$

where *k* is the number of age intervals, *del(t)* is the expected developmental time, and $\Delta a$ is an increment in age. From (A1.1) we obtain

$$\frac{dN_i}{dt} = \frac{k}{del(t)}[N_{i-1}(t) - N_i(t)] - \mu_i(t)N_i(t) \tag{A1.2}$$

where $N_i$ is the density in the *i*th cohort and $\mu_i(t)$ is the proportional net loss rate. In terms of flux $r_i(t) = N_i(t)v_i(t)$, yields

$$\frac{d}{dt}\left[\frac{del(t)}{k}r_i(t)\right] = r_{i-1}(t) - r_i(t)] - \frac{del(t)}{k}\mu_i(t)r_i(t). \tag{A1.3}$$

The model is implemented in discrete form (see [31]).

Aging occurs via flow rates $r_{i-1}(t)$ from $N_{i-1}$ to $N_i$, births enter the first age class of the population, deaths at maximum age exit the last or $k^{\text{th}}$ age class, and net age-specific proportional mortality (losses and gains) from all factors is included in $-\infty < \mu_i(t) < +\infty$. The mean developmental time of a population is *v* with variance *V* with the age width of an age class being *v/k* and $k = v^2/V$. The number of individuals (or mass units) in age class *i* is $N_i(t) = {}^{r_i(t)v}\!/_{k}$ , and that in the total population is $N(t)=\sum_{i=1}^{k} N_i(t)=\frac{v(t)}{k}\sum_{i=1}^{k} r_i(t)$. If $k$ is small, the variability of developmental times is large and *vice-versa*. A value of $k$ =45 was chosen to produce a roughly normal distribution of developmental times.

The developmental time of herbivore larvae varies with fruit host age, and both the host and the larvae age on their own temperature-time scale (see below). Hence larvae initially infesting specific age fruits at time *t* will in the course of their development experience changing host characteristics that affect their developmental times, mortality and potential fecundity as an adult. To handle this biology, a two-dimensional time-invariant distributed maturation time model with flows in the fruit age and age of pest dimensions is utilized (eqn. A2).

$$\frac{dN_{i,j}}{dt}=\frac{k}{del(t)}[N_{i-1,j-1}(t)-N_{i,j}(t)]-\mu_{i,j}(t)N_{i,j}(t) \qquad \text{(A2)}$$

The mean developmental rate of a cohort of larvae (*v(t,i,j)*) is transient and depends on host fruit age. Hence, if *i* is larval age and *j* is its host fruit age, the model is updated for flow first in the $i^{th}$ and then the $j^{th}$ dimension taking care to correct for differences in developmental time scales between cells. For convenience, the net proportional mortality term $\mu_{nij}(t)N_{i,j}$ is applied in the $i^{th}$ dimension and assumed zero in the $j^{th}$ dimension. This scheme also allows mortality to herbivore eggs and larvae due to fruit subunit shedding to be applied to larvae in each *i,j* cohort. The number density of the population is computed as follows:

$$N(t)=\sum_{j=1}^{k}\sum_{i=1}^{k} N_{nij}(t)=\sum_{j=1}^{k}\frac{v(t,j)}{k}\sum_{i=1}^{k} r_{nij}(t)\,. \qquad \text{(A3)}$$

**Physiological time and age -** The plant and pests are poikilotherms, and hence time and age in the model are in physiological time units (e.g., degree-days or proportional development on temperature). Both linear and non-linear models are commonly used model temperature dependent development. For example, the linear degree-day model (A4) is often to model the temperature (*T*) dependent development rate ( $\Delta v\big(t(T)\big)$, usually because sufficient data across the full range of temperatures are unavailable.

$$\Delta v\big(t(T)\big)=\frac{1}{v\big(t(T)\big)}=c_1+c_2T(t) \qquad \text{(A4.1)}$$

Constants $c_1$ and $c_2$ are fitted to species data. The lower developmental temperature threshold for the plant and the herbivore (and higher trophic levels) may differ and be computed at

$\Delta v\big(t(T)\big)=0$. A time step in each model is a day of varying physiological time (degree days $d^{-1}$ = $\Delta dd$) computed above appropriate threshold using the half sine method [32]. A non-linear model might be that of Lactin et al. [33] or others.

$$\Delta v\big(t(T)\big)=\frac{1}{v\big(t(T)\big)}=\psi\{\exp(\rho T-\exp(\rho T_{\max}(T_{\max}-T)/c\} \qquad \text{(A4.2)}$$

where $\psi$, $\rho$, $T_{max}$ and $c$ are fitted parameters where $\psi$ is the y intercept and $T_{max}$ is the supra-optimal temperature where $\Delta v(T) = \psi$.

**Modeling mass growth**

The mass dynamics of a species be it plant or animal may also be followed with the acquisition and allocation computed as follows.

**Growth rates -** As rates, per capita resource acquisition (*S(u)*) is allocated in priority order to egestion ($\beta$) respiration (i.e., $Q_{10}$), costs of conversion ($\lambda$) and to reproductive and growth rates (*GR*).

$$GR(t)=\phi^*(t)(S(u)\beta-Q_{10})\lambda \qquad \text{(A5.1)}$$

The realized *GR* must also include the effects of other limiting factors. This is done using the scalar ($\phi$*) that is the product of the daily supply-demand ratios for the other essential resources (see below). Resource acquisition *S(u)*) involves search and depends on the organism’s maximum assimilative capacity (i.e., its demand, $D(u)$). This quantity may be estimated experimentally under conditions of non-limiting resource.

$$D(u)\approx S(U)=(GR_{\max}(t)/\lambda+Q_{10})/\beta. \qquad \text{(A5.2)}$$

**Resource acquisition (*S(U)*) -** Plants capture light, water and inorganic nutrients and herbivore larvae attack plant subunits (e.g., fruit). The biology of resource acquisition by a population of plant or animal consumers (*N(t)*) involves search under conditions of time varying resource (*R(t)*). The maximal population demand is *D=D(u)N*. Resource acquisition (*S*) is modeled using the ratio-dependent Gutierrez and Baumgärtner [34] functional response model (eqn. A6, see [35]) that is a special case of Watt’s model [36] because it includes eqn. A5.2 (see [31], p. 81 for the derivation of this model). We simplify the notation as follows.

$$S=Dh(u)=D\left[1-\exp\left(\frac{-\alpha R}{D}\right)\right]. \qquad \text{(A6)}$$

*h(u)* is the proportion of the resource demand (*D*, eqn. A5.2 ) that is obtained and $\alpha$ is the search parameter. $\alpha$ may be a convex function of *N* making (A6) a type III functional response (i.e., $\alpha = 1 - \exp(-sN)$ with search constant *s*. As a function of *N*, $\alpha$ for plants becomes Beer's Law and for animals it is the classic Nicholson-Bailey model. Note that intra-specific competition enters the model via the ratio of available resource to population demand $(\frac{-\alpha R}{D})$. Note also that inter-specific competition also enters in this manner.

For plants, the resource (*R*) is the light energy incident per m$^{-2}$ of ground at time *t* (e.g., cal m$^{-2}$d$^{-1}$) multiplied by a constant that converts it to g dry matter m$^{-2}$d$^{-1}$.

For herbivores (e.g., PBW) attacking fruit (*F*), the resource (*R*) is the sum of all age fruit (or leaves, age=*j*) corrected for preference ($0 \le \xi_j \le 1$).

$$R = \sum_{j=1}^{J} \xi_j F_j \tag{A7}$$

Note that stages with preference values equal to zero are effectively removed from the calculations.

In general, the total age specific consumer demand (*D*) across ages (*i= 1, k*) may be computed in mass or number units as appropriate for the population.

$$D = \sum_{i=1}^{k} D_i^* N_i \tag{A8}$$

In plant, the demand rate (g dry matter d$^{-1}$) is the sum of all subunit population maximum demands for growth under current conditions corrected for the costs of conversion of resource to self and respiration [32] (eqn. A5.2, see Gutierrez and Baumgartner, 1984).

In pests such as PBW, the demand rate is the maximum per capita adult demand for oviposition sites and is computed using eqn. A9.

$$D_{i=a}^* = \theta \phi_T(T) f(a) \tag{A9}$$

where $f(a) = \frac{ca}{d^a}$ is the maximum age (a) specific per capita fecundity at the optimum temperature with parameters *c* and *d* (*cf.* [37]).

$\theta = 0.5$ is the sex ratio.

$\phi_T(T)$ is the concave correction for the effect of temperature dependent respiration.

**Supply-demand effects** - Consumer resource acquisition success is estimated by the acquisition supply/demand ratio ( $\phi_{S/D}(t)$ ) obtained by dividing both side of eqn. A6 by the population demand $D$.

$$0 \le \phi_{S/D}(t) = {}^{S}\!/\!_{D} = h(u) < 1 \cdot \qquad \text{(A10)}$$

Some consumers may have multiple resources and they must be included in the computation (see below).

In plant, success in meeting its demand is measured by the photosynthate *supply*/*demand* ratio (e.g., $0 \le \phi_{\mathrm{cot},S/D} < 1$) but there may be shortfalls of water ($w$) and inorganic nutrients (η) that may also computed using variants of (eqn. A6). For example, the water $0 \le \phi_{\omega} = S_w/D_w < 1$ ratio is computed in three steps: (i) the potential evapo-transpiration ($D_w = PET$) and evaporation from the soil surface (*ES*) are estimated using a Penman based biophysical model; (ii) $D_w$ along with available soil water in the root zone ($w = W_{max} - W_{wp}$) above the wilting point ($w_{wp}$) are substituted in eqn. A6 to compute evapo-transpiration ($S_w = ET$, i.e., water use by the plant); and (iii) the input-output model balances rainfall (*rain*, *ES*, *ET)* and runoff or flow above maximum soil water holding capacity ($W_{max}$) (see [24]).

$$w_{WP} \le w(t+1) = w(t) + rain(t) - ES(t) - ET(t) \le W_{\max} \qquad \text{(A11)}$$

Similarly for nitrogen, $0 \le \phi_{\eta} = S_{\eta}/D_{\eta} < 1$ is computed using analogues of eqns. A6-A 8 and A10. The combined effect of shortfall of all essential resources is captured as the product of the independent supply-demand ratios (eqn. A12).

$$0 \le \phi^{*} = \phi_{(S/D)}\phi_{(w)}\phi_{(\eta)} \ldots < 1. \qquad \text{(A12)}$$

Eqn. A12 is functionally Liebig’s Law of the Minimum because if any component of $\phi^{*}$ causes the supply to fall below a limiting value (e.g., respiration in plant, see A6), it becomes the limiting factor. In plants, after respiration and conversion costs have been subtracted from $\phi^{*}D$, the remaining photosynthate is allocated in priority order to meet demands for reproduction and then vegetative growth and reserves (see [31,35]). In addition to slowing the growth rates of subunits, $\phi^{*}$ also reduces the production rate of new subunits, the survival of extant ones (e.g., fruit shedding), and in the extreme may causes the death of the whole plants.

Individual PBW larvae infest individual fruit making their behavior more akin to that of a parasitoid. For this reason, the effects of temperature on respiration and hence fecundity are introduced in a similar way. In poikilotherms, respiration increases with temperature and a plot of the net assimilation rate (supply – respiration) on temperature typically yields a humped or concave function over the range favorable for development with zero values occurring at the lower and upper thermal thresholds and the maximum assimilation rate occurs at $T_{opt}$. This concave function arises naturally in our plant model as the difference between the acquisition rate and the respiration rate, and when normalized is used to capture the effects of temperature on fecundity (i.e., the physiological index for temperature. The simplest form for $\phi_T$ is convex symmetrical (eqn. A13).

$$\phi_T = \begin{cases} 1 - \left( \frac{(T - T_{\min}) - \gamma}{\gamma} \right)^2 \text{ if } T_{\min} \leq T \leq T_{\max} \\ \text{otherwise } 0 \end{cases} \qquad \text{(A13)}$$

The lower and upper temperature thresholds for development are $T_{\min}$ and $T_{\max}$ respectively, and $\gamma = T_{\max} - T_{\min})/2$ is half the favorable range.

**Model output -** Typical output of the cotton model is illustrated in Fig S2b for Londrina, PR, Brazil. Similar output was computed daily for every 2850 lattice cell in India for all of the years of the study. In the GIS analysis, summary variables such as total yield and total pests would georeferenced and mapped.

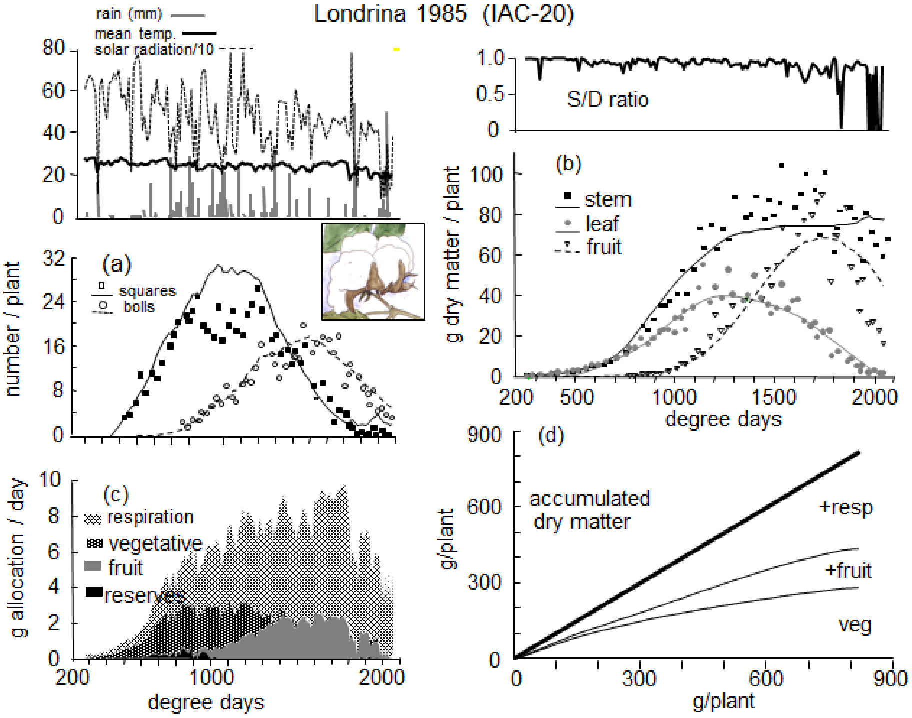


**Fig. S2b.** The level of detail simulated for all year for every lattice cell in India using data for Londrina, PR, Brazil during 1985 as an example (i.e., an average cotton plant of IAC-20 cotton). The predictions of the model (lines) are independent of the data (symbols) the model reproduces. The inset in the upper left is rainfall, solar radiation and average temperature, (a) square and bolls, (b) is the dry matter growth in leaves, stem, roots and fruit, (c) daily allocation of photosynthate to respiration, vegetative growth, fruit and reserves, and (d) cumulative allocation to respiration, vegetative growth and reserves and to fruit. The supply/demand ratio (S/D, upper right) regulates much of the growth dynamics of crop growth and development (see [24]).

**Figure S3. The effects of Bt cotton on cotton herbivores.**

The effects of Bt toxins in cotton on different herbivore species in cotton are illustrated in **Fig. S3**. The effects of one and two toxins were incorporated in the cotton model to estimate the effects on pest dynamics, cotton yields and the development of resistance in the herbivores (see [27,38]). Pink bollworm is highly susceptible to the Bt toxin and some species are tolerant (armyworm, loopers) and others are immune (plant bugs, whitefly). Note that these effects vary with the variety of Bt cotton and the plant part (and its age) attacked. Because the goal of the study was to assess the root ecological problem before the use of insecticides and Bt cotton, we did not explore the effects of the Bt technology in our study because it was not required to meet our objectives (see [20,38]), but this may be possible in future studies.

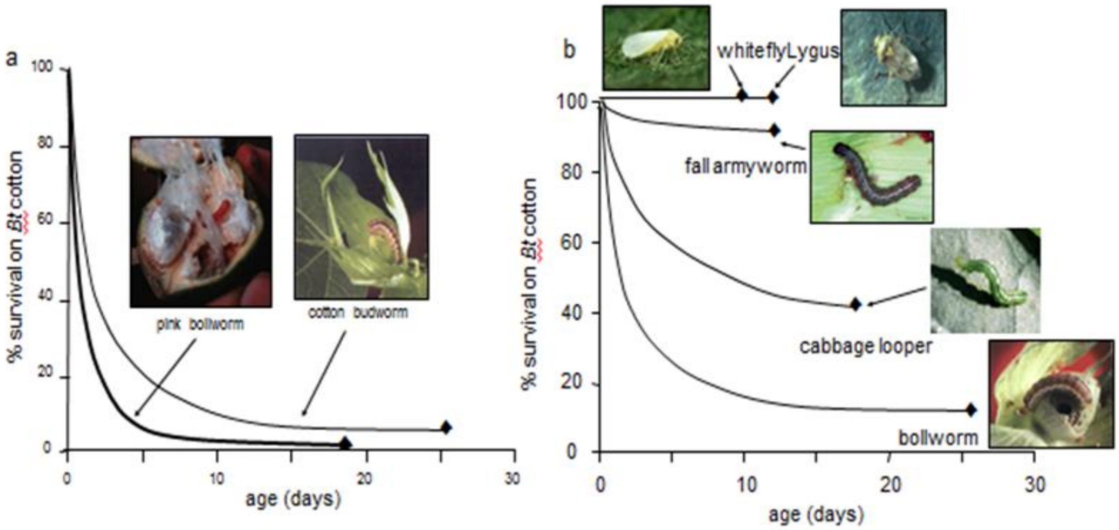


**Fig. S3.** The relative susceptibility to Bt toxin of different cotton pests is illustrated in the bottom two figures where the  ordinate is survivorship and the abscissa is days of exposure (see [38]). The proportion completing successful development is indicated by symbol ◊.

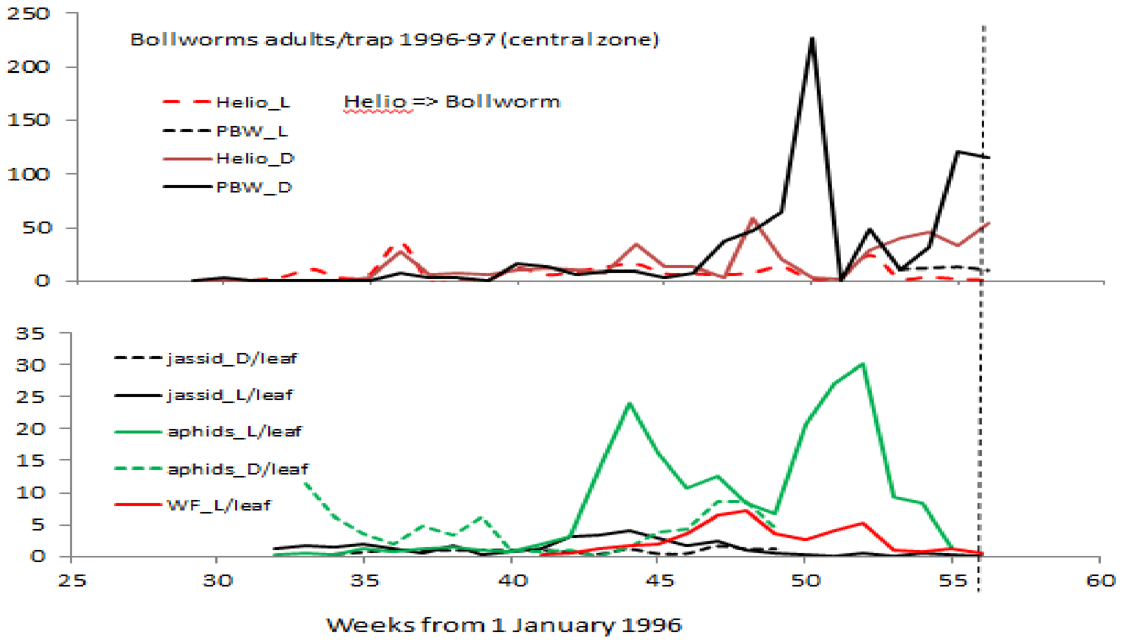
## Figure S4. Phenology of cotton pests in Central India before and after the introduction of Bt cotton.

Data on pest phenology before the introduction of Bt cotton in India are rare in the accessible literature, the densities are influenced by the location of the traps, abundance of alternate host plants, control measures (etc.), and hence the figures below are ***representative samples having little computational value.***

### Before the introduction of Bt cotton

Figure S4a illustrates typical dynamics of cotton pest at two locations (D, L) in central India in insecticide treated cotton **before the introduction of Bt** cotton in 2002. The pest densities may considerably during different years and locations, hence the important point is their phenology – when they occur. Trap catches of adult pink bollworm indicate it is late season pests while bollworm occurring during most of the season. PBW was more common than bollworm, but bollworm is far more destructive (red lines). The data suggest poor control and outbreaks.

Cotton aphid, jassids and whitefly (WF) were estimated by counting their numbers on leaves. These pests were common through out the season with aphids being the most common and all were late season pests. These pests are insecticide induced.



### After the introduction of Bt cotton

The phenology of bollworm, spiny bollworm (*Erias* sp.), pink bollworm and the defoliator *Spodoptera litura* in trap catches of adult moths at five locations in Central India (BA, JU, RA, SU) during 2011-12 **when Bt cotton adoption was >90%.** Note that the number of adults trapped differs greatly among species. Bollworm and *S. litura* occurs earlier than pink bollworm which builds late in the season as seen in the 1996-97 data above and in the simulations (see text). Bt cotton gives excellent control of PBW, and yet PBW exhibits a late season surge in density. Bollworm occurred at low levels throughout the season reflecting the action of Bt. The defoliator *Spodoptera litura* was highly abundant throughout the season, while the spotted bollworm was mostly a late season pest. Jassids and mealybugs are common in Bt cotton but were not reported in the data.

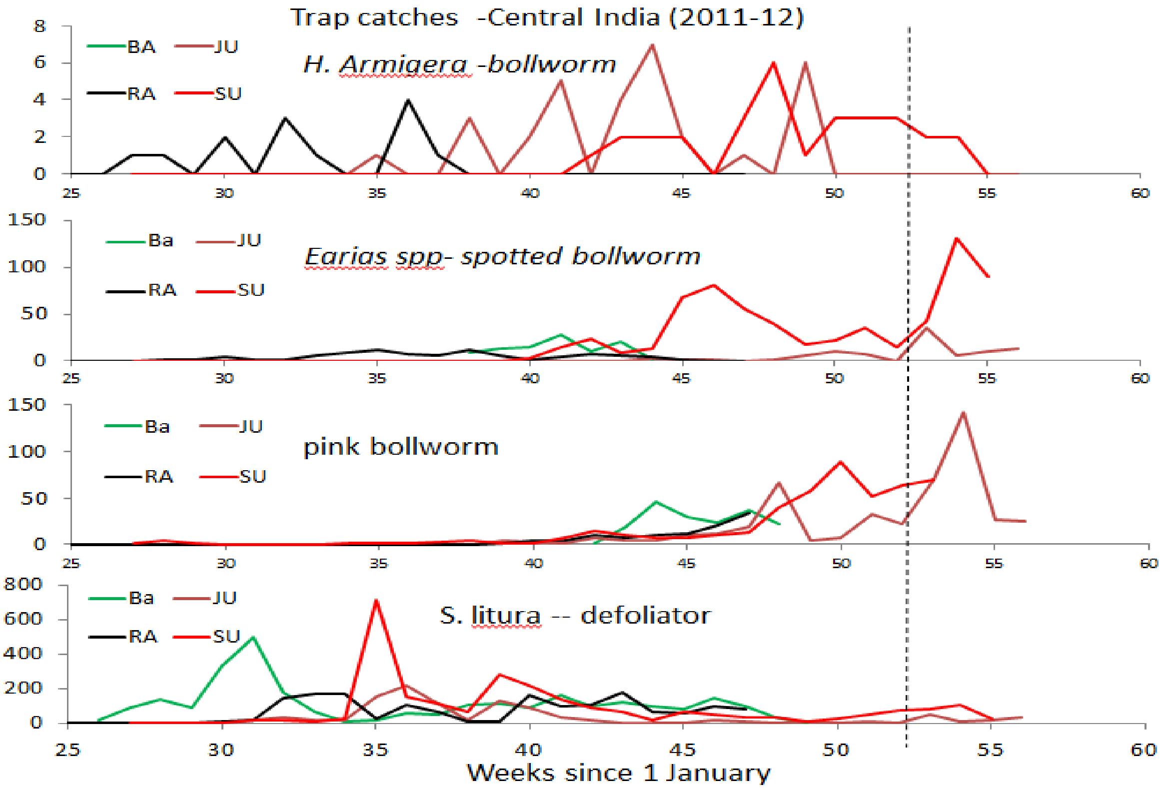
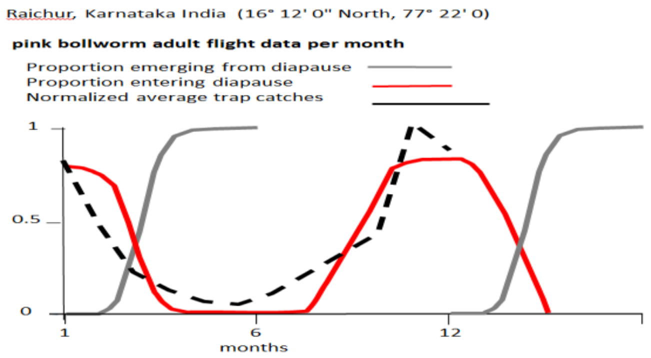
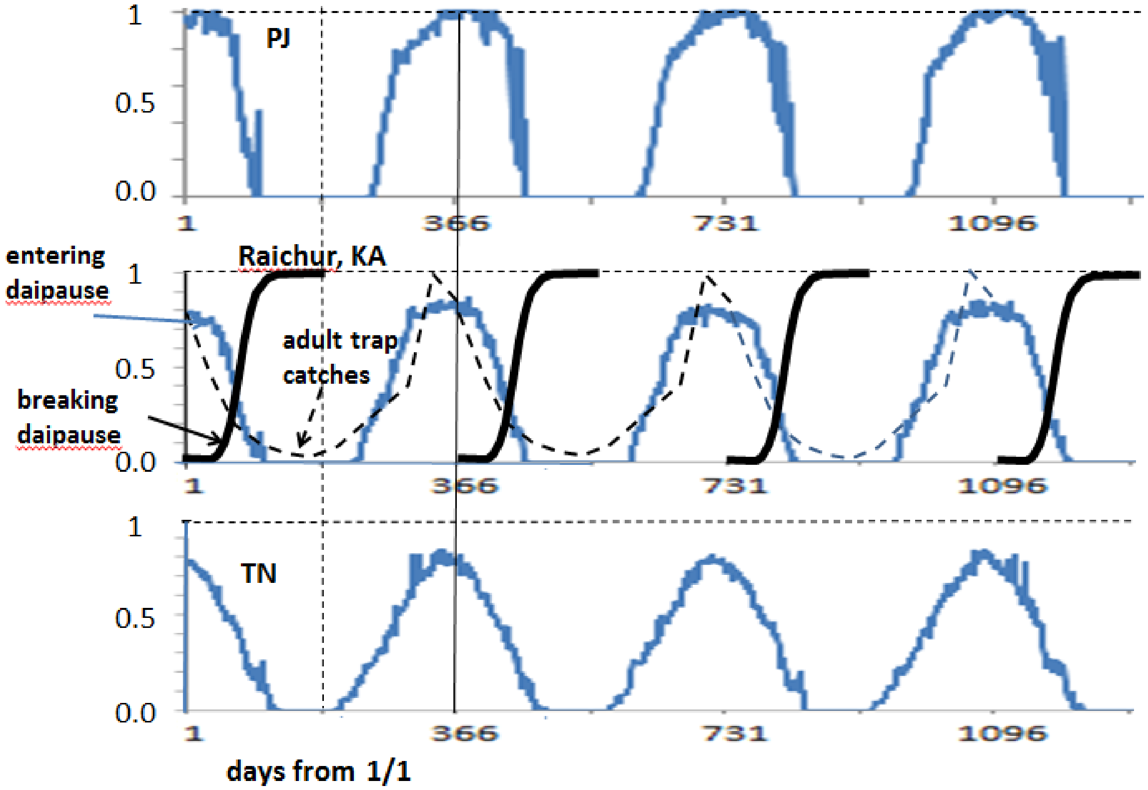


**Figure S5. Diapause in pink bollworm in the Punjab, Karanataka and Tamil Nadu**. Diapause enables pest such as pink bollworm to survive from one crop season to the next. The figure below is for Raichu, Karnataka, with the red line being the proportion of pink bollworm larvae predicted entering diapause, the dashed black line is the normalized average number of adults caught per pheromone trap per month (data -- max of 56), and the grey line the cumulative proportion of adults that emerged from diapause from the previous season. Most of the adults emerge before mid year (see text) before the start of the monsoon rains and before fruit in rainfed cotton are available.



Below are predicted diapause induction patterns (blue) for the Punjab (PJ), Raichur, Karanataka (KA) and Tamil Nadu (TN).



In the Punjab (PJ) the proportion of larvae entering diapause reaches unity, but in Karnataka only about 85% and 80% Tamil Nadu (TN) enter diapause showing the potential for nearly continuous populations given fruit availability. This finding is confirmed by Raina and Bell [39] who reported a non diapausing strain of PBW in southern India. Similar non diapause PBW proportions were found at Londrina, PR, Brazil (see [24]). PBW begins entering diapause earlier in the south in response to shorter day length than in the north.

**Figure S6. Variability of rain fall in Central India during 2002-2010.**

Rainfall varies widely both spatially and temporally with observed average rain fall being negatively related to the coefficient of variablity as a percent (CV) (Fig. S6a). Similar relationships are found between average cotton yield and CV (see text), while the relationship between yield and rainfall if positive linear (see text). Note that yields at ~1000mm rainfall is about 500kg.

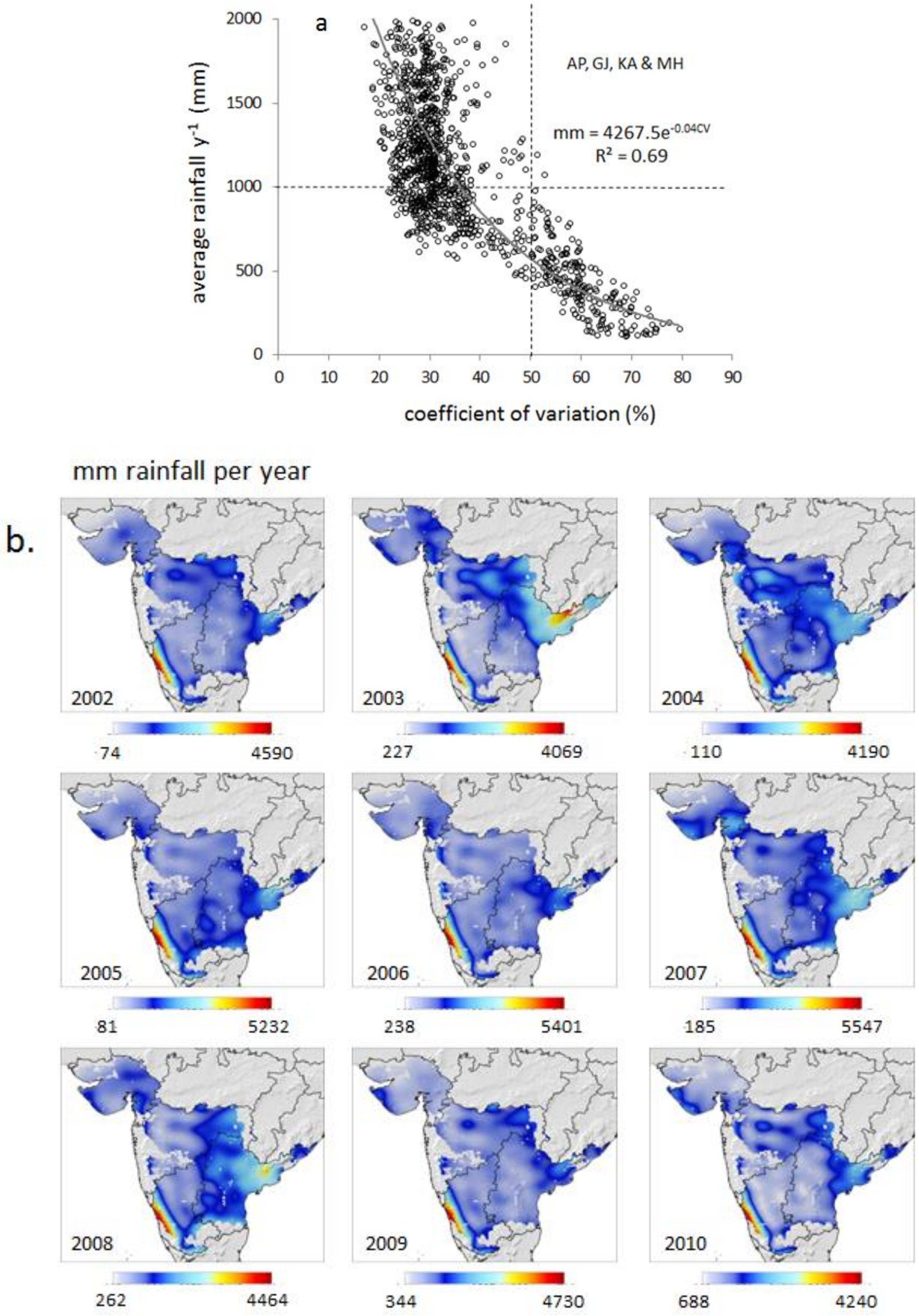


**Fig. S6a.** Plots of (a) observed average annual rainfall on coefficient of variation for rain (years 1996 to 2010) and (b) maps of annual rain fall totals for AP, GJ, KA and MH during 2002 to 2010.

Cotton yields in rainfed areas depend on the time and quantity of rain fall, and hence vary in a similar time-space maner as illustrated below for the central and south Indian staes of MH, AP and KA (Fig. S6c).

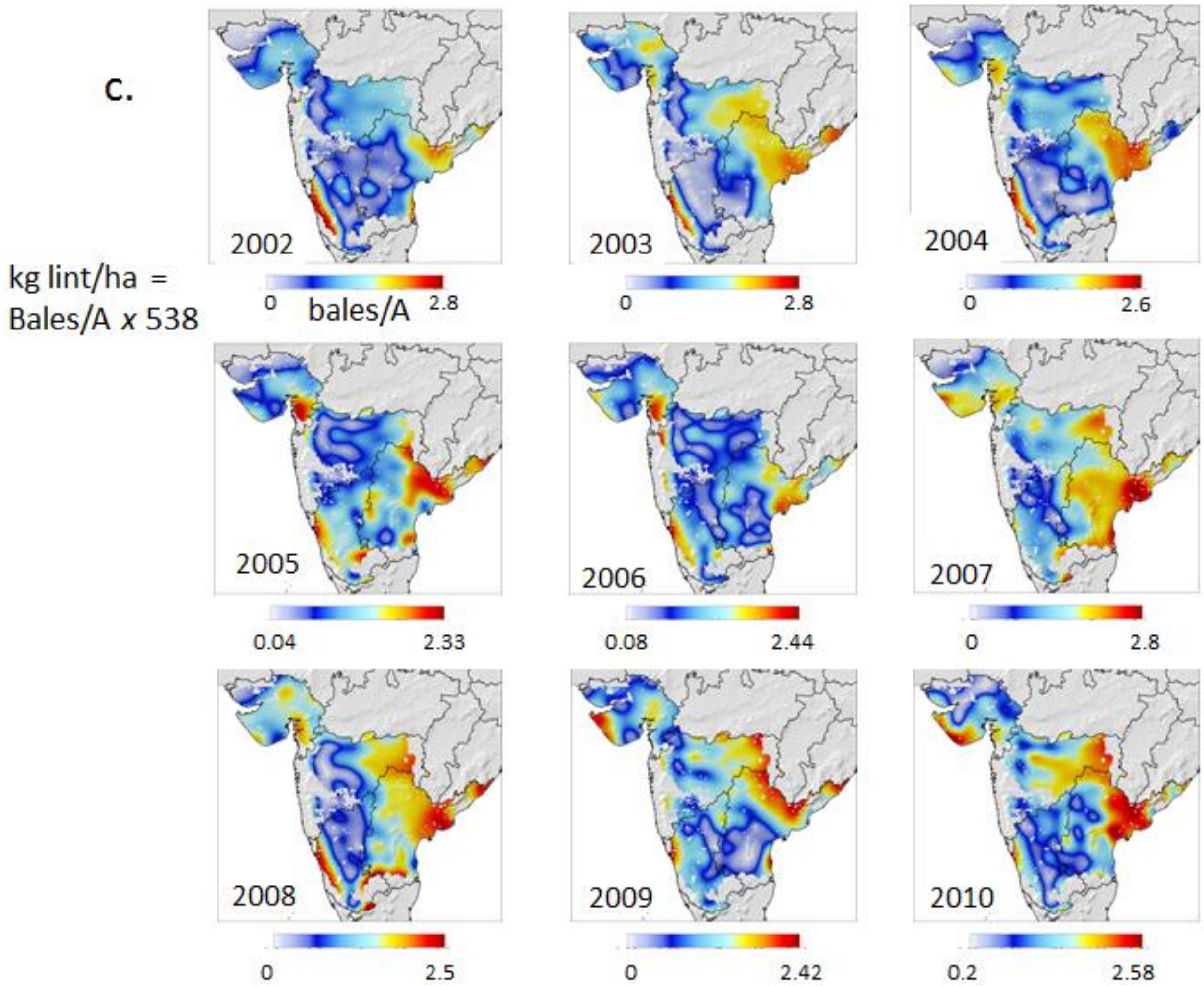


**Fig. S6c.** Mapping of yield during 2002 to 2010 for AP, GJ, KA and MH is in US bales (480 pound bales per acre). The conversion constant of bales to kg/ha is 538.

**Figure S7. The effects of planting density in rainfed and irrigated cotton at Yavatmal, MH using 1995-2010 weather.**

Until recently, recommended planting densities were ~2 plants m$^{-2}$. At such low densities, plants require time and energy to fill the available growing space at the expense of producing and maturing cotton fruit, while at high planting densities, yields may below because of inter-plant competition for light, water and nutrients. The optimum plant density depends upon varietal growth characteristics, soil properties, climatic conditions and management regime (e.g. [40]) and will vary annually with weather, especially in rainfed areas (see below).

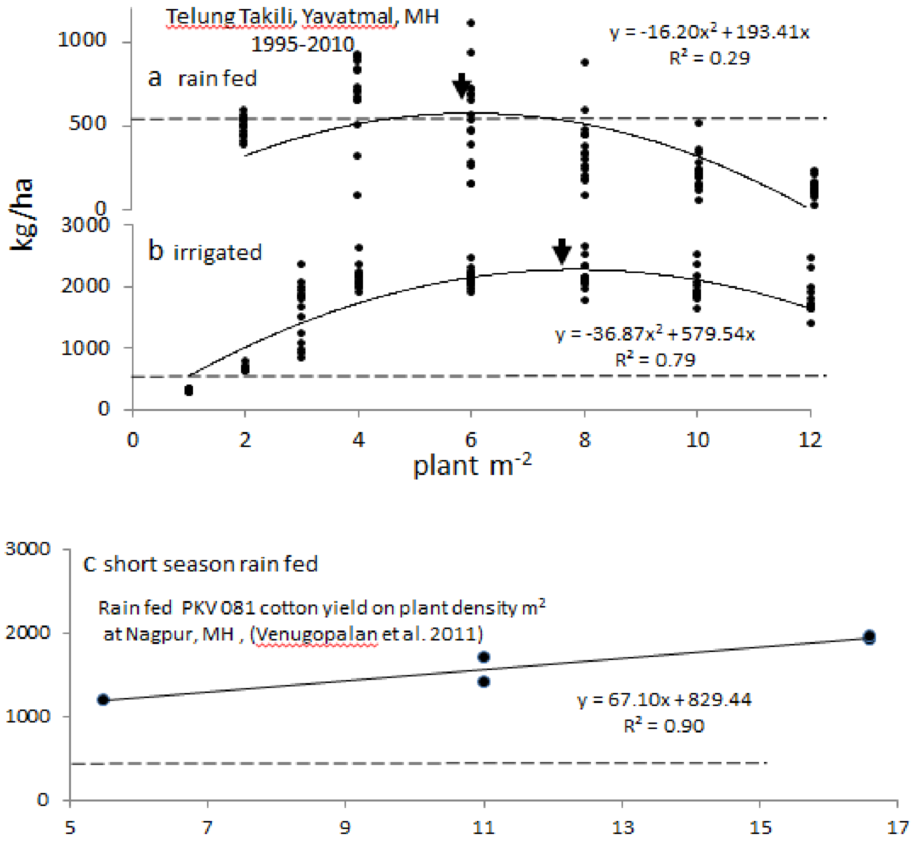
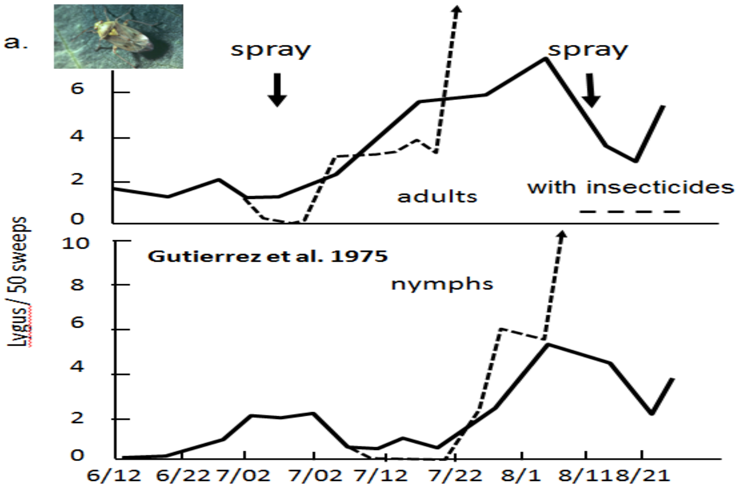


**Fig. S7.** Irrigation (see text) and plant density effects yield: (a) rainfed cotton and (b) irrigated cotton at Yavatmal, MH, and (c) short season high density cotton at Nagpur, MH [42].

The simulated effect of planting density on yield of the Upland cotton used in our study is illustrated in Fig. S7 for Yavatmal, MH during 1995-2010 under rainfed (a) and (b) irrigated conditions. The horizontal dashed line is the 500kg/ha reference line. Prospective yield under rainfed and irrigation conditions are summarized by polynomial regressions of yield on planting density. The plant density that maximizes average yield is determined by solving the equations at $dy/dx = 0$ (the down arrows). Under rainfed conditions, average maximum yield occurs at 5.8 plants $m^{-2}$, but predicted yields are highly variable due to the timing and quantity of rainfall and, the patterns of solar radiation (and increasing [CO2]) that affect photosynthesis, carbohydrate stress and fruit shedding. Under irrigation, water is not limiting and max yield is predicted at 7.8 plants $m^{-2}$, with yields being roughly four-fold higher and less variable than under rainfed conditions. [The variety e.g., short season cotton), and its optimal planting density can be used strategically to avoid pests (see below and [41]).] Genotype x spacing studies using fertile non-Bt *G. hirsutum* and Desi (*G. arboreum*) varieties showed significant yield differences with one variety [39] yielding 1,967kg ha$^{-1}$ of lint cotton at 16.6 plants m$^{-2}$ that was >60% higher than at 5.5 plants m$^{-2}$ (see bottom of fig. S7) [42]. These are similar to the planting densities used in the Central Valley of California [43].

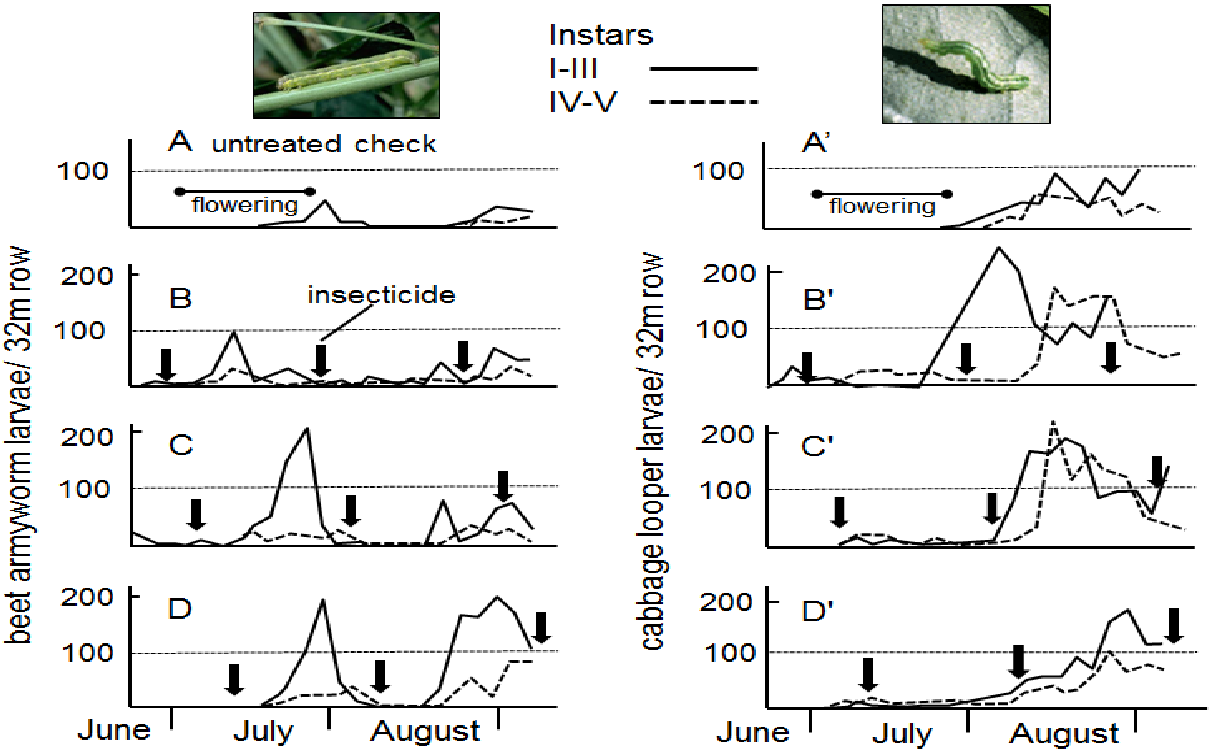
**Figure S8. Ecological disruption in cotton with insecticide use.**

A well documented cases of insecticide disruption and of markel failure occurred in the Great Central Valley of California (see text) where lygus bug (*Lygus hesperus*) was considered the key pest responsible for yield losses and yield variability. The dynamics of lygus bug adults and nymphs with (dashed line) and without (solid line) insecticides are shown in Fig. S8a showing the effects of insecticides on pest resugence [18]. The insecticide treatments were imbedded in a 1.61 km$^2$ block of cotton (i.e., 640 acres). Approximately 95% of the cotton was untreated.



Gutierrez et al. 1975

The next figure shows the effects of insecticide use (down broad arrows) on outbreaks of two common defoliators (cabbage looper and beet army worm) compared to the untreated check. The horizontal dashed lines are a reference density across treatments, showing clearly the effects of ecological disruption on pest phenology and density.  Note that pest numbers were lowest in the untreated check because natural enemies of the pest were largely unaffected by the insecticide.



**Gutierrez et al. 1975**

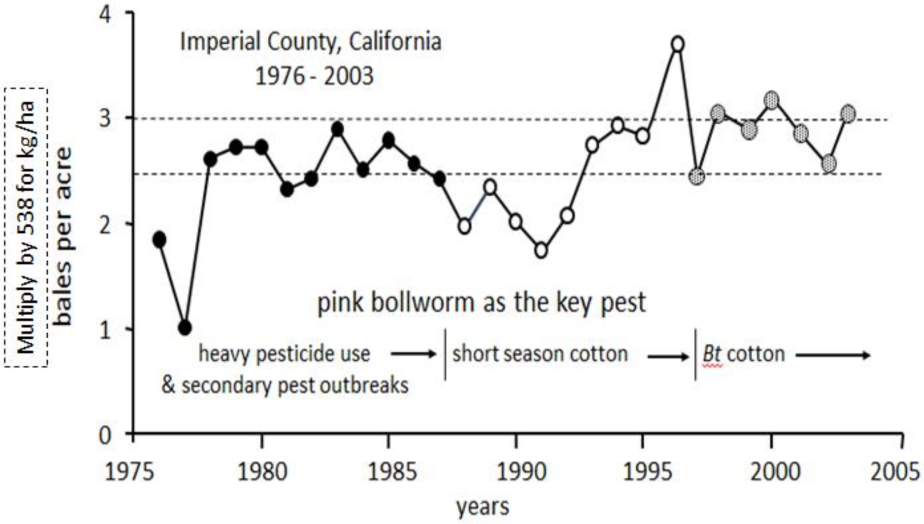
| **treatments** | **bales/acre** |
|---|---|
| untreated A | 2.8 |
| B | 2.7 |
| C | 2.6 |
| D | 2.6 |

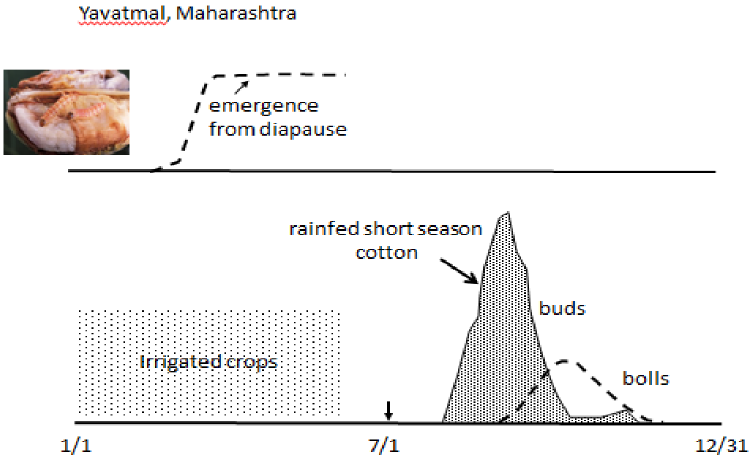
**loss = yield loss + cost of pesticides**
**Gutierrez et al. 1975**

The effects of insecticide use on final yields including bollworm damage is shown above. Yields in the untreated area (A) where higher than in any of the insecticide treatments (B, C, D) , and similar to yield in other managed areas on the farm. The results show that farmers were spending money on insecticide to lose money via increased yield loss. We note that the yield in the treated areas would have been larger had the treatment not been embedded in the 1.61km$^2$ block of largely untreated cotton. Note that pink bollworm does not survive in the Cenntral Valley [43], and Bt cotton has made little inroad.

**Figure S9. High-density short-season cotton in Imperial County CA.**

Pink bollworm invaded the southern desert valleys of California in the early 1970s and initially caused severe yield declines despite heavy insecticide use. Yield from the Imperial County Agricultural Commissioner's Reports for 1976-2006 [44] are plotted in Fig. S9. The figure shows the effects on yield of ecological disruption during 1975-1987, the learning curve effects of the transition (1988-1992) to short season cotton, and the adoption of Bt cotton (1997 - 2005). Without the heavy use of insecticide, yields of short season cotton during 1993-1996 where about same as during the subsequent period of Bt cotton (1997-2004 to the present). [Yield in 480 lbs. bales can be converted to kg/ha by multiplying 538.] Yields in the Imperial Valley are approximately 10% higher for short season and Bt cotton than yields in the Central Valley (see Fig. S8).





On a regional basis, high density short season rainfed cotton could be grown in central India avoiding PBW infestations (see figure above), with irrigation water during the period before the monsoon used for the production of other crops.

**Figure S10. Suicides among males by age class in AP, GJ, KA and MH (see text).**

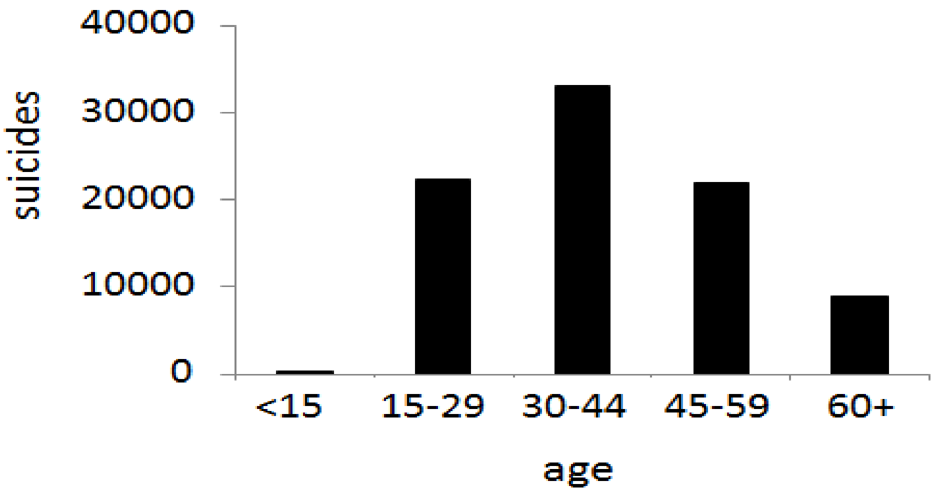


**Figure S11. Plots of independent variables on annual suicides in AP, GJ, KA and MH (see text and eqn. 3) (see text)**

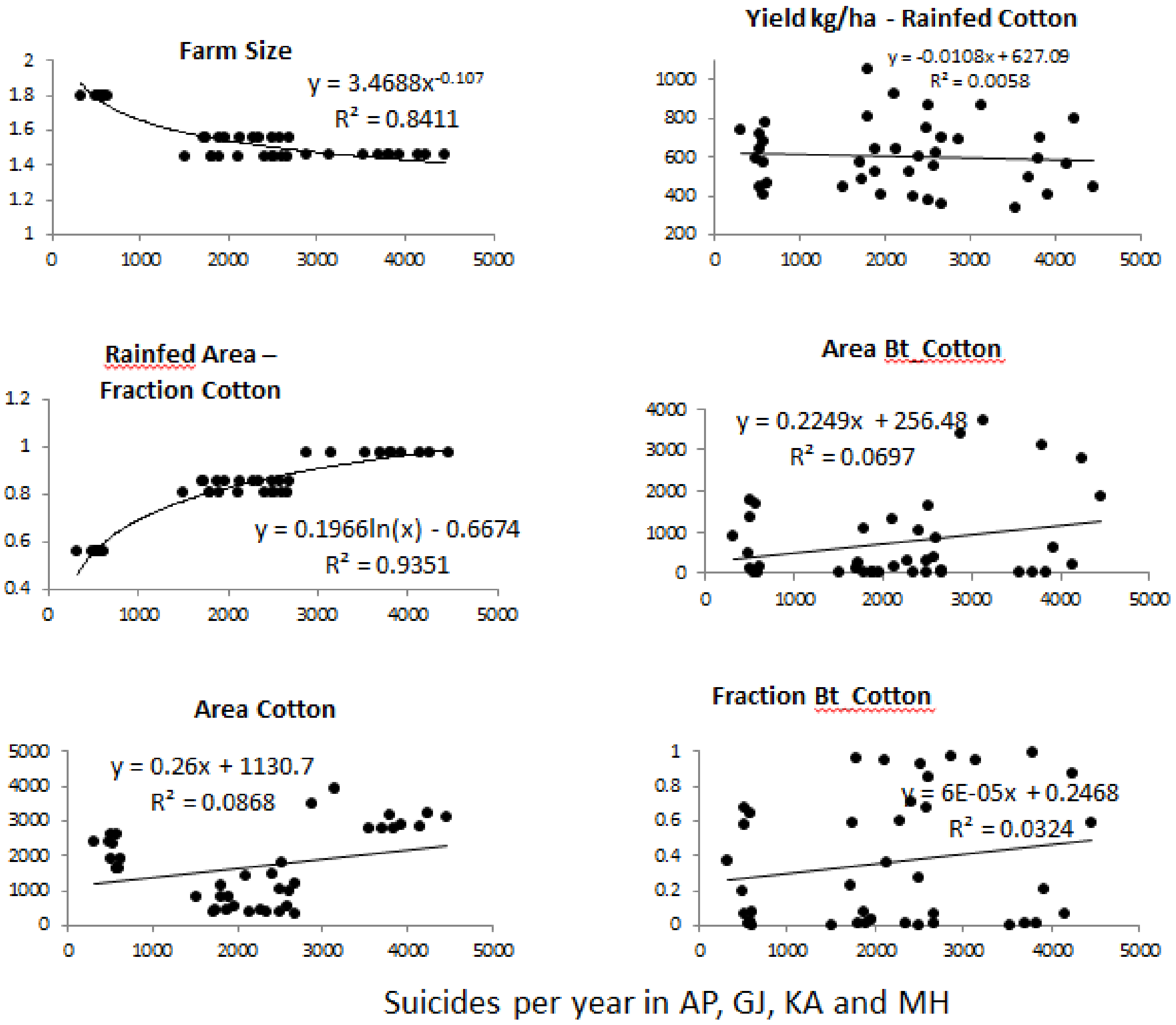
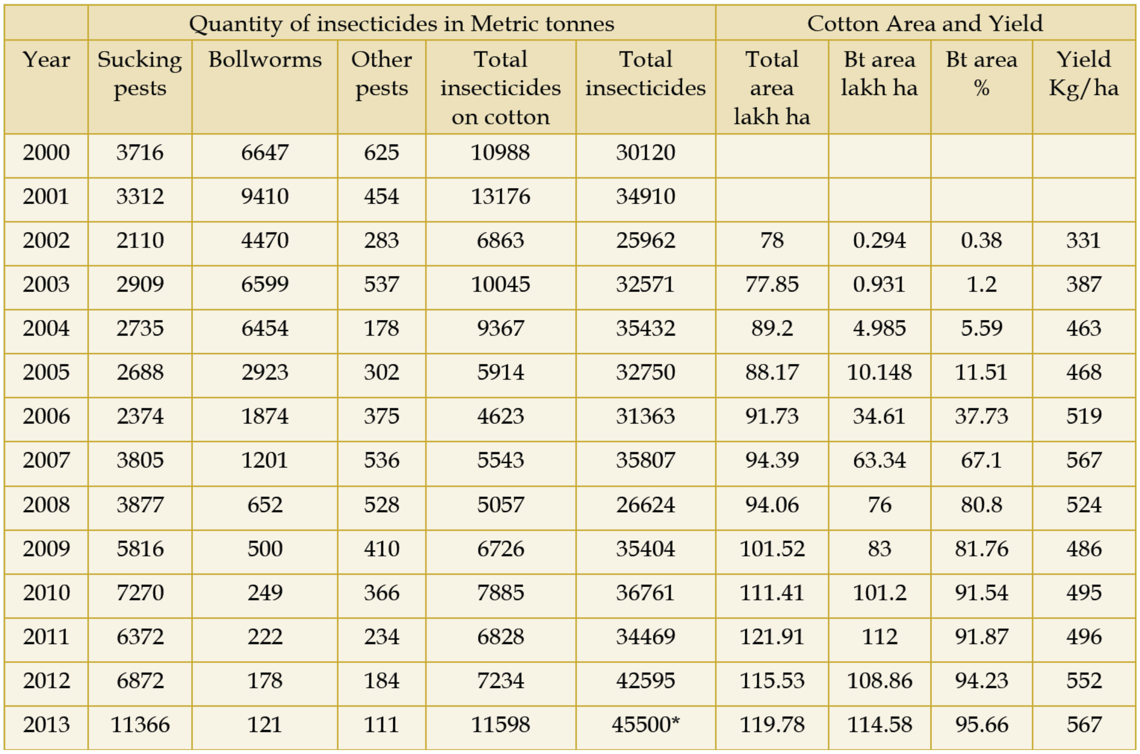


**Table S1**. **Changes in insecticide use nationally in Indian cotton during 2000-2013 [23] [23] (Kranthi, K.R., 2014, text available from APG)**



| | Quantity of insecticides in Metric tonnes | | | | | Cotton Area and Yield | | | |
|---|---|---|---|---|---|---|---|---|---|
| Year | Sucking pests | Bollworms | Other pests | Total insecticides on cotton | Total insecticides | Total area lakh ha | Bt area lakh ha | Bt area % | Yield Kg/ha |
| 2000 | 3716 | 6647 | 625 | 10988 | 30120 | | | | |
| 2001 | 3312 | 9410 | 454 | 13176 | 34910 | | | | |
| 2002 | 2110 | 4470 | 283 | 6863 | 25962 | 78 | 0.294 | 0.38 | 331 |
| 2003 | 2909 | 6599 | 537 | 10045 | 32571 | 77.85 | 0.931 | 1.2 | 387 |
| 2004 | 2735 | 6454 | 178 | 9367 | 35432 | 89.2 | 4.985 | 5.59 | 463 |
| 2005 | 2688 | 2923 | 302 | 5914 | 32750 | 88.17 | 10.148 | 11.51 | 468 |
| 2006 | 2374 | 1874 | 375 | 4623 | 31363 | 91.73 | 34.61 | 37.73 | 519 |
| 2007 | 3805 | 1201 | 536 | 5543 | 35807 | 94.39 | 63.34 | 67.1 | 567 |
| 2008 | 3877 | 652 | 528 | 5057 | 26624 | 94.06 | 76 | 80.8 | 524 |
| 2009 | 5816 | 500 | 410 | 6726 | 35404 | 101.52 | 83 | 81.76 | 486 |
| 2010 | 7270 | 249 | 366 | 7885 | 36761 | 111.41 | 101.2 | 91.54 | 495 |
| 2011 | 6372 | 222 | 234 | 6828 | 34469 | 121.91 | 112 | 91.87 | 496 |
| 2012 | 6872 | 178 | 184 | 7234 | 42595 | 115.53 | 108.86 | 94.23 | 552 |
| 2013 | 11366 | 121 | 111 | 11598 | 45500* | 119.78 | 114.58 | 95.66 | 567 |

Starting in 2000, insecticide use decreased to half by 2006, but then increased to 2000 levels in 2013. Insecticide use decreased for bollworm control but increased for control of sucking pests that currently plague Bt cotton.

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