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Bio-economics of Indian hybrid Bt cotton and farmer suicides

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Abstract

Background: The implementation of hybrid Bt cotton unique to India has been heralded as a grand success by government agencies, seed companies and other proponents, and yet yields have stagnated at low levels and production costs have risen 2.5–3-fold. The low-yield hybrid cotton system of India contributes thousands of farmer suicides to the annual national toll. Conceptual and methodological barriers have hindered bioeconomic analysis of the ecological and social sustainability of such cross-scale agro-ecological problems in time and geographic space, under global technology and climate change. As a paradigm shift, we use conceptually simple, parameter-sparse, theoretically based, mechanistic, weather-driven physiologically based demographic models (PBDMs) to deconstruct the bioeconomics of the Indian cotton system.

Results: Our analysis of Indian hybrid cotton system explains some extant ecological and economic problems, and suggests a viable solution. Specifically, the model accurately captured the age-stage mass dynamics of rainfed and irrigated cotton growth/development and the interactions with the key pest pink bollworm across five south-central Indian states, and enabled identification of proximate bioeconomic factors responsible for low yield and their relationship to farmer suicides. The results are reinforced by analysis of Ministry of Agriculture annual state-level data. We explain why short-season, high-density non-GM cotton is a highly viable solution for Indian cotton farmers in rainfed and irrigated cotton areas of the five states, and possibly nationally. The transition from a theoretical bioeconomic construct to a real-world regional bioeconomic analysis proved seamless.

Conclusions: The hybrid long-season Bt technology for rainfed and irrigated cotton is unique to India, and is a value capture mechanism. This technology is suboptimal leading to stagnant yields, high input costs, increased insecticide use, and low farmer incomes that increase economic distress that is a proximate cause of cotton farmer suicides. The current GM Bt technology adds costs in rainfed cotton without commensurate increases in yield. Non-GM pure-line high-density short-season varieties could double rainfed cotton yield, reduce costs, decrease insecticide use, and help ameliorate suicides. The GM hybrid technology is inappropriate for incorporation in short-season high-density varieties.

Keywords: Bioeconomic theory, Ecosystem complexity, Pink bollworm, GIS, Short-season cotton, Ecological disruption

Background

The ecological basis of the Indian cotton production system was examined by Gutierrez et al. [1]. This paper (a) extends those results, (b) reviews bioeconomic theory and models applicable to the analyses of genetically modified (GM) Bt hybrid cotton across south-central India, (c) uses simulation and Indian Government data

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to identify the factors that contribute to stagnant yields, high production costs, and high numbers of suicides among cotton farmers, and (d) evaluates the use of short-season high-density non-GM cotton as a solution. We first address the dual problems of modeling the complexity and the application of relevant bioeconomic theory, and then apply our models to the analysis of the real-world problem of Bt hybrid cotton and farmer suicides in India.

Modelling complexity and bioeconomic theory

How to analyze the complexity and bio-economics of populations, species and their interactions as driven by weather in natural and agricultural ecosystems has been center stage for decades. Palladino [2] posed a fundamental question: *Is nature idiosyncratic?* (i.e., can it be modelled?) Dormann et al. [3] opined that "*The ecological reality of most species is... frustratingly complex, temporally variable, and full of interactions with other species, direct or indirect, of unknown intensity and importance*". In contrast, Evans [4] proposed that we must use holistic general methods to investigate problems that at every level are ecological and bioeconomic in nature—to develop "*... models based on understanding the processes that result in a system behaving the way it does, ... remaining valid indefinitely*". To do this, we must seek reliable rules ("Laws") of nature common to all ecosystems that include thermodynamics and mathematical descriptions of population and trophic interactions [5]. In our analysis of the Indian cotton system, we take a holistic approach

based on bioeconomic rules common to all species. Alternative approaches for the analyses of ecosystem complexity are reviewed in Additional file 1: S1.

Economist Georgescu–Roegen [6, 7] coined the term bio-economics and posited the "*... biological origins of the economic process and thus ... the problem of mankind's existence with a limited store of accessible resources, unevenly located and unequally appropriated*". He defined as endosomatic the biological endowments of organisms in nature that enable individuals and species, including primal humans, to utilize and manage resources (energy/mass) sustainably. In contrast, modern humans developed exosomatic "organs" (e.g., tools, technology) that enable access to renewable resources beyond sustainable levels. Dual papers see [8, 9, 10] proposed foundational bioeconomic theory applicable to all organisms including humans based on a simple mass conservation balance model (i.e. the metabolic pool; MP) of level i acquiring resource from level $i-1$ (Fig. 1; Eq. 1) [8, 9, 11, 12]. The notation can be simplified by aggregating terms, but we keep the detail for heuristic reasons.

$$
\begin{aligned}
\frac{dM_i}{dt} = \dot{M}_i &= \lambda_i \{(\beta_i D_i h(u_i) \\
&\quad - \nu_i - \mu_i) M_i\} - D_{i+1} h(u_{i+1}) M_{i+1} \\
\frac{dM_{i+1}}{dt} = \dot{M}_{i+1} &= \lambda_{i+1} \{(\beta_{i+1} D_{i+1} h(u_{i+1}) \\
&\quad - \nu_{i+1} - \mu_{i+1}) M_{i+1}\} - D_{i+2} h(u_{i+2}) M_{i+2}
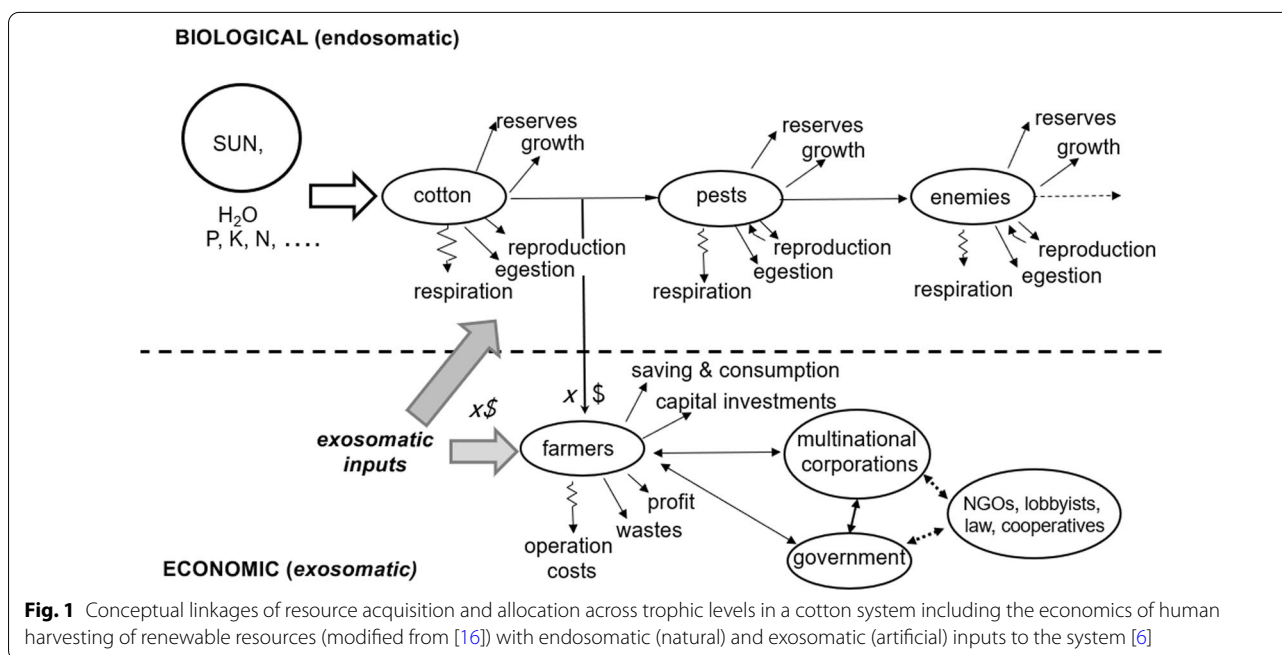\end{aligned}
$$
$$(1)$$

Fig. 1 Conceptual linkages of resource acquisition and allocation across trophic levels in a cotton system including the economics of human harvesting of renewable resources (modified from [16]) with endosomatic (natural) and exosomatic (artificial) inputs to the system [6]

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Using trophic subscripts, D_i is the per-unit demand rate of consumer population M_i, $S_i = D_i h(u_i)$ is the per-unit supply acquired via the demand-driven type II ratio-dependent (i.e. $\frac{\text{accessible resource}}{\text{population demand}} = \frac{\alpha_i M_{i-1}}{D_i M_i}$) functional response search model ($0 \le h(u_i) = (1 - \exp(\frac{\alpha_i M_{i-1}}{D_i M_i})) < 1$) with search rate $0 \le \alpha_i < 1$. Inter- and intra-specific competition enter the analysis via the exponent. The parameter $0 < \beta_i < 1$ corrects for egestion (wastage), ν_i is the temperature dependent respiration rate, μ_i is the net death rate and $0 < \lambda_i < 1$ is the efficiency of conversion of assimilate to consumer biomass. In Eq. 1, $S < D$ because of imperfect search (i.e., $h(u) < 1$).

In this model, all organisms, including humans (firms/farms), are consumers (i.e., predators in a general sense), that despite a myriad of strategies, all have the same problems of renewable resources acquisition and allocation. Although the input–output functions have different units and rates, all have similar shapes and functions. At each level, acquired resources are first corrected for egestion (wastage) and then in priority order to conversion costs, respiration, reproduction, and growth (including reserves) (Eq. 1) [13, 14]. Versions of the acquisition model (e.g. $S = Dh(u)$) are used to estimate photosynthesis by leaves, and water/nutrient uptake by roots, as well as herbivory and predation by higher trophic levels [11]. Mass (energy) transfers connect plants, plant sub-units, herbivores, predators, parasites, and parasitoids.

Central to all economies is the interplay between supply (S) and demand (D) that differ in natural and human systems. In nature, the demand for a resource is what organisms can assimilate, while in human economies, the demand may be all that is available and more. Similarly, the supply in biology is that part of the demand an organism acquires given its search capacities at current levels of available resource, while in human economics, the supply of a resource species may be all that is available in the environment, that in the case of renewable resource species may be harvested beyond sustainability driving them to extinction [8, 9]. In biology, D is a genetically determined constant and hence $S < D$ is the rule because of imperfect search (Eq. 1), while in human economies, D may increase via tools, technology, and human avarice beyond the maximum stock of available resource so that $D > S_{\max}$ may occur, making the system unsustainable. Timely feedback between S and D must inform sustainability. Equation 1 is the theoretical basis for modeling the dynamics of complex systems such as Indian cotton and other systems [8].

Figure 1 illustrates the flow of energy/matter within and between species (i.e., Eq. 1) in a cotton food chain (or food web) including human harvesting that is multiplied by price with the analogous notion of predation on farmers (households) being economic. Exosomatic inputs occur in agriculture that may have little basis in long-term stability, and at the governmental level, the flow is complex and vexing [15]. (The economic analogies between natural and human economies are summarized in Additional file 1: S2.) We next review the bioeconomic model of cotton used in our analysis.

The Cotton PBDM system

The dynamics inherent in Eq. 1 are core to the weather-driven physiologically based demographic model (PBDM) for cotton (*Gossypium hirsutum* L.) and its pests—models originally developed in California [11, 17, 18]. Wild species of cotton evolved worldwide and some were domesticated [19], but all can be modeled using the same PBDM structure by altering a few measureable species (varietal) parameters [20] (see Methods and Additional file 1: S3). Briefly, a cotton plant may be viewed as composed of age-mass structured populations of leaf, stem, and root, and of fruit numbers having mass and stage structure with realized growth rates of subunits determined by weather-driven photosynthesis, herbivore attack, and other factors impacting *S/D* mediated acquisition and allocation rates and priorities. For simplicity, a cotton crop is viewed as a canopy of plants with populations of higher trophic levels species linked to plant subsystems models (see Fig. 2). An important attribute of PBDMs is that they are readily transferable to other locations, regions and times with different conditions including climate change (e.g. India).

The species of herbivores attacking cotton(s) vary globally, but the ecological niches filled are analogous. The major herbivores modeled using PBDMs are illustrated in Fig. 3a with which side of the supply–demand divide each affects indicated [11]. Supply-side pests (and diseases) affect the capacity of plants to produce and allocate photosynthate, and include defoliators (*Spodoptera exigua*, *Trichoplusia ni*) and vascular feeding species (aphids (*Aphis gossypii*), whitefly (*Bemisia tabaci*)) that may also vector diseases (see Fig. 2). In contrast, demand side herbivores attack buds and growing fruit that are sinks for photosynthate (e.g., cotton boll weevil (*Anthonomus grandis*), and generalists herbivores such as plant bugs (*Lygus hesperus*), bollworm (*Helicoverpa zea*), and budworm (*Heliothis virescens*)). These pests cause fruit damage and shedding that alters current and future demand dynamics. In contrast, the invasive stenophagous pink bollworm (*Pectinophora gossypiella,* PBW), native to south Asia, is the key pest in the SW USA and in India where it attacks the standing crop of buds and fruit. It does not cause appreciable shedding though its feeding damage can greatly reduce yield and quality [21].

Most herbivores in cotton are secondary pests controlled at low levels by natural enemies (generalist
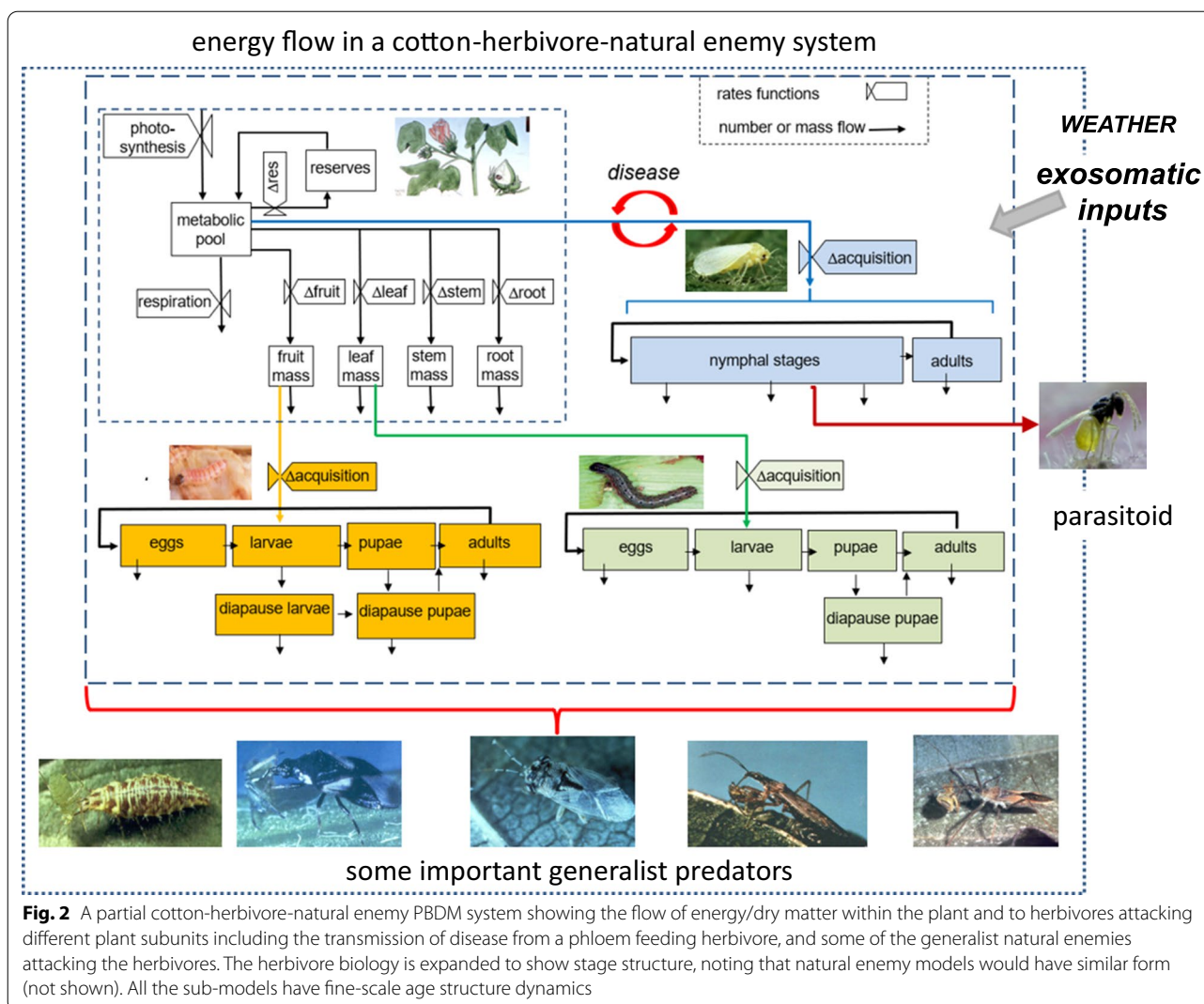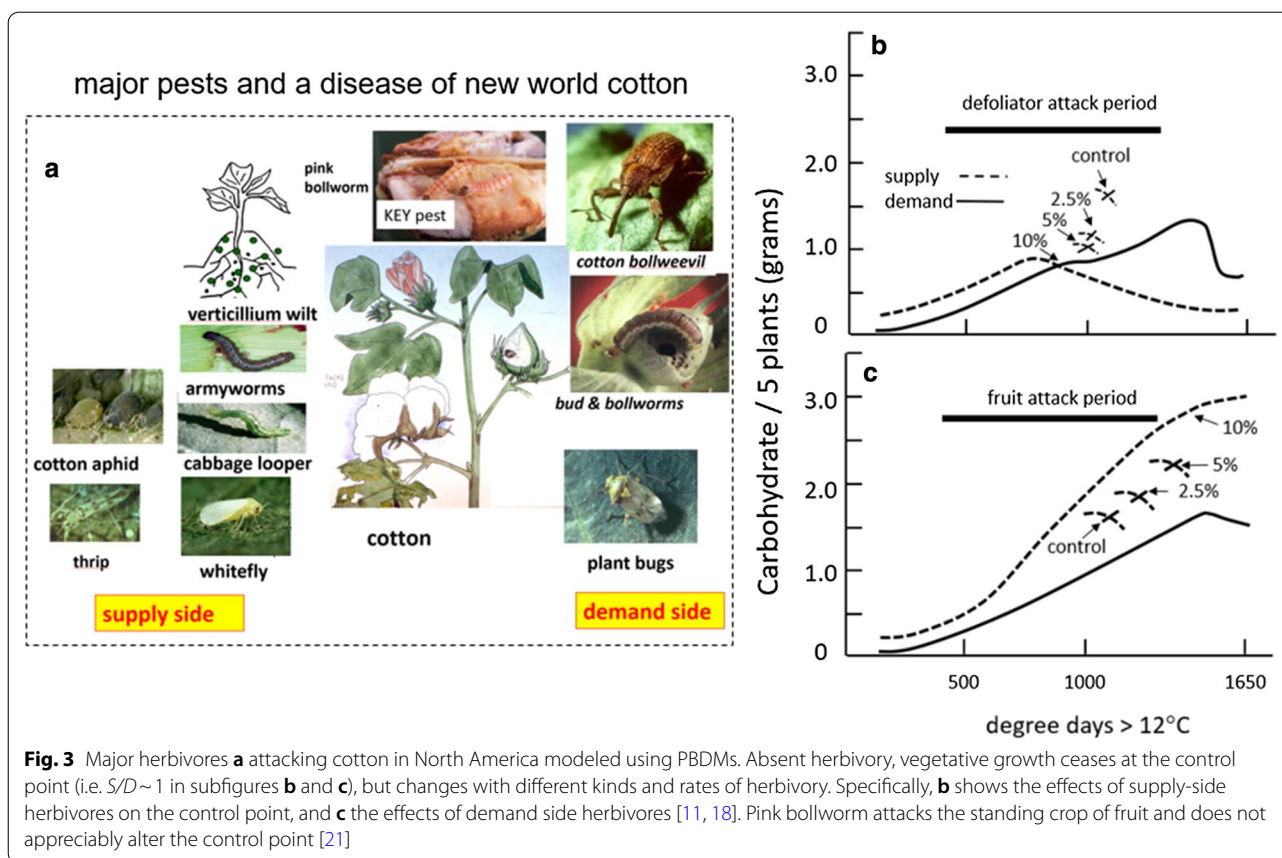
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Fig. 2 A partial cotton-herbivore-natural enemy PBDM system showing the flow of energy/dry matter within the plant and to herbivores attacking different plant subunits including the transmission of disease from a phloem feeding herbivore, and some of the generalist natural enemies attacking the herbivores. The herbivore biology is expanded to show stage structure, noting that natural enemy models would have similar form (not shown). All the sub-models have fine-scale age structure dynamics

predators, parasitoids, Fig. 2), while the key pest PBW has no effective natural enemies. Insecticides kill natural enemies, releasing the reproductive potential of secondary pests that can reach high damaging levels (i.e. ecological disruption) and cause greater damage than the initial target pest (e.g. PBW) [17].

Absent herbivore attack, vegetative growth and bud production continue until shortly after flowering when fruit begin rapid growth (i.e. the *control point*; Fig. 3b, c). After this time, $S/D < 1$, and the rates of vegetative growth and bud production slow or cease, and photosynthate is redirected to meet the demands of growing fruit that have higher priority (i.e., the reproductive imperative). Under herbivore-free conditions, more than half of all cotton buds initiated are shed due to $S/D < 1$ with little loss of time and energy (i.e. the reproductive surplus), and the crop achieves maximum potential yield under

extant weather [11, 18]. However, supply-side pests (defoliator attack and disease) cause the control point to occur earlier in time resulting in stunted plants and reduced yields (Fig. 3b). In contrast, demand-side pests that cause fruit abscission delay the time of the control point, reduce yields, and if severe enough may cause the plant to continue growing vegetative (Fig. 3c). Supply and demand-side herbivores are commonly active at the same time, and affect current and future growth dynamics. Natural enemies reduce herbivore populations and have a top-down influence on plant S/D regulated growth and development, and vice versa (i.e. bottom-up and top-down regulation [14, 22]). All these effects are accommodated by the modular structure of the model using Boolean variables to enable the inclusion of any combination of species in a simulation (see Figs. 2, 3). The PBDMs developed in California for cotton and PBW [17, 18, 23]

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Fig. 3 Major herbivores **a** attacking cotton in North America modeled using PBDMs. Absent herbivory, vegetative growth ceases at the control point (i.e. *S/D ~* 1 in subfigures **b** and **c**), but changes with different kinds and rates of herbivory. Specifically, **b** shows the effects of supply-side herbivores on the control point, and **c** the effects of demand side herbivores [11, 18]. Pink bollworm attacks the standing crop of fruit and does not appreciably alter the control point [21]

(albeit with varietal parameter changes [20]) underpin the bioeconomic analysis of the genetically modified (GM) hybrid Bt Indian cotton where many of the same issues and analogous herbivores occur, but where the ecological, economic, and social outcomes are grossly different.
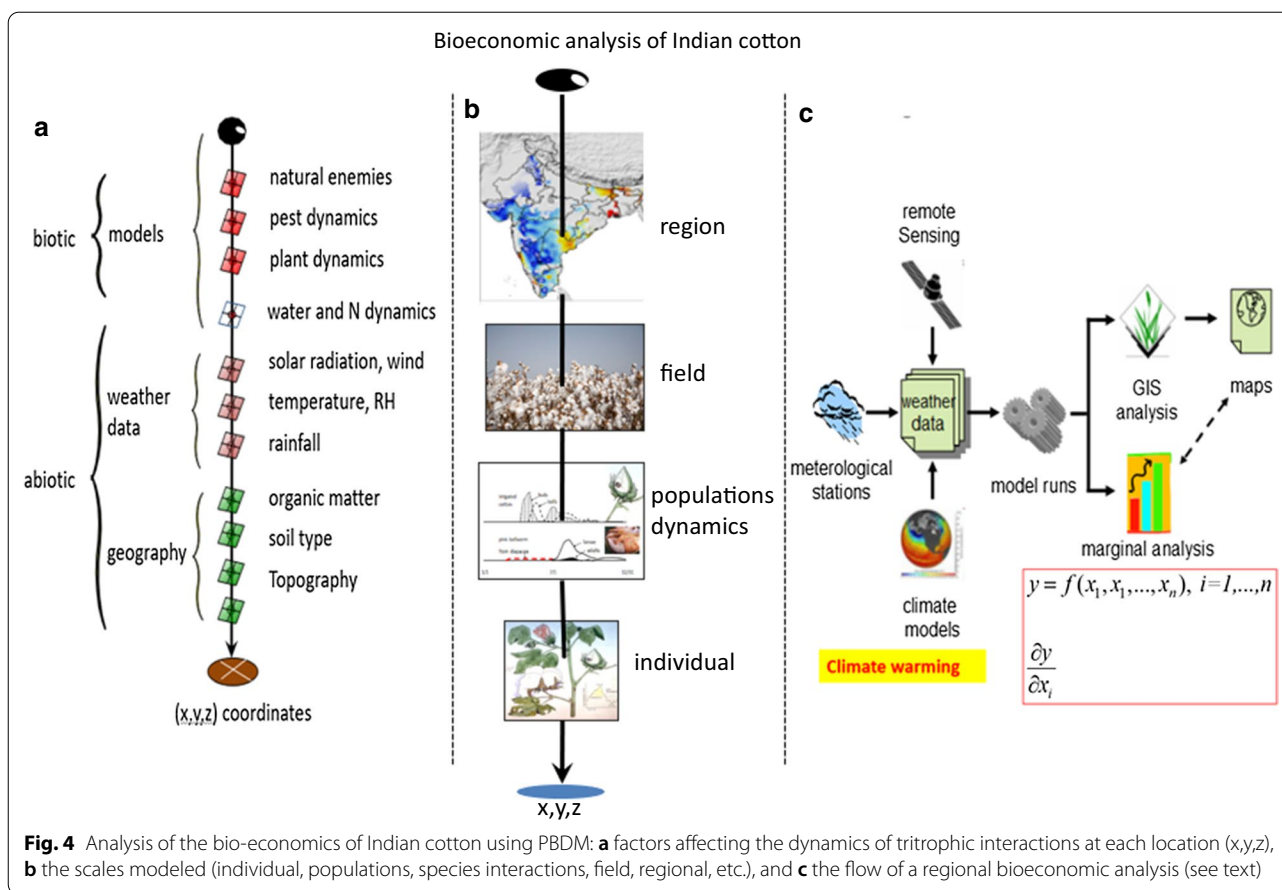
Bioeconomic analysis

The analysis at local and regional scales in India is illustrated in Fig. 4. The major biotic and abiotic factors affecting the system are listed in Fig. 4a, with Fig. 4b illustrating the biological levels and geographic area modeled, and Fig. 4c shows the steps in the analysis at the local and regional GIS levels.

Socio-agroecological context of Indian cotton

Native diploid "Desi" cottons (*G. arboreum* and *G. herbaceum*) have been grown in India for more than 5000 years without synthetic inputs [18]. Indian cotton was the source of fiber for the textile industry in England through the first half of the industrial revolution. Starting in 1790, new world, open-pollinated *G. hirsutum* cotton and later *G. barbadense* were introduced to increase export fiber quality and yield. In the mid-1970s, higher

yielding hand-pollinated long-season F1 hybrid cottons (normally *G. hirsutum*) unique to India were developed [24] ushering increased use of fertilizers, and of insecticide to protect against the native PBW and cotton leafworm (*Spodoptera litura*) [25, 26]. Predictably, insecticides induced regional outbreaks of indigenous secondary pests (i.e. the native bollworm *Helicoverpa armigera*, whitefly, native jassid leafhoppers, aphids, and the invasive mealybug *Phenacoccus solenopsis*) that proved more damaging than PBW [1, 26]. To solve PBW and bollworm problems, transgenic hand-pollinated F1 hybrid long-season Bt cottons unique to India were introduced starting in 2002 [25, 26]. Although F1 Bt hybrid seed is fertile, the F2 seed harvested from F1 plants is not saved for replanting, because highly variable phenotypes result, forcing farmers to purchase seed annually [1]. This provides a value capture mechanism that enables the seed industry to side-step intractable intellectual property rights (IPR) issues in seed saving Indian communities.

By 2012, more than 1000 Bt hybrid varieties of variable quality were planted on > 93% of the cotton area, initially gave good control of PBW (and bollworm), and reduced insecticide use [26–28]. The Bt technology is not yield enhancing, and the modest yield gains that accrued by

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Fig. 4 Analysis of the bio-economics of Indian cotton using PBDM: **a** factors affecting the dynamics of tritrophic interactions at each location (x,y,z), **b** the scales modeled (individual, populations, species interactions, field, regional, etc.), and **c** the flow of a regional bioeconomic analysis (see text)

2006 when Bt cotton adoption was less than 30%, were due to increased use of fertilizer and reduced use of insecticide [26, 28–30]. However, insecticide use began to increase reaching pre-Bt cotton levels by 2012, but now targeted induced hemipteran pests not controlled by Bt cotton [26, 27, 30]. Insecticide resistance in pests increased, a viable refuge strategy failed to develop, and resistance in PBW to Bt toxins became wide spread [31, 32]. Average yields in India are low and in the major cotton growing state of Maharashtra (MH) have plateaued at ~ 350 kg ha^{-1}, and about ~ 550 kg ha^{-1} nationally [30]. At the same time, the costs of labor, hybrid seed, and insecticide greatly increased, while yields remained low and stagnant [30, 33].

The ecological, economic, and social problems in Indian Bt cotton garnered increasing international attention as > 300,000 farmers in all crops committed suicide during 1995–2014 [34, 35]. As this tragedy unfolded, > 95% of cotton farmers became trapped on biotechnology [1, 26] and insecticide [35] treadmills, and access to fertile non-GM seed fell dramatically. The overwhelming evidence is that hybrid Bt cotton in India was failing (Counter Affidavit in the Delhi High Court (2015) (WP(C) No. 12069) (https://indiagminfo.org/uoi-count er-to-mmbl-wp-21-1-2016/; https://indiagminfo.org/Bt-cotton-official-reports) [27, 34].
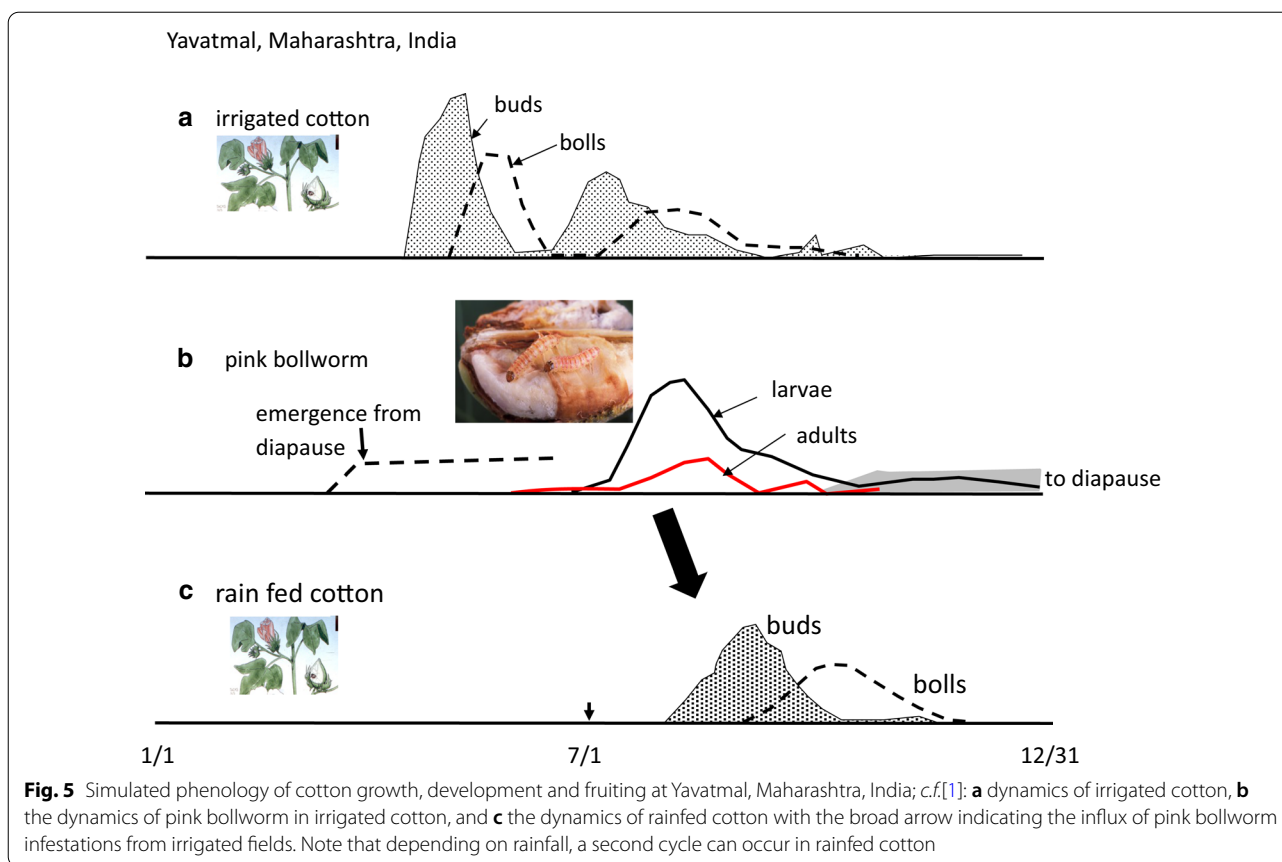
Results
Agroecology of Indian cotton and PBW
Using the analysis path illustrated in Fig. 4, we unpack the Indian cotton system and explore the bioeconomic links to cotton farmer suicides. We first examine cotton at Yavatmal, Maharashtra, India in the heartland of high farmer suicides, to develop an initial understanding of the Indian cotton system, and then we conduct a regional analysis across five states of south-central India. The model computes the full daily age-mass structured dynamics of cotton for all locations (see Additional file 1: S3), but only summary annual statistics are reported here. A robust model to predict initiation of winter dormancy in PBW in response to temperature and photoperiod, and of diapause termination in spring proved critical (Additional file 1: S4, Fig. S9) [36].

Yavatmal, Maharashtra, India
In the state of Maharashtra, the majority of cottons are long-season varieties planted at low densities (~ 2.5 plants

Fig. 5 Simulated phenology of cotton growth, development and fruiting at Yavatmal, Maharashtra, India; *c.f.*[1]: **a** dynamics of irrigated cotton, **b** the dynamics of pink bollworm in irrigated cotton, and **c** the dynamics of rainfed cotton with the broad arrow indicating the influx of pink bollworm infestations from irrigated fields. Note that depending on rainfall, a second cycle can occur in rainfed cotton

m^{-2}). Less than 10% of the cotton is irrigated and planted in early spring, and may grow as late as December–January, resulting in two or more fruiting cycles (Fig. 5a). Absent PBW (and other pests), predicted simulated average irrigated yield during 1998–2010 under non-limiting fertilizer is 671 ± 38.7 kg lint cotton ha^{-1}. (Hereafter, yield is lint cotton ha^{-1}.) However, spring emergence of PBW adults from winter dormant larvae is well timed to infest irrigated cotton (Fig. 5b), and absent control, infestations develop (8.79 ± 0.27 larvae/boll) reducing yield and quality ($0 < \varphi(\text{PBW}) = 1 - 0.0611$ larvae / boll < 1; [36]). This level of infestation reduces average yield to 311.16 kg ha^{-1} see [23, 37, 38].
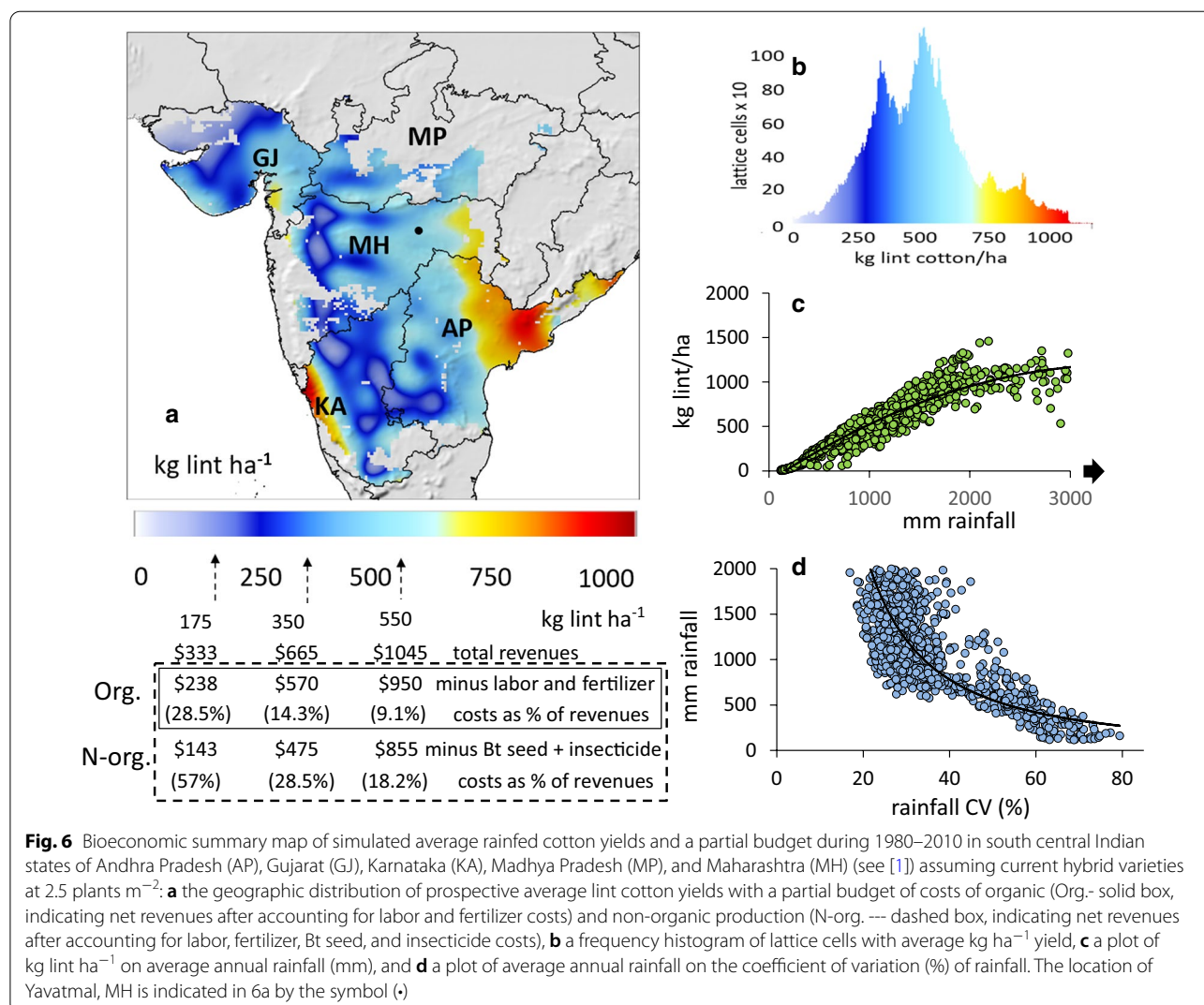
In contrast, $>90\%$ of the cotton in Maharashtra is rainfed, germinates with the onset of monsoon rains in mid-summer (Fig. 5c), and largely escapes infestation by emerging overwintering PBW adults, though infestation inoculum can come from irrigated cotton (i.e., broad solid arrow in Fig. 5). Absent pests, simulated prospective average yield is $503.40 + 56.80$ kg lint ha^{-1}. Depending on rainfall, the rainfed cotton season can extend into December, further increasing the potential for region-wide outbreaks of bollworm and other secondary pests in both irrigated and rainfed cotton [1, 27]. The phenology

of PBW at Yavatmal, MH illustrates the inherent conflict of interest between irrigated and rainfed cotton cultivation in many areas of India.

Regional analysis across south-central India

We explore the bioeconomics of cotton production across 1276 lattice cells (38×38 km) in the south-central states of Andhra Pradesh, Gujarat, Karnataka, Madhya Pradesh, and Maharashtra (AP, GJ, KA, MP, MH). The goal is to provide overview, and to compare model predictions qualitatively to state yield data as a basis for exploring proximate factors that may influence cotton farmer suicides.

Under pest-free conditions, simulated average lint yields of rainfed non-GM long-season cotton planted at 2.5 plants m^{-2} under non-limiting fertilizer are mapped in Fig. 6a, while a histogram summarizes the distribution of average lint yields (Fig. 6b). Simulated yield across the region increases with total annual rainfall (mm) (Fig. 6c; kg ha$^{-1} = -0.0001$ mm$^2 + 0.742$ mm $- 114.71$, $R^2 = 0.84$), and average rainfall is negatively correlated to its coefficient of variation (%) (mm $= 224,996$ CV$^{-1.535}$,

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Fig. 6 Bioeconomic summary map of simulated average rainfed cotton yields and a partial budget during 1980–2010 in south central Indian states of Andhra Pradesh (AP), Gujarat (GJ), Karnataka (KA), Madhya Pradesh (MP), and Maharashtra (MH) (see [1]) assuming current hybrid varieties at 2.5 plants m^{-2}: **a** the geographic distribution of prospective average lint cotton yields with a partial budget of costs of organic (Org.- solid box, indicating net revenues after accounting for labor and fertilizer costs) and non-organic production (N-org. --- dashed box, indicating net revenues after accounting for labor, fertilizer, Bt seed, and insecticide costs), **b** a frequency histogram of lattice cells with average kg ha^{-1} yield, **c** a plot of kg lint ha^{-1} on average annual rainfall (mm), and **d** a plot of average annual rainfall on the coefficient of variation (%) of rainfall. The location of Yavatmal, MH is indicated in 6a by the symbol (•)

$R^2 = 0.66$, Fig. 6d) (i.e. the lower the rainfall, the higher the variability of rainfall and hence of yield).

The yield map (Fig. 6a) is used to estimate partial budgets for organic and non-organic cottons using the yield plateau values of 350 kg ha^{-1} in Maharashtra (MH) and 550 kg ha^{-1} nationally as reference values [30, 33]. The goal is not precise prediction, but rather to provide a basis for comparing organic and non-organic production. The model makes the realistic assumption that the potential yield of organic and non-organic cotton under pest-free conditions are the same. The partial budgets below Fig. 6a are for organic (solid box) and non-organic rainfed cotton (dashed box), while the color bar for yield can be used qualitatively to extrapolate economic results to the region.

For organic cotton (Eq. 2a), $Y_{ij}(u, \overline{w}_{ij})$ is average yield of rainfed cotton in the absence of pests in lattice cells with longitude–latitude coordinates i,j, $\boldsymbol{u}$ is the biology of cotton and PBW, and $\overrightarrow{w}_{ij}$ the vector of daily weather data. The average net revenue ($\Pi_{i,j}$) is kg cotton ha^{-1} multiplied by price ($P_y = \$1.90$ kg^{-1}) minus average exosomatic costs of fertilizer ($C_{\text{fertilizer}}$) and labor (C_{labor}). In reality, organic cotton commands a higher price but that is ignored here. Because the costs in each of the cells are unknown, we use a conservative average of \$95 ha^{-1} for fertilizer + labor. In seed saving India, seed costs are small and are ignored.

$$\Pi_{i,j} = \varphi(\text{PBW}) P_y Y_{ij}(u, \vec{w}_{ij}) - C_{\text{fertilizer}} - C_{\text{labor}}. \quad (2a)$$

At 350 kg lint ha^{-1}, gross revenues for organic cotton are \$665 ha^{-1} (~\$1.82 day^{-1} ha^{-1}), but after correction for fertilizer and labor costs, the net income is ~\$1.56 day^{-1} ha^{-1} (and \$2.60 at 550 kg ha^{-1}). Excluding labor costs increase net daily income by ~\$0.15.

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However, if PBW infestations from irrigated cotton occur, additional exosomatic input costs are incurred for control, converting organic to non-organic cotton. Furthermore, insecticides can induce secondary pests (*SP*) such as the native bollworms and others resulting in higher insecticide use (see text). To control PBW and bollworm, hybrid Bt seed was introduced, noting that Bt toxin does not control hemipteran pests (e.g., whitefly, plants bugs), resulting in continued insecticide use. Hence, we must add the costs of hybrid Bt seed (C_{seed}) and insecticides ($C_{\text{insecticide}}$) ($53 and $42 ha^{-1}, respectively) to the basic costs for organic production (Eq. 2b).

$$\Pi_{i,j} = \varphi(\text{PBW}, \text{SP})P_y Y_{i,j}(u, \vec{w}_{ij}) - C_{\text{fertilizer}} - C_{\text{labor}} \\ - C_{\text{insecticide}}(\text{PBW} = 0, \text{SP} = 0) - C_{\text{seed}}$$

(2b)

For simplicity, we assume that Bt seed effectively controls PBW and bollworm, and that insecticide used does not induce outbreaks of secondary pests (i.e. the best-case scenario, PBW=0, SP=0). In this scenario, Bt seed and insecticide costs decrease income to $1.30 day^{-1} ha^{-1} at 350 kg ha^{-1}, and $2.34 at 550 kg ha^{-1}, with the total costs of production being about 28.5 and 18% of revenues at 350 and 550 kg ha^{-1}, respectively.

With insecticide (*I*) use, new secondary pests are induced requiring still more insecticide with per kg price P_I, making the costs $C_{\text{insecticide}} = P_I I_{i,j}(\text{PBW}, \text{SP})$. Furthermore, secondary pests lower yield and quality ($\varphi(\text{PBW} = 0, \text{SP})$). These additional costs and losses cannot be quantified for each lattice cell, but national data suggest a loss of about 108 kg ha^{-1} per kg^{-1} ha^{-1} of insecticide used due to ecological disruption [33].

To fund production, subsistence farmers may borrow money at interest rates of 5–10% per month [1]. In low rainfall areas such as Yavatmal, MH, the combination of variable low yield due to high variability of rain and pests, and high increasing production costs, increase economic uncertainty and social distress, and likely increase suicides (see [33]).

Analysis of state data on average yield and farmer suicides

Average annual state-level data on yield and costs of inputs (rupees ₹ ha^{-1}) during 1999–2014 are used to explore links between yield and net income on suicides across the five central Indian states. The state-level yield data were summarized graphically [30], but are explored here in greater detail and related to the simulation data (see Additional file 1: S6).

Yield

Multiple linear regression (MLR) of the state data (Eq. 3) shows that combined yield of irrigated and rainfed long-season hybrid varieties increased with kg fertilizer ha^{-1} (*t*

value = 5.56), % of arable land under irrigation ($t = 4.37$), average rainfall during June–December monsoon season in central India (mm rain, $t = 2.03$) ($p < 0.05$), and though not significant, decrease with kg insecticide ha^{-1} ($t = -0.87$). Average rainfall is a metric of the strength of the annual monsoon in central India. The % of area planted to Bt cotton is not significant, but is positively correlated to the increase use of fertilizer (see [30]). Fertilizer and % area under irrigation are the strongest correlates of yield.

$$\text{yield ha}^{-1} = 317.9 + 1.469 \text{ fertilizer} + 9.276\%\text{irrigation} \\ + 0.336 \text{ mm rain} - 34.55 \text{ insecticide}$$
$$R^2 = 0.51, \text{df} = 65, F = 16.79$$

(3)

Ignoring costs of labor (~ 0.15 $/day; Eq. 2a), average annual net revenues per hectare are computed as price x average yield minus average annual costs of seed, fertilizer, and insecticide (e.g., Eq. 2b). Annual lint cotton prices are listed in $, and were corrected by year specific exchange rates (e.g., 75₹ per $ currently). The average percent of total revenues spent on inputs by state during 2012–14 were: AP (23.6%), GJ (17.7%), KA (18.5%), MH (41%) and MP (17.9%) (see Additional file 1: S6, Figs. S10, S11). Eq. 4 is the linear regression of state-level average net profit on average yield (Eq. 4).
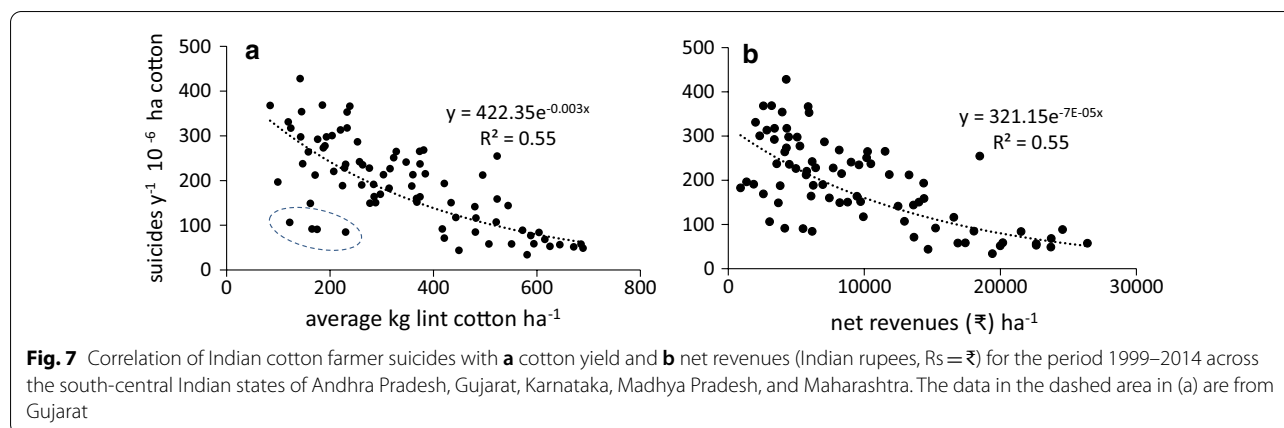
$$₹ ha^{-1} = 150.98 \text{ kg ha}^{-1} -15,661; R^2 = 0.755, df = 65 \quad (4)$$

At 350 and 500 kg ha^{-1}, average incomes are $1.47 and $2.35 d^{-1}, respectively, at 69.12₹/$. These values are similar to the simulation estimates in Fig. 6a.

Farmer suicides

The total number of suicides among farmers in all crops in the five states was 176,844 during 1999–2014. Adjusting for the fraction of farmers growing cotton, 22,763 (12.9%) suicides were estimated to be cotton farmers. Annual numbers of cotton farmer suicides in each state were further adjusted per million ha of cotton and plotted on average cotton yield ha^{-1} and average net revenues ha^{-1} (Fig. 7a, b). The results suggest suicides decrease with increasing yield (Fig. 7a), and net revenues (rupees ₹, Fig. 7b), with the latter being a metric of economic well-being. Plots of suicides on yield, and of net revenues and costs on year are summarized by state in Additional file 1: S6, Fig. S12. The adjusted suicides at low yield in Gujarat are ~ 1/3rd those at the same yield in Maharashtra, and net revenues in Gujarat are generally more than threefold higher. Removal of the Gujarat data does not appreciably alter the relationships in Fig. 7a, b nor R^2.

MLR analysis (Eq. 5) suggests that suicides decrease with increasing yield (kg ha^{-1}, *t* value = − 4.74), cost (₹)

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Fig. 7 Correlation of Indian cotton farmer suicides with **a** cotton yield and **b** net revenues (Indian rupees, Rs = ₹) for the period 1999–2014 across the south-central Indian states of Andhra Pradesh, Gujarat, Karnataka, Madhya Pradesh, and Maharashtra. The data in the dashed area in (a) are from Gujarat

of fertilizer ($C_{fertilizer}$, $t = -2.82$), and % of farmers using irrigation ($t = -3.52$), but increase with costs of *Bt* seed ($t = 2.22$), insecticides ($t = 1.97$), and with rainfall (mm, $t = 2.11$) during the June–September period. High monsoon rainfall extends the season into December (and January) increasing late season pest levels and control costs [38]. In summary, factors that increase yield are correlated with decreased suicides, whereas factors that increase costs but do not contribute to yield (costs of Bt seed, cost of insecticides) are correlated with increased suicides.

$$
\begin{aligned}
\text{suicides } 10^{-6}\text{ha} = {} & 201.03 + 0.033\,C_{seed} + 0.0225 C_{insecticide} \\
& + 0.219\,\text{rain}_{(June-Sept)} - 0.395\,\text{kg lint} \\
& - 0.020\,C_{fertilizer} - 5.039\%_{irrigation} \\
& R^2 = 0.67, \text{df} = 63, F = 21.1,
\end{aligned}
$$

(5)

Suicides among cotton farmers are correlated with factors contributing to economic distress exacerbated by increasing costs in the face of stagnant yields [26, 30].

A bioeconomic solution

Average yield of current hybrid Bt cotton in India is less than half that of many developing economies. For example, during the 2019–20 season, the following developing countries harvests were more than double that of India's 466 kg/ha: China (1758 kg/ha), Brazil (1727 kg/ha), Turkey (1705 kg/ha), Mexico (1644 kg/ha), Kyrgyzstan (1391 kg/ha), Venezuela (1234 kg/ha), Syria (1219), and South Africa (1017 kg/ha), none of which use hybrid cotton, and many do not use the Bt technology [39]. Even African countries with far less scientific infrastructure and lower per capita gross domestic product (GDP), produced higher cotton yields (e.g., Sudan (~ 650 kg/ha) > Ethiopia > Cameroon > Côte d'Ivoire (~ 525 kg/ha). Among the major reasons for low stagnant yields in India

are inappropriate hybrid long-season varieties, sub-optimal planting densities, and insecticide-induced secondary pests [1, 26, 33, 38].

Field trials on rainfed short-season high-density (SS-HD) pure-line, non-hybrid, non-Bt varieties at the Central Indian Cotton Research (CICR) at Nagpur, Maharashtra produced considerably higher yields relative to standard Bt hybrid varieties [40]. For example, variety PKV-081 yielded ~ 668 kg lint cotton ha^{-1} at 16.6 plants m^{-2} under 1005 mm rain (see [40]). Such SS-HD varieties would appreciably increase rainfed yields, reduce seed costs, avoid heavy PBW infestations (see Fig. 5b, c), greatly reduce insecticide use, better utilize available monsoon rain, reduce yield variability, and allow seed saving for replanting. At 668 kg ha^{-1}, net income would increase 2.5 fold to ~ $3.2/day, reduce production-related indebtedness, and likely lower farmer suicides to a background level (see Fig. 7). Still higher yields are possible, as India has the relevant technology to accomplish this [38]. Incorporating the hybrid Bt technology in SS-HD varieties would not increase yield, and the higher planting densities would increase seed costs 6-sevenfold (> $300 ha^{-1}) and reduce income to ~ $2.40 day^{-1}. As in developed economies, fertile pure line Bt SS-HD varieties could be developed providing cheaper seed than current Bt hybrids, but IPR enforcement would be difficult in small farm, seed saving India.

Non-GM SS-HD cotton coupled with early crop termination and plowing saved the irrigated desert cotton industry in California during the mid-1970s from the ravages of the invasive Indian pink bollworm, while giving the same high yield with minimal insecticide use [23, 41]. The SS-HD solution in California was avoidance of dormancy induction in overwintering PBW, while in India, it would be avoidance of emerging adults from winter dormancy. However, implementation of pure-line non-GM SS-HD varieties would require farmer training in field

schools to transition them from long-season cotton practices and insecticide use.

Effects of climate change on Indian cotton

From an agronomic perspective, climate change is simply another weather pattern. Comparison of simulated average yields of current hybrid Bt cotton at optimal densities of 6–8 plants m^{-2} during 1975–1985 to average yields under + 1.5 °C climate change during 2040–2050, predicts an average increase of ~ 50 kg ha^{-1} (see [1]). (We note that increased levels of CO_2 would increase yield further [42], the effects of which can be easily added to the model.) The increase in yield has a simple explanation: temperatures during the cooler monsoon season would increase under climate change becoming more favorable for cotton. However, the 2.5–3.5-fold increase in hybrid Bt seed costs at 6–8 plants m^{-2} would off-set the gains. The effects of climate warming on other crops is unknown, but has been posited to increase farmer suicides [43].

Discussion and conclusions

Nature is not idiosyncratic (see [2]), because despite the myriad of life history strategies in nature, all species have common bioeconomic underpinning processes for resource acquisition and allocation enabling the development of stability and persistence of natural ecosystems [6–9]. The myriad species have different resource bases, units, and per capita rates, but all organisms, including humans (and firms), acquire renewable resources, that after correction for egestion (wastage), are allocated by analogy in the same priority order to conversion costs (production costs), respiration (maintenance costs), reproduction (profits), and growth (infrastructure development) [8, 9, 13, 14]. Humans have adapted some natural systems for agricultural purposes (e.g., corn, coffee, cotton, rice), but mismanagement may threaten their sustainability. It is increasingly recognized that large cross-scale problems in agriculture (and natural systems) are bioeconomic in nature, and that extant methodological barriers can be surmounted with mechanistic process-based models of mass-energy flow dynamics [44, 45]. Physiologically based demographic models (PBDMs) have been used to capture the time-varying, age-stage structured dynamics of species and their interactions, enabling assessment of the bioeconomy of individuals to multi-species populations across geographic space, time, and technology and climate change (see [46]). The PBDM construct is conceptually simple and has few parameters, and though not cast as physics, describe open systems

that conforms to the Laws of Thermodynamics (cf [47, 48]).

The PBDM approach was used here to analyze the energy flow dynamics underpinning the complex bio-economics of the dystopian Indian cotton system. The transition from simple bioeconomic theory was straight forward. The PBDMs captured the dynamics of irrigated and rainfed cotton and the dynamics of its key pest, the native pink bollworm (PBW), across five states of south-central India; (see [1]). The model explained how PBW infestations from irrigated long-season cotton to rainfed cotton increased insecticide use in both systems leading to regional outbreaks of primarily indigenous secondary pests such as the native bollworm. F1 hybrid long-season Bt cotton unique to India was introduced starting in 2002 to solve the insecticide-induced bollworm problem, and resulted in unanticipated adverse ecological–social consequences. Though, hybrid Bt cotton initially provided good control of PBW and bollworm and reduced insecticide use, by 2012, insecticide use increased to pre-2002 levels, but now targeted still newer induced hemipteran pests not controlled by the Bt toxins [26, 27, 29, 30]. Furthermore, yields plateaued nationally at low levels despite > 93% Bt cotton adoption [26, 30], insecticide resistance in pests increased, and resistance to Bt toxin(s) in pink bollworms is becoming widespread [32]. Long-season hybrid Bt cotton and high seed prices encourage low planting densities (~ 2.5 plants m^{-2}), and are important factors in stagnant low average yield and income in the face of increasing production costs, making the technology economically unsustainable for subsistence Indian cotton farmers, especially under rainfed conditions. Furthermore, most of the yield increase after Bt cotton introduction was due to increased use of fertilizer [28, 30]. When viewed from an objective perspective, a failed picture emerges of an unsustainable eco-social hybrid Bt cotton system based on a dystopic relationship between those who control and sell the inputs, and the vast majority of farmers that given their level of information and education attempt to implement them. This situation greatly increased economic and social distress among subsistence cotton farmers. Though suicides occur for various reason, the annual statewide data show that suicides year^{-1}10^{-6} ha cotton are inversely correlated to net income (Fig. 7b).

In India, analysis of suicide data is difficult due to a dearth of reliable data. Based on utility theory from economics, Hamermesh and Soss [49] in 1974 proposed a theory of suicides. They found the age distribution of suicides differs among developed countries, and hypothesized that an individual commits suicide when the total

remaining lifetime utility reaches zero, that the expected suicide rate increases with age and is inversely related to permanent income, but the marginal absolute effects on suicide declines as permanent net income increases. In contrast, the annual income of subsistence Indian rainfed cotton farmers is highly variable, especially in areas of low rainfall with high variability. Cotton farmer suicides in India peak in the age bracket normally associated with the most productive years of life, but as suggested by the correlation in Fig. 7b, the rate decreases with increasing net income. We note that economic and related health-social distress are also increasing suicides among farmers in the developed countries [50].

For India, field trial data show that pure-line short-season (SS), high-density (HD), non-GM rainfed varieties are a viable alternative [39] to hybrid Bt varieties [33, 38]. SS-HD cotton would largely escape pink bollworm infestations and the buildup of late season pests, greatly reduce the need for insecticides, allow seed saving, and double yield and increase net income, and likely reduce suicides (see Fig. 7). In the mid-1960s in California, SS-HD cotton and post-harvest plowing saved the irrigated cotton industry from the invasive pink bollworm by curtailing the development of dormant overwintering stages [41]. In India, rainfed SS-HD cotton would largely avoid infestation by adults emerging from winter dormancy (see Fig. 5). Furthermore, the hybrid Bt technology is incompatible with the SS-HD technology, because GM seed costs would greatly increase due to higher seeding rates without commensurate increases in yield, and would prevent seed saving. If cotton is grown organically, profit would accrue due to soil improvements, through reduced exposure to toxic chemicals and lower input costs, which in turn reduces dependency on money lenders [51]. Fertile pure-line SS-HD non-GM cottons have been available for quite some time in India, but have not been widely implemented, and the obvious question is why? However, despite their utility, SS-HD cotton varieties are not a guarantee against the *gamble of the monsoon*, but they would lessen the impact.

Materials and methods
Energy-mass flow models
An exposé of the principles used to model the biology of cotton systems under time-varying conditions is found in the Additional file 1: S3, with simplifications outlined in S4. The models for all species are intrinsically the same, and much of the computer code is recycled in an object-oriented mode. Furthermore, PBDM systems have a modular structure allowing different species to be included in runs using Boolean variables.

Models with age, stage, and mass structure
Two linked age-structured dynamics model for mass and numbers are used to model plant reproductive units with sub-stages (s = buds, flowers, maturing fruits, and mature fruit), while single age-mass structured models are used for each of the other subunits (leaves, stem, roots). A similar approach is used for the mass and number dynamics of each life stage of an insect (s = egg, larval, pupae, adults, etc.). Ignoring the stage script, the dynamics models for number (n) and mass (m) dynamics of a population can be modeled using Eq. 5a, ii below [11, 52, 53] or alternately see [54].

$$\frac{dn_i}{dt} = \frac{k\Delta_x}{\Delta}[n_{i-1}(t) - n_i(t)] - {}^n\mu_i(t)n_i(t), \qquad (5a)$$

$$\frac{dm_i}{dt} = \frac{k\Delta_x}{\Delta}[m_{i-1}(t) - m_i(t)] - {}^m\mu_i(t)m_i(t), \quad (5b)$$

where n_i and m_i are the linked number and mass as rates, respectively, for the ith age class ($i = 1,...,k$) at time t with the number of age classes $k = \Delta^2/$variance approximating the Erlang distribution of observed developmental times, dt is the change in time (e.g., a day), Δ is the expected mean developmental time in physiological units (e.g., degree days), Δx is the daily increment of physiological age, and ${}^n\mu_i(t)$ and ${}^m\mu_i(t)$ are the proportional age-specific loss rates as modified by temperature, age, migration and mortality due to S/D < 1, and natural enemies. Note that ${}^m\mu_i(t)$ also includes the proportional increase or decrease of biomass allocated to the ith stage-age [11]. The number and mass density functions of a life stage (left superscript s) are ${}^sN(t) = \sum_{i-1}^{k} n_i(t)\Delta/k$ and ${}^sM(t) = \sum_{i=1}^{k} m_i(t)\Delta/k$ respectively, with average mass of a stage being ${}^s\overline{M}(t) = {}^sM(t)/{}^sN(t)$. The daily time step in the cotton model is a day of variable physiological time (degree days or proportional development). The numerical solution for Eqs. 5a, 5b, uses Euler's integration [see code in Additional file 1: S5; ([11]. p. 227)].

Simulations and weather data
The landscape of India, excluding Andaman and Nicobar Islands, was divided into 2855 38×38 km lattice cells, and daily weather data (i.e., max−min temperature, solar radiation (W m^{-2}d^{-1}), mm rainfall, and % RH) for each cell during 1979 to 2010 were used to run the models. The weather data were obtained from the Climate Forecast System Reanalysis (CFSR) of the United States National Centers for Environmental Prediction [55]. The CFSR is a global, high-resolution, coupled atmosphere-ocean-land surface-sea ice system that estimates the

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state of these coupled domains. Regional average annual rainfall was used in the statistical analysis as a metric of the strength of the annual monsoon rains. All simulations and GIS maps (GRASS GIS: a multi-purpose Open Source GIS [56]) were made on a laptop computer.

Agronomic data

The annual state average data on cotton yields (Y_{MA}), irrigated area, percentage of cotton farmers, and averages of insecticide and fertilizer (amounts and costs) ha^{-1} were obtained from the Government of India, Ministry of Agriculture. Prices per kg lint cotton during the period 1995 to 2019 are from https://www.indexmundi.com/commodities/?commodity=cotton&months=310&currency=inr. A second data set for annual state average cotton yields are available from the Ministry of Textiles (Y_{MT}), Government of India, but are less consistent, especially for the state of Madhya Pradesh which show little change in cotton yield during 1999–2015 (see [30]). The relationship between the two data sets for yield (kg/ha) is $Y_{MT} = 0.75\ Y_{MA} + 195.47$ ($R^2 = 0.53$). The regression for Madhya Pradesh data alone yields $R^2 = 0.001$. Removing the Madhya Pradesh data gives $Y_{MT} = 1.05\ Y_{MA} + 60.4$ ($R^2 = 0.83$).

Suicide data

The data on farmer suicides across all crop systems for the period 1999–2014 are from the National Crime Records Bureau, Ministry of Home Affairs, Government of India (https://ncrb.gov.in/adsi-reports-of-previous-years). The method of recording suicides changed after 2014 and the data are inconsistent with the prior data, and hence were not used in the analysis.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1186/s12302-020-00406-6.

Additional file 1: S1. Approaches to analyze ecological complexity. **S2.** Analogies between biological and human economic systems. **S3.** Physiologically based demographic models. **S4.** Simplifying PBDM development using biodemographic functions (BDFs). **S5.** Borland Pascal code for the delay model with and without attrition. **S6.** Summaries of statewide data for AP, GJ, KA, MH, and MP used in the text.

Abbreviations
Bt: GM modification of cotton to produce toxin(s) from the bacteria *Bacillus thuringiensis* to control moth pest; GIS: Geographic information system technology; GM: Genetically modified; SS-HD: Short-season high-density cotton; IPR: Intellectual property rights; PBDM: Physiologically based demographic model; PBW: Pest pink bollworm.

Availability of data and materials
All the data were from Government of India sources referenced in the text. Similarly, all the weather data are available from cited sources. The Borland Pascal code for the distributed maturation time model with and without attrition used in PBDMs is available in the supplementary materials.

Ethics approval and consent to participate
Not applicable.

Consent for publication
All authors have read and approved the manuscript.

Competing interests
The authors declare no competing interests in this public good research.

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