Green to evergreen revolution: ecological and evolutionary perspectives in pest management

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The experience and lessons learnt from the green revolution make it imperative that sustainable productivity requires strict adherence to agricultural practices which ensure integrity of the ecological foundations of agriculture. Use of chemical fertilizers and pesticides, no doubt, result in enhanced productivity over short periods, but lead to degradation of soil health, freshwater and biodiversity in the long term. Evergreen revolution defined as achieving productivity in perpetuity 'without' causing ecological harm involves less dependence on chemical and more on biological inputs. With special reference to pest management, this article brings out how in a chemical pesticide-free environment, the predators and parasites (natural enemies of pests) keep the damage caused by crop pests 'below economic injury level'. Hence, culturing biopesticides (e.g. Trichogramma chilonis, Trathala flavo-orbitalis) and releasing them in the crop fields provide 'pro-nature', 'pro-poor' and 'pro-women' solution to reducing loss by borers in cotton, brinjal, etc. When these are done by landless women who are facilitated to undertake production of biopesticides as an ecoenterprise, the famine of rural livelihood is also tackled. Scientific, environmental and socio-economic aspects of biopesticides have been briefly presented here.

Keywords: Eco-friendly approaches, green to evergreen revolution, pest management, productivity in perpetuity.

Green to evergreen revolution

IN his commentary, Gahukar[1] has brought out the role of phytochemicals in pest management. He has also aptly pointed out that toxicity of phytochemicals to beneficial insects (honey bees, pollinators, predators, parasitoids) should, however, be first assessed.

The significance of eco-friendly and economical methods of pest management in the realm of 'evergreen agriculture'[2–7], to fight the famines of food as well as rural livelihood with technologies having pro-nature, pro-poor and pro-women orientation needs no overemphasis. The purpose of this article is to describe why the 'exploitative' green revolution of the 1960s and 1970s needs to be transformed into an 'evergreen revolution' (eco-friendly 'second' green revolution), and the effective eco-friendly approaches to manage crop pests, especially the lepidopteran borers such as American bollworm (*Helicoverpa armigera*) and brinjal fruit and shoot borer (*Leucinodes orbonalis*) at below 'economic injury level'.

Today, it is widely acknowledged that the 'yield gains' associated with the green revolution of the 1960s and 1970s have tapered off largely because of deterioration in the structure, quality and fertility of the soil. Further, the groundwater source for irrigation has become greatly depleted, as also the useful genes locked up in several locally adapted indigenous varieties and land races, for future food security. This is so because the low-yielding but locally adapted indigenous varieties are no longer widely cultivated in view of the greater economic attractiveness of the high-yielding green-revolution varieties of wheat and rice. The goal, rather myopic, is immediate economic gains than 'long-term sustainable yields' by maintaining ecological integrity, especially of soil, freshwater, biodiversity, renewable energy, etc.

It is indeed unfortunate that this situation has resulted in spite of appropriate analysis of the ecological risks of the then new 'green revolution' and the 'precautionary principle' proposed as early as 1968 by Swaminathan[8], who had been specially mentioned as the major architect of India's green revolution by the Nobel laureate late Norman Borlaug. Swaminathan[8] had emphasized, 'exploitative agriculture offers great dangers if carried out with only an immediate profit or production motive. The emerging exploitative farming community in India should become aware of this. Intensive cultivation of land without conservation of soil fertility and soil structure would lead, ultimately, to the springing up of deserts. Irrigation without arrangements for drainage would result in soils getting alkaline or saline. Indiscriminate use of pesticides, fungicides and herbicides could cause adverse changes in biological balance and lead to an increase in

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the incidence of cancer and other diseases, through the toxic residues present in the grains or other edible parts. Unscientific tapping of undergroundwater will lead to the rapid exhaustion of this wonderful capital resource left to us through ages of natural farming. The rapid replacement of numerous locally adapted varieties with one or two high-yielding strains in large contiguous areas would result in the spread of serious diseases capable of wiping out entire crops, as happened prior to the Irish potato famine of 1854 and the Bengal rice famine in 1942. Therefore the initiation of exploitative agriculture without a proper understanding of the various consequences of every one of the changes introduced into traditional agriculture, and without first building up a proper scientific and training base to sustain it, may only lead us, in the long run, into an era of agricultural disaster rather than one of agricultural prosperity.'

It is of interest to note that the term 'green revolution' was coined by William Gadd (US Department of Agriculture), whereas Swaminathan[8] referred to it as 'exploitative agriculture', and that it would cause more damage than good in the long run, if practised without adherence to scientific principles of soil, water management, and biodiversity conservation and enhancement. What is indeed an expanding misfortune in the current Indian farming system scenario is that the bitter lessons learnt from the green revolution are either forgotten or set aside as inconvenient, for whatever reasons. The *Bt*-hybrid cottons which require large inputs of chemical fertilizers and pesticides (although in reduced quantities) largely follow the green-revolution pathway. Hence, it is most likely that in the course of the next few years, there would be adverse ecological impact in the present *Bt*-cotton tract of India. Further, evolution of *Bt*-resistant bollworms would be a serious setback to contend with.

During the decades after the green revolution, it became evident that although it resulted in food security at the national level, it did not percolate down to the individual level of millions of resource-poor, marginal farming, fishing and landless rural families. Hence, India continues to be home to the largest number of hungry people in the world. It is not because of lack of availability of food in the country, but due to lack of income-generating livelihoods, particularly in the rural areas. Nearly 700 million people live in India's villages numbering to more than 600,000. Today, about 20% of Indians suffer from endemic hunger and nearly 25% are malnourished. The Indian food security scenario at the national and individual levels has been aptly described as a paradox of 'mountains of grains on the one hand, and millions of hungry people on the other'.

Over the years, precipitous degradation of freshwater sources, soil quality, biodiversity, renewable energy sources and forests on the one hand, and unabated population growth rate also coupled with unsustainable consumerism on the other has led to serious threat to livelihood and food security, especially in the rural areas. Many great thinkers, both natural and social scientists, became deeply concerned with the ever-increasing 'ecological footprint', and decreasing 'biocapacity' of India. Therefore, the need for sustainable agriculture, sustainable management of natural resources for sustainable food security and rural development became a major preoccupation. Taking stock of all the problems and the best options available to solve these, Swaminathan[3–12] proposed that the green revolution should be transformed into the evergreen revolution which he defined as 'achieving productivity in perpetuity without accompanying ecological harm'. Although the green revolution has been essentially commodity-centred, the evergreen revolution is based on a 'systems approach'. The maintenance of ecological integrity in the farming system is indeed the cornerstone for evergreen revolution. The term 'productivity' alluded to by Swaminathan[3,9–12] in the evergreen revolution includes both the productivity of crops and farm animals, as well as of on-farm and non-farm eco-microenterprises run by rural women and men, mostly by forming self-help groups (SHGs)[13]. In essence, the evergreen revolution consists of sustainable management of local resources available in a given village for developing 'mixed dynamic farming' (crops plus farm animals) in one of several models of eco-friendly agriculture[14] and also on-farm and non-farm eco-microenterprises for livelihoods, especially for the landless, and the resource-poor, marginal farming and fishing families[13,15]. These essentially describe how with knowledge and eco-technological empowerment of the resource-poor, largely illiterate and unskilled rural women and men, it would be possible to transform both the green revolution and subsistence farming agriculture into vibrant evergreen revolution. With its eco-agriculture and eco-enterprise components, the evergreen revolution is the most viable option yet available to fight both the famines of food and rural livelihoods without causing ecological harm. E. O. Wilson (Harvard University) has acknowledged Swaminathan's evergreen revolution as the best available option to produce adequate food to meet the needs of the rapidly growing human populations and at the same time, save the rest of life on planet earth[16]. The M.S. Swaminathan Research Foundation (MSSRF) with its headquarters in Chennai, and field centres in Kerala, Orissa, Maharashtra, Tamil Nadu and Puducherry has been engaged for over two decades in training and capacity-building, facilitating the rural women and men in eco-agriculture and sustainable management of several eco-microenterprises. Eco-technologies are the resultant of blending frontier technologies with traditional knowledge and ecological prudence of the rural and tribal people. In their development and dissemination to rural communities, the eco-technologies have pro-nature, pro-poor and pro-women orientation. Thus they not only rest on well-established scientific foundation, but also integrate traditional knowledge and wisdom which have the advantage of having been tested on field over long periods of time. It should also be mentioned that both the eco-agriculture and eco-microenterprises within the framework of the evergreen revolution are not only pro-nature, pro-poor and pro-women in orientation, but also 'bottom-up' in design, development and execution. There are several hundreds of eco-enterprises based on eco-technologies and in the present context, biopesticide, an egg parasitoid (*Trichogramma chilonis*) production by landless rural women is particularly relevant.

Eco-microenterprise of biopesticide

With primary goals of achieving both food security and livelihood security in perpetuity without causing degradation of the ecological foundations of agriculture, care needs to be taken to develop and use biopesticides and biofertilizers within Integrated Pest and Nutrition Management (IPNM) schedules. In the scientific literature, it is well-documented that chemical pesticides are not pro-nature, pro-poor and pro-women. Because they kill several non-target beneficial organisms[17] (e.g. pollinators, predators, parasitic wasps, earthworms, birds, etc.), they are not eco-friendly. The carcinogenic action of pesticide residues and the increased incidence of cancers among the farmers and their family members in the green revolution belt is well documented. Further, the chemical pesticides are becoming increasingly expensive, costing beyond the means of the resource-poor, marginal and small farmers. And the India's farming system predominantly consists of over a hundred million resource-poor, marginal farmers who cannot afford to buy and spray the chemical pesticides. Hence, these are not pro-poor. Further, the chemical pesticides are not amenable to be produced in the huts and small houses of the marginal farming and landless women in terms of high-level technology, capital investment and management. So, it is not pro-women in nature. Hence, MSSRF has demystified the production of a biopesticide, an egg parasitoid, *T. chilonis* (Hymenoptera, Trichogrammatidae) and trained several landless women in over dozens of villages in Tamil Nadu and Puducherry to culture and market these. The *Trichogramma*, an effective egg parasitoid, lays its eggs on the eggs of cotton bollworm (*H. armigera*). On hatching, the *Trichogramma* larvae feed on the egg contents of the bollworm leading to significant reduction in the population of the pest. The 'economic injury level' is not totally eliminated, but consistently managed in a 'win-win' manner between ecology, health of the farmers and economics. The biopesticide effectively reduces the damage caused by bollworms to a level that still allows appreciable levels of productivity and profit, leaves no toxic residue to nontarget organisms (i.e. biodiversity is left intact) and does not increase the incidence of cancers to the exposed workers and members of the farming families. In addition, the predator and parasitic species which are not targeted and killed by *T. chilonis*, also participate in attacking the bollworm. The largely illiterate, landless women forming themselves into SHGs are trained to produce *Trichogramma* biopesticide in large quantities by culturing these on rice moth (*Corcyra cephalonica*). The training is imparted through a 'pedagogic method of learning by doing'. Swaminathan[18] coined the term 'techniracy' to describe the same. The details of culturing *Corcyra* and *Trichogramma* and distribution of the parasitized eggs to the farmers at a certain price, or selling these to companies on reasonable profit are published elsewhere[19]. The production and marketing of *Trichogramma* biopesticide by landless women SHGs for eco-friendly management of bollworm is a good example of a pro-nature, pro-poor and pro-women technology. It is pro-nature because it does not leave any toxic effect in the environment, substantially parasitizes the eggs of bollworm (*H. armigera*) and to a lesser extent the fruit and shoot borers (*L. orbonalis*). It is strikingly pro-poor and pro-women in orientation because it provides income-generating, eco-friendly livelihood for landless women who earlier had been living in abject poverty. It is also pro-nature since its use does not diminish the continued presence of a larger number of predator and other parasitic species in the fields in comparison to those fields, where mostly chemical pesticides in non-integrated pest management (IPM) mode are used (Table 1).

That chemical pesticides have caused ecological havoc and enhanced the incidence of cancer, especially among the members of the farming families in the green revolution belt (Punjab and Haryana) of India, is well documented. Further, the cost of chemical pesticides is steeply increasing. This, leads to spurious and ineffective chemical substances being sold, resulting in unbearable economic loss to thousands of resource-poor farmers.

Bt-transgenics in evergreen revolution

General

It is now widely acknowledged that modern biotechnology (r-DNA technology) to develop genetically modified crops (GM crops) is not a panacea for increasing food production to meet the increasing demand. However, this technology could be useful in providing genetic shielding against an array of biotic and abiotic stresses of the crop plants. Biotic stresses to crop plants are caused by insect pests and plant pathogenic organisms (fungi, bacteria and viruses). Modern biotechnology provides a means to transfer *Bt*-toxin (*Cry1AC*, *Cry1AB*, etc.) to the crop plants. The toxic 'Cry proteins' are said to kill selectively the lepidopteran insect species which include *Helicoverpa*, *Leucinodes*, etc. *Bt*-toxin produced by the trans-

Table 1. Prevalence of pests and their natural enemies in the IPM and non-IPM cotton fields

Arthropod fauna	Population status: IPM adopters*	Population status: Non-IPM adopters**
Insect pests		
Helicoverpa armigera	2–3% damaged fruiting bodies; one larva per 10 plants; one damaged boll/plant from 20 randomly selected plants	30% damaged fruiting bodies; one larva per plant; three damaged bolls/plant from 20 randomly selected plants
Pectinophora gossypiella	5% infested flowers/bolls	10% infested flowers/bolls
Amrasca biguttula biguttula	One jassid/nymph per five leaves; third-grade jassid injury	Two jassids/nymph per leaf; second-grade jassid injury (yellowing in the margin of leaves)
Bemisia tabaci	Less than five nymphs per leaf	5–10 nymphs per leaf
Beneficial insects		
Parasitoids		
Egg parasitoids	*Trichogramma* spp.	Absent
Larval parasitoids	*Campoletis chlorideae*, *Bracon hebetor*, *Bracon greeni*, *Apanteles* sp., 1–2 cocoons/parasitized larvae per 5 plants	Absent
Predators		
Coccinellids	*Cheilomenes sexmaculatus*, *Coccinella septempunctata*, *Cryptolaemus montrouzieri*, *Anagyrus* sp., 10–20 per 5 plants	Absent
Dragon flies	*Pantala flavescens*	1 or 2 per plant
Damsel flies	*Agriochemis feminafemina* – abundant	
Green lace wings	*Chrysoperla carnea* – 5–10 adults per plant	1 or 2 per plant
Aranae		
Spiders	*Oxyopes* sp. and *Tetragnatha* sp. – numerous	
Predatory birds		
House sparrow	*Passer domesticus*	Absent
Black drongo	*Dicrurus macrocercus*	
Common mynah	*Acridotheres tristis* – abundant	
Others		
Earthworms	60% population	10–15% population

*IPM includes use of biopesticide as spray, *Trichogramma* cards, pheromones, mechanical elimination with a few chemical pesticides sprays.
**Use of mostly chemical pesticides as sprays.

genic *Bt*-plants is not so well exposed to sunlight and therefore, not so readily degraded as the *Bt*-biopesticide formulation for use as spray. *Bt* when used as a biopesticide spray degrades on exposure to sunlight in a few days. Hence, the degradation of *Bt* in transgenic plants is much slower, with toxic activity lasting longer.

Studies reveal that *Bt*-transgenic crops could adversely affect the non-target monarch butterfly larvae[20,21]. A matter of even greater concern, however, is that it could cause harm to organisms other than lepidopterans. The claim that *Bt*-Cry toxin proteins do not cause any harm to non-lepidopteran insect species is challenged by observations that *Cry1Ab* is toxic to the beneficial predator, *Chrysoperla carnea*, which belongs to Neuroptera[22]. There have been studies describing the adverse effects of *Bt*-corn litter and *Bt*-transgenic plant root exudates on the earthworm (*Lumbricus terrestris*)[23–26].

Similar results from in-field monitoring of beneficial insect populations in transgenic corn expressing *Bt*-toxin have been reported from USA[27]. Recently, scientists from the University of California, USA, have shown that *Bt*-Cry5B protein is highly efficacious as a single-dose therapy (SdT) against an intestinal roundworm infection in mice[28]. The roundworm infection is now recognized as one of the 'neglected tropical diseases'. The point is that these observations need to be taken seriously, from both ecological and human health points of view, and more studies using appropriate experimental designs have to be carried out in future. However, the purpose here is not to review the literature in this regard, but to emphasize that *Bt*-transgenics do not seem to selectively destroy only the lepidopteran borers, but also possibly other non-target species, including beneficial organisms. In this regard, data from the field studies (Table 2) carried out by MSSRF indicate the possible susceptibility of a wide spectrum of pests and beneficial insect species to *Bt*-transgenic.

A recent study reports[29] that bollworm has become resistant to *Bt*-toxin. It describes that large number of pink bollworms from Bollgard cotton, a first-generation

Table 2. Pests and natural enemies of eggplant in a few areas in Tamil Nadu

Arthropod fauna	Scientific name	Family
Pests		
Hemiptera		
Aphids	*Aphis gossypii*	Aphididae
Leaf hoppers	*Amrasca devastans*	Cicadellidae
Mealy bugs	*Centrococcus insolitus*	Pseudococcidae
White flies	*Bemisia tabaci*	Aleyrodidae
Lacewing bugs	*Urentius hystricellus*	Tingidae
Stink bugs	*Nezara viridula*	Pentatomidae
Cow bugs	*Oxyrhachis tarandus*	Membracidae
Lepidoptera		
Fruit and shoot borer	*Leucinodes orbonalis*	Pyraustidae
Leaf miner	*Pthorimaea operculella*	Gelechiidae
Coleoptera		
Spotted leaf beetles	*Henosepilachna vigintioctopunctata*	
Ash weevils	*Myllocerus* spp.	
Acarina		
Red spider mites	*Tetranychus cinnabarinus*	Tetranychidae
Natural enemies		
Parasitoids		
Egg-larval parasitoids	*Phanerotoma* sp.	Braconidae
Larval parasitoids	*Campyloneurus mutator*, *Iphiaulax* sp.	
Larval–pupal parasitoid	*Trathala flavoorbitalis*	Ichneumonidae
Larval parasitoids	*Peristomerous testaceus*, *Diadegma apostata*, *Eriborus argentiopilosus*, *Eriborus sinicus*	
Predators		
Coccinellids	*Cheilomenes sexmaculatus*, *Coccinella septempunctata*, *Brumoides suturalis*, *Scymnus coccivora*	Coccinellidae
Syrphid flies	*Ischiodon scutellaris*, *Paragus serratus*	Syrphidae
Green lace wings	*Chrysoperla carnea*	Chrysopidae
Aranae		
Spiders	*Oxyopes* sp. and *Tetragnatha* sp.	Oxyopidae, Tetragnathidae

From refs 31–33.

GM hybrid expressing a single *Bt*-toxic protein, were collected during 2009 from cotton fields in Gujarat. These were also found to resist normally lethal concentrations of *Bt*-toxin fed to them in the laboratory.

Right from the beginning, evolutionary biologists have been cautioning that successive generations of bollworm feeding on *Bt*-cotton would develop resistance to the toxin on account of mutations (possibly directed mutagenesis) and natural selection. Not all the bollworms in the *Bt*-cotton are killed by the *Bt*-toxin. Several of them survive and reproduce. It is in these survivors that mutations in the gametes conferring resistance to *Bt*-toxin spontaneously occur. When the gametes carrying mutant alleles participate in fertilization, the resulting embryos carrying these alleles initially in heterozygous state, may show some resistance. The natural selection within the *Bt*-transgenic population would, however, favour the *Bt*-resistant allele in successive reproduction. In other words, gametes bearing the Bt^{+} (resistant) allele would gain advantage in a random mating population. In the succeeding generations, there will be increasing number of homozygous *Bt*-resistant bollworms – 'the super pest'. With *Bt*-resistant genes already present in their genomes, it should not take a long time for them to develop appreciable resistance against bollgard-2 as well. Since the very beginning, the protagonists of *Bt*-transgenics have been insisting on growing several rows of non-*Bt*-crops as 'refuge crop' to attract the borers away from the transgenic crops. This idea has never been seriously questioned as to how effective it would be, and for how long! Commercial expediency rather than a strong scientific premise of sustainable agriculture in the best interests of the resource-poor, marginal cotton growers has led to the decision to rush *Bt*-cotton into market. It must also be mentioned here that *Bt*-transgenic hybrid cottons developed with the intention of getting better yields have much in common with the 'negative aspects' of the green revolution. These require not only high-level inputs of chemical fertilizers, irrigation, etc. but also application of chemical pesticides to buttress the killing effect of *Bt*-toxicity.

The distinction between 'biotic' and 'abiotic' stress to crop plants needs to be kept in view in developing transgenics as a solution. Darwinian evolution operates in the world of biological pests and parasites, and would lead to the emergence of resistant organisms sooner than later, and therefore, transgenic biotic resistance in crop plants cannot be a sustainable long-term solution. Environmental factors (salinity, drought, etc.) exerting 'abiotic' stress on the other hand, would be free from the dynamics of organic evolution, and the transgenic crops with genetic shielding for salinity and drought tolerance might, therefore, be more stable. Uncertainties arising from random unpredictable insertion of the alien gene, its possible 'position effect' and possible detrimental effects on consumers, other non-target organisms and biodiversity are still the same. It would, therefore, be prudent to search for genes for abiotic stress among the closely related varieties, land races and species isolated, or not, by barriers to sexual reproduction. These facts emphasize the need for greater priority to conserve biodiversity, particularly agro-biodiversity.

Specific to brinjal (eggplant)

Srinivasan[30] has presented an impressive list of several predator and parasitoids attacking the eggplant (brinjal) fruit and shoot borer (EFSB) (*L. orbonalis*) in nature, and how especially the parasitoid, *Trathala flavo-orbitalis* effectively reduces the EFSB population. In combination with sex pheromone, this parasitoid becomes even more effective. Use of chemical pesticides results in killing much larger number of the beneficial predators and parasitoids than EFSB, which remains deep inside the shoots and fruits. MSSRF has studied the pests and natural enemies of eggplant (*Solanum melongena*) in Tamil Nadu (Table 2).

The transgenic *Bt*-brinjal would, in the initial years, be significantly free from severe damage by EFSB, although the damage caused by various other pests would remain the same or even increase. The major problem will be that EFSB in the *Bt*-brinjal would be favoured by Darwinian evolution to develop *Bt*-resistant EFSB. As mentioned earlier, this has already happened in the case of *Bt*-cotton. There are no data available on the adverse effects, if any, on the *Trathala* larvae, developing in the EFSB larvae feeding on shoots and fruits of *Bt*-brinjal. In general, there is a serious gap in our understanding of the interrelationships among the *Bt*-host plants, lepidopteran borers of shoots and fruits as well as their natural enemies, particularly the egg parasitoids. The *Bt*-transgenic brinjal provides a suitable medium for origin of *Bt*-resistant mutations, and natural selection favouring the emergence of *Bt*-resistant EFSB. This certainly is a risky prospect, especially in view of the fact that India is a primary centre of origin of brinjal. Well over 2500 varieties of brinjal (*S. melongena*) are reported to grow in India, and several of them are also naturally resistant to EFSB to varying degrees. With such a rich biodiversity providing useful genes, it is imprudent to develop *Bt*-transgenic brinjal that inevitably would break down within a few years.

Since *Bt*-transgenics could break down with the evolution of *Bt*-resistant EFSB, it does not seem to be a sustainable solution for consideration of inclusion under the evergreen revolution, both from eco-agricultural and micro-eco-entrepreneurial points of view. On the other hand, the IPM strategy that fits in well with evergreen revolution consists of native 'genes' from naturally resistant cultivars, sex pheromone, crop rotation, and cultural, mechanical and biological control methods.

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Received 26 April 2010; accepted 26 August 2010