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Emergence of minor pests becoming major pests in GE cotton in China

What are the reasons? What are the alternative practices to this change of status?

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A recent study in China by Lu et al.[1] shows that populations of an occasional cotton pest, mirid bugs (Heteroptera: Miridae), increased following the introduction of genetically engineered (GE) cotton plants. The GE cotton produces a delta-endotoxin from the bacteria *Bacillus thuringiensis* (*Bt*) to control the cotton bollworm. Before the introduction of *Bt* cotton in China, mirid bugs were usually controlled by broad-spectrum pesticide sprays targeted against the cotton bollworm, *Helicoverpa armigera* Hübner (Lepidoptera: Noctuidae), the most important pest of cotton in China. The effectiveness of the control of *H. armigera* by *Bt* cotton cultivation has resulted in a decrease in the amount of insecticides used on *Bt* cotton compared to conventional cotton. This has led to a lack of control of mirids on *Bt* cotton due to the reduction in broad-spectrum insecticide use and consequently to a transformation of a minor pest to a main one. We discuss the scientific evidence available in the literature of this phenomenon. We examine the reasons of the emergence of minor pests to become major pests in *Bt* cotton in China and possible solutions to this change of status.

The cotton crop has numerous invertebrate pests and more than one thousand species are found on cotton but only ten or a dozen of them are significant potential pests.[2] The heliothine lepidopteran species complex (*Heliothis virescens*, *Helicoverpa armigera*, *Helicoverpa zea*) is considered as the most dangerous, attacking numerous other cultivated plants which are often associated with cotton in a range of cropping systems to this change of status. In China, the major pests of cotton include heliothine as cotton bollworm (*Helicoverpa armigera*), aphids (*Aphis gossypii*, *A. atrata*, *A. medicaginis* and *Acyrthosiphon gossypii*), the pink bollworm (*Pectinophora gossypiella*), spider mites (*Tetranychus cinnabarinus*, *T. truncates*, *T. turkestani* and *T. dunhuangensis*), thrips (*Frankliniella intonsa, Thrips tabaci* and *T. flavus*), mirids (*Adelphocoris suturalis*, *A. lineolatus*, *A. fasciaticollis*, *Lygus lucorum* and *L. pratensis*), whiteflies (*Bemisia argentifolii* and *B. tabaci*), the Asian corn borer (*Ostrinia furnacalis*), the beet armyworm (*Spodoptera exigua*), spiny bollworms (*Earias cupreoviridis*, *E. fabil* and *E. insulana*), the cotton looper (*Anomis flava*) and leafhoppers (*Empoasca biguttula* and *E. flavescens*).[3] The distribution of these species varies across regions. In China, the pink bollworm is mainly found in the Changjiang River region and aphids (*A. atrata, A. medicaginis* and *Acyrthosiphon gossypii*) cause damage only in northwestern China.[3]

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Certain pest species of cotton have few deleterious effects on production. These species are called 'minor' or 'secondary' species. The status and the relative economic importance of these different pests vary depending on the agro-ecosystem considered and changes in response to selection pressure to which they are subject. The often spectacular impact of the range of early-season pests, as thrips, cutworms, leafminers and aphids, has frequently no significant effect on the potential yield, because of the strong capacity for growth compensation of cotton during its vegetative growth stage provided by agronomic conditions.[2] In addition to mirid species, aphids and thrips are also mentioned as secondary pests of cotton in China.[4] The status of minor or major pest depends on climatic conditions, thus aphids (*A. atrata, A. medicaginis* and *Acyrthosiphon gossypii*) cause damage only in northwestern China.

Improving the use of biotechnological and classical plant resistance for herbivore pest control with less reliance on chemicals critically depends on predictable interactions with secondary pests. The status of the minor pest can evolve according to the agricultural practices used by farmers, as exemplified for mirids on *Bt* cotton in the study conducted over 10 years in northern China.[1] Before the introduction of *Bt* cotton, mirid bugs caused little damage as insecticide treatments against primary pests such as Lepidoptera (*H. armigera*, etc.) also limited mirid populations (Lygus spp., etc.). It can be noted that this phenomenon is not new since the same authors have already documented it previously[5] and these authors proposed a ranking of four species of Lygus as among the most devastating pests on *Bt* cotton. The emergence of secondary pests is not a phenomenon associated with *Bt* crops, it is as old as crop protection itself. Pest resurgence and replacement are usually ascribed to alterations in pest management regimes.[6] In crop protection, when the primary pest is targeted, other species are likely to rise in its ecological place and multiply. For example, cotton aphid (*Aphis gossypii*) evolved as a primary pest of cotton in the mid-1970s because of intensive insecticide use for *H. armigera* control.[7] The boll weevil (*Anthonomus grandis* Boheman) was once the main worldwide threat to cotton. As farmers sprayed pesticides against the weevils, bollworms developed resistance and rose to become the primary pest. Similarly, stink bugs have replaced bollworms as the primary pest in the southeastern US since *Bt* cotton was introduced.[8]

The change in status of herbivory has been observed for a long time as soon as insecticide use is reduced. The best example concerns the campaigns for the eradication of the boll weevil in the US. This program enabled cotton farmers to reduce their use of pesticide by between 40 and 100% and to increase their yields by at least 10% since its inception in the 1970s. With the progress in eradication of the boll weevil and the adoption of transgenic insecticidal cottons for control of lepidopterous pests, the tarnished plant bug (*Lygus lineolaris* Palisot de Beauvois) has also become a key pest of cotton in the Mid-South.[9] The tarnished plant bug has taken on added importance as a pest of cotton in the Cotton Belt after successful eradication efforts against the boll weevil.[10] Historically during the flowering and boll maturation periods, tarnished plant bugs were inadvertently controlled by organochlorine, organophosphate, carbamate and pyrethroid insecticides targeting boll weevil and heliothines. The success of the boll weevil eradication programs and wide-scale adoption of *Bt* cotton eliminated many of those applications. In addition, the use of more selective insecticides that target Lepidopteran pests (i.e., spinosad, indoxacarb and emamectin benzoate) increased survival of tarnished plant bugs. Finally, tarnished plant bug resistance to a variety of insecticides (organophosphates, carbamates, pyrethroids) in the mid-south US has contributed to the elevated status of this insect pest.[11] Even if eradication programs were successful, the emergence of secondary pests previously controlled by spray programs targeting boll weevil may occur. For example, European corn borer (*Ostrinia nubilalis*), soybean looper (*Pseudoplusia includens*) and stink bugs (*Euchistus servus* and *Acrosternum hilare*) became more prevalent in the southeastern US during the time of the full-scale eradication programs.[12]

The modification status on *Bt* cotton is not only associated with a decrease in insecticide use, it is also associated with the ineffectiveness of *Bt* cotton against these secondary pests. *Bt* cotton plants are genetically engineered to produce insecticidal toxins from the *Bacillus thuringiensis* Berliner (Bacillales: Bacillaceae) a gram-positive bacteria. Cry toxins have specific activities against insects of different orders—Lepidoptera (moths and butterflies), Diptera (flies and mosquitoes), Coleoptera (beetles), hymenoptera (wasps, bees, ants and sawflies) and invertebrates such as nematodes.[13] Cry toxins are ineffective against insects such as sap sucking and piercing insects [leaf bugs (*Lygus lucorum* and *Adelphocoris suturalis*), cotton spider mites *(Tetranychus cinnabarinus),* cotton aphids and whiteflies *(Bemisia tabaci)*] and against root-dwelling pests.[14]

The change of status of the pest was highlighted in numerous studies that were published before the study in China by Lu et al.[1]

In China, in the Province of Anhui, *Lygus pratensis* causes severe damage on *Bt* cotton in the same way as *Prodenia litura* and *Thrips tabaci*.[15] This study measures the patterns of insecticide use based on farm-level from 1999 to 2006. The analysis demonstrates a rise in insecticide use to control mirids between 2001 and 2004, secondary insect infestations is largely related to the rise of mirids, but this rising did not continue in more than half of sample villages studied in 2004–2006. Moreover, the increase in insecticide use for the control of secondary insects is far smaller than the reduction in total insecticide use due to *Bt* cotton adoption. Further econometric analyses show that rise and fall of mirids are largely related to local temperature and rainfall.

In the coastal agricultural region of Jiangsu Province, piercing-sucking insect populations (Mirids: *Lygus lucorum*, *Adelphocoris suturalis*; Acarians: *Tetranychus cinnabarinu*; Aphids: *Aphis gossypii*; *Bemisia tabaci*) are more important in *Bt* cotton fields than in conventional fields.[16] In this study the insect community structure in the *Bt* fields differed sharply from that in the conventional fields during 2004–2005. The populations of the lepidopterous pests, such as cotton bollworm, corn borer, diamond bollworm (*Earias cupreoviridis*) and cotton leaf caterpillar Spodoptera, decreased significantly in the *Bt* fields, while the populations of non-target pests with piercing-sucking mouthparts, such as leaf bugs (*Lygus lucorum* and *Adelphocoris suturalis*), cotton spider mites (*Tetranychus cinnabarinus*), cotton aphids (*Aphis gossypii*) and whiteflies (*Bemisia tabaci*), significantly increased. Many more predators, such as spiders, ladybirds and less parasitoids of *Helicoverpa armigera* were observed in the *Bt* fields.

In the Province of Hebei, *Lygus lucorum* has become an important pest in *Bt* cotton, to the point that trials were set up to determine the best methods of pest management.[17] The authors show that four peak periods of *L. lucorum* adults and three peak periods of *L. lucorum* nymphs occurred during the whole *Bt* cotton growth season. During the whole *Bt* cotton growth season the average number of adults and nymphs in the *Bt* cotton fields were higher than those in the integrated and chemical control fields. There was no significant difference in the integrated and chemical control fields.

In the US as well, the introduction of *Bt* cotton in agricultural fields caused a strong decrease in insecticide treatments against Lepidoptera, which consequently caused a resurgence of mirids and mirid damage as well as other sucking pests (Pentatomidae) in the mid-south and southeast states of the cotton belt.[2] In this study sucking pests are progressively coming to displace the vegetative and fruit feeding caterpillars as key pests of *Bt* cotton. Taking into account the spatio-temporal dimension of natural population regulatory factors has led to changes in agricultural practices and production systems. In cotton production systems maintaining permanent ground cover are having increasing success. Intercropping and trap cropping have been favorable to the maintenance of beneficial arthropod complexes and unfavorable to the growth of pest populations.

Problems in pest management due to this change of status arose very fast after the adoption of *Bt* cotton in Mississipi from

1992 to 1995. It was shown the susceptibility of *Bt* cotton to mirids.[18] In this study *Bt* cotton cultivars were tested in small plot and larger plot on-farm studies to determine efficacy against cotton pests. *Bt* cotton provided excellent control of bollworm and tobacco budworm (*Heliothis virescens*). *Bt* cotton was highly effective for control of cabbage looper (*Trichoplusia ni*) and showed significant suppression of beet armyworm (*Spodoptera exigua*). *Bt* cotton cultivars tested showed no greater attractancy for or more susceptibility to tarnished plant bug or cotton aphid (*Aphis gossypii*) than other comparable cultivars. *Bt* cotton showed, in some cases, greater square set than other adapted varieties protected with insecticides. Similar results were observed in Mississipi from 1995 to 1997.[19] *Bt* cotton fields may be at greater risk to attack by tarnished plant bugs and boll weevils presumably due to the reduction of insecticidal inputs. However, attempts to prophylactically control plant bugs in this study did not have a significant benefit.

In the US, numerous other publications highlighted the problem of the change of the status of secondary pests.[20] In field studies in Minnesota, comparison of *Bt* and nectariless cottons with non-*Bt* commercial varieties showed no significant differences in the number of beneficials, bollworm and tobacco budworm eggs, fruiting sites per plant and percentage square set. Significantly more tarnished plant bugs and percentage of 'crazy cotton' (fruitless plant) were observed in *Bt* variety compared with other varieties, suggesting no effect of *Bt* gene insertion in cotton on the number of tarnished plant bugs. *Bt* cotton had significantly fewer bollworms and budworms, cabbage loopers and percentage of damaged squares than the other varieties, 75% as many beet armyworms and had no effect on fall armyworm. Boll weevil and tarnished plant bug cause economic damage when fewer or no sprays are used for bollworm and budworm in cotton.

In other major cotton-producing countries, such as India, the same questions were brought up. In 2000, it was noticed that one of the problems due to the cultivation of *Bt* cotton is the resurgence of sucking insects.[21] Development of resistance to *Bt* cotton, resurgence of sap sucking insects and cotton stainers and poor activity on Spodoptera are the problems associated with *Bt* cotton in this study. The lepidopteron specific *Bt* gene, *cry1Ac*, offers protection against all the major species of Indian bollworms. These bollworms, especially *Helicoverpa armigera*, have been responsible for heavy yield losses and frustrating the cotton growers for more than three decades.

In 2006, it was shown that mirids become pests damaging *Bt* cotton in India.[22] A similar occurrence was also shown with the pest, the tobacco caterpillar (*Spodoptera litura*), which is known to survive *Cry1Ac*.[22] In this study at least three spray applications meant for bollworm control were saved due to the *Bt* technology. Secondary insect pests such as mirid bugs *(Creontides biseratence)* were found to increase to damaging numbers in unsprayed cotton fields. The tobacco caterpillar was also found to stage a come back as an economic pest of *Bt*-cotton. The *Bt* cotton currently released in India is only moderately toxic to the caterpillar. It is known that the use of synthetic pyrethroids has significant negative impacts on the populations of Spodoptera and several other miscellaneous bugs such as the mired bugs, *Creontiodes biseratence.* The authors suggest that reduction of pyrethroids and several conventional insecticides on *Bt*-cotton is expected to result in the increase of several non-target species.

In China in 2002, it was shown that mirids become primary pests as a consequence of successful trials of stacked genes (including *Bt* gene and protease inhibitor gene) in transgenic cotton.[23] In this study mirid damage on unsprayed *Bt* cotton was significantly higher due to a reduced number of insecticide sprays against *H. armigera* compared with the number of sprays in the conventional cotton. The authors suggest that the mirids have become key insect pests in *Bt* cotton fields and that their damage to cotton could increase further with the expansion of the area planted to *Bt* cotton if no additional control measures are adopted.

While it is true that sucking pests have become a more significant part of the pest complex in *Bt* crops in some countries.[23,24] Furthermore, the Figure S1 from the supporting online material in the recent Chinese publication[1] indicates also that the amount of insecticides used to treat secondary pests are less than the amount of pesticides saved by the use of cotton. In Australia, on average 60% reduction in sprays applied against Helicoverpa was accompanied by no change in sprays for mirids, aphids, mites and thrips.[25] But the cultivation of *Bt* cotton is not soley responsible: change in mirid bug status of secondary pests could also be due to other modifications in agricultural practices: development of insecticide resistance in tarnished plant bug and boll weevil eradication and the development and availability of more target-specific foliar-applied insecticides.[26] In this study although tarnished plant bug can damage cotton throughout most of the growing season in many states of the USA, economic damage is most likely to occur during the period from first square through early bloom due to feeding on small squares and subsequent abscission of these squares. During this period, excessive damage by high tarnished plant bug populations may result in reduced yields or delayed maturity. However, current research suggests that cotton can tolerate low levels of tarnished plant bug damage without sustaining yield loss.

Numerous analyses were made at the local level. But very rapidly an analysis at the regional level, at an agro-landscape level, or even at a higher level, appeared imperative, because *Bt* cotton became the dominant culture in certain regions as well as in certain countries. While there are numerous studies which assessed the impact of this situation on pests not-targeted by *Bt* cotton at a field level, there is little data concerning the impact of *Bt* cotton on non-target pests at the regional level. In the 1990s in the US, a large-scale inventory of these mirids pest species was made.[27]

In India, it was shown that the presence of mirids is not similar in all states and this is probably due to the cultivated area of *Bt* cotton.[28] A roving survey was undertaken during cropping period in different *Bt* cotton-growing Karnataka districts to determine the incidence of mirid bug (*Creontiades biseratense*). The incidence of mirid bug was high in Haveri district probably due to higher area under Bt cotton. In other districts, the mirid bug incidence was low to moderate. The peak incidence was observed during the October and November months. The maximum incidence was noticed in Haveri during the second fortnight of November.

In the recent Chinese publication, a relatively exhaustive and geographically vast analysis of this question was also carried out in China. It should be mentioned that these results are not confirmed by all other publications.[1] It was shown that even though an increase of mirids was observed between 2001 and 2004, that increase was not observed between 2004 and 2006.[29] Both studies agree that the amount of insecticides used to treat secondary pests which have changed status is significantly lower than the amounts of insecticides saved by the cultivation of *Bt* cotton. However, the necessity of increasing the number of insecticides applications targeting mirids is not correlated to the extension of the cultivated area of *Bt* cotton but rather to climatic conditions.[29] In another study, between 2002 and 2004 in Xinjiang Province, no difference in densities of mirid populations (*Lygus pratensis* and *Adelphocoris lineolatus*) was observed in GE cotton fields (with either a *Cry* gene alone or with stacking a *Cry* gene and a cowpea trypsin inhibitor *CpTI* gene) versus conventional cotton fields.[30]

In Australia, 20% less insecticide treatments are applied on conventional cotton than on *Bt* cotton to fight against the mirids, which exercise more pest pressure on *Bt* cotton than on conventional cotton.[31] In this study comparing pesticide applications, the number of sprays on conventional crops across all valleys was 9.9 while Bt cotton was sprayed 4.6 times on average. The average number of sprays to control Heliothis in conventional cotton was 9 applications. Heliothis in *Bt* cotton were sprayed just over 3 times throughout the season. Mirids and mites were sprayed more frequently in *Bt* fields. A large reduction in sprays was observed during each stage of crop growth, the largest reduction recorded between squaring and first flower.

Since no pesticide treatment was applied against primary pests on *Bt* cotton as *Bt* produced an insecticide protein, secondary pests occupy an ecological niche without primary pests and, as a consequence, with little substantial pesticide application, they can develop and cause important damage. Therefore environmentally sound and sustainable management alternatives are urgently needed. Pesticide treatment is envisaged as a solution to combat only those secondary pests becoming primary pests in *Bt* cotton fields. Currently, insecticide use is the sole pest management option available for most Chinese cotton farmers. Since 1997 in the US pesticide treatment was proposed to combat mirids in *Bt* cotton.[32,33] Approximately half of Mississippi's area of cotton was planted with *Bt* varieties in 1998.[33] *Bt* fields sustained significantly less boll damage induced by lepidopteran larvae and received significantly fewer foliar insecticide treatments for control of bollworm and tobacco budworm. However, *Bt* fields sustained significantly more boll damage due to tarnished plant bug and received significantly more treatments for control of boll weevils. Although the *Bt* variety received significantly more foliar sprays to control bollworm, it also sustained significantly more larval boll damage than the average for all other Bt varieties.

In China bioassays of susceptibility to insecticides were assessed to set up this practice[34] which is implemented in certain situations.[35]

Other alternate solutions are envisaged, such as the implementation of *Bt* cotton in a strategy of integrated pest management (IPM)[36-39] or possibly of biological control.[40-42] Planting refuge concurrent with *Bt* adoption provides for the sustainable development of *Bt* technology. The pesticide required to maintain the refuge will reduce the threat of the secondary pest before they proliferate to a damage concentration. The profits lost on the refuge could be compensated by substantial savings on pesticides that otherwise would be used to combat outbreaks of the secondary pest in the future.

These solutions could decrease mirid damage until the development of transgenic resistant varieties. Already in 1998, the USDA considered the development of transgenic cotton varieties resistant to mirids a crucial task.[43] Two traits that have been shown to be of great help in reducing Lygus populations are nectarilessness and earliness. Numerous studies showed that nectariless cotton reduces Lygus by an average of 49%. Nectariless has no known deleterious effects on yield or fibre properties. Under heavy Lygus pressure it has consistently produced higher and earlier yields than nectaried cultivars. Earliness is valuable in producing a crop quickly, thus escaping late season insect buildups and weather losses. It would be advantageous to the cotton grower if nectarilessness, earliness, some forms of smoothleaf and *Bt* were combined in a modern conventional-transgenic breeding program.

This solution of the development of transgenic insect-resistant cotton varieties was also recommended in India (2006).[23] The stacked genes are expected to increase the spectrum of toxicity to a wide range of lepidopteran insects to include *Spodoptera litura.*

The development of transgenic insect-resistant cotton varieties was also suggested in Australia to provide a foundation for more sustainable, economically acceptable IPM with the integration of a range of non-chemical tactics and much less reliance on pesticides.[44] IPM must be founded on a thorough understanding of the ecology of pest and beneficial species and their interaction with the crop and will provide a range of tactics which must be integrated by the producer to achieve economic and environmental sustainability.

For example in China some transgenic cotton varieties expressing both *Bt* and *CpTI* genes effectively control mirids if cotton fields are located away from fruit orchards (which shelter mirids).[45] In this study *L. lucorum* was effectively controlled in cotton fields far from orchard fields with uneven plant spacing and under rational chemical control. Plantations of transgenic *Bt* plus *CpTI* cotton reduced *L. lucorum*, but had no effect on native predators. Intercropping with sunflower increased native predator number and reduced *L. lucorum* in cotton fields. The results suggested that planting transgenic *Bt* plus *CpTI* cotton in field far from orchard at rational density and uneven spacing with rational chemical control can effectively control *L. lucorum* in transgenic cotton fields.

On the other hand, biological control methods could help to fight against the damage of secondary pests on *Bt* plants.[46] To determine the compatibility of biological control and insect-resistant transgenic crop trait within IPM programs, it needs to understand the bi-trophic and prey/host-mediated ecological pathways through which natural enemies interact within cropland communities and how transgenic crops alter the agroecosystems in which natural enemies live. Insect-resistant crops can affect the quantity and quality of non-prey foods for natural enemies, as well as the availability and quality of both target and non-target pests that serve as prey/hosts. This vegetational diversity is fundamental to biological control when it serves as a source of habitat and nutritional resources. Some inherent qualities of both biological control and GE crops provide opportunities to improve upon sustainable IPM systems. For example, biological control agents may delay the evolution of pest resistance to transgenic crops and suppress outbreaks of secondary pests not targeted by transgenic plants.

In the eastern and western United States the tarnished plant bug and the western tarnished plant bug are important pests of many crops respectively, several parasitoids and predators are candidates for use in augmentative biological control, as a component of area wide IPM for Lygus spp. management.[40] These include the parasitoids *Anaphes iole* Girault, *Peristenus stygicus* Loan and *Leiophron uniformis* (Gahan) and the predators *Geocoris punctipes* (Say), *Orius insidiosus* (Say) and possibly even Chrysoperla spp. To be useful, these natural enemies must be available in large numbers and thus arises the need for mass rearing techniques. Currently, even for those species that are available from commercial sources, rearing systems do not have the capacity to produce these insects in sufficient numbers to support biological control of Lygus spp. in cotton.

Management of secondary pests in cotton can also be envisaged by cultural methods to help in the management of Lygus populations.[47] The use of transgenic or nectariless cotton cultivars that are resistant to Lygus could be easily implemented if they were available. Other kinds of cultural controls, such as management of alternate hosts, may not be adopted on a large scale unless they are part of an area-wide management program or until additional evidence of cost efficiency is demonstrated. Adoption of cultural approaches will be largely influenced by the availability and efficacy of alternative management practices, including insecticides and other socioeconomic factors. Cultural approaches are best suited in systems with low use of disruptive insecticides, where natural enemies are relied upon most heavily to maintain cotton pests below economically damaging levels.

Management of secondary pests in cotton can also be envisaged by a sustainable and cost-effective IPM method combining trap cropping, biological control and minor chemical use, which is currently being tested in China.[48]

In conclusion reductions in insecticide use associated with *Bt* cotton create an environment conducive to conserving the function of resident and immigrant natural enemies. Indeed the publications we discussed in this review show that damage of secondary pests such as mirid on unsprayed *Bt* cotton was significantly higher due to a reduced number of insecticide sprays against cotton bollworm compared with the number of sprays in the non-*Bt* cotton. Mirid bugs have filled the gap created by killing other pests of cotton. The mirids have become key insect pests in *Bt* cotton fields, and that their damage to cotton could increase further with the expansion of the area planted to *Bt* cotton if no additional control measures are adopted at an agro-landscape level. The emergence of secondary pests could be exacerbated in GE crops if the efficiency of the pest control leads farmers to neglect other measures of good farming practice, such as crop rotation, which help to prevent and limit pest pressure naturally.

Interactions between biological control agents (insect predators, parasitoids and pathogens) and transgenic crops exceed simple toxicological relationships, a priority for assessing risk of transgenic crops to non-target organisms. Genetically engineered systems provide opportunities for integrating biological control with IPM as no insect-resistant transgenic crop produced to date is immune to all herbivores. There is a continued need to have an effective complex of natural enemies in place to help manage pests that are not targeted by the insecticidal transgenes. The extent to which biological control would be affected in an insect-resistant transgenic crop will likely depend on (1) the relative contributions of generalist and specialist enemies to pest management in the system (if generalist enemies are important, then little or no change might be expected), (2) the degree to which pest stages targeted by the transgene products function as an important host/prey base for the enemy complex, (3) the relative abundance, acceptability and suitability of non-target hosts/prey for enemies in the system and (4) the importance of the crop fields relative to extra-field habitats as food/host sources for enemies.[46] There are few studies of natural enemy efficacy in transgenic crops, but the few examples available indicate that biological control of non-target stages or species in insecticidal transgenic crops is unaffected relative to that occurring in conventional varieties not treated with insecticides.[49] Similarly, in two studies predation of several non-target prey species was comparable in *Bt* and non-*Bt* cotton.[50,51] In a review of eight studies that assessed biological control in *Bt* cotton, maize and tobacco none indicated any consistent effect of the transgenic crop on biological control function.[49]

In cotton production, biological control by introduction and acclimation of beneficial arthropods has not been notably successful because of the difficulty of developing a suite of beneficial organisms capable of responding effectively to the diversity of pests in the system, the annual nature of the crop, and the disrupting effects of chemical control measures directed against the remaining pests.[2] Only inundative biological control has had significant success and then in particular cases where the pressure of chemical insecticides has been reduced. More benefit is to be obtained from the active conservation of the indigenous fauna of beneficial organisms.

Therefore, it is important to develop pest control using a broad spectrum of practices. These include crop rotation, tillage, high biological diversity in the farming system and promotion of the pests' natural antagonists. Taking into account the spatio-temporal dimension of natural population regulatory factors has led to changes in agricultural practices and production systems.[2] In cotton, production systems maintaining permanent ground cover are having increasing success. Intercropping and trap cropping have been favorable to the maintenance of beneficial arthropod complexes and unfavorable to the growth of pest populations. This new design context for crop protection in general and for cotton in particular, in applying the principles of agroecology, moves towards the concept of a sustainable pest management characterized by a movement from a paradigm of pest control field-by-field, through farm-by-farm and agroecosystem-by-agroecosystem, to a landscape.[2] The pest control must keep sight of the whole ecosystem. The impact of transgenic crops must be assessed on the landscape level.

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References

1. Lu Y, Wu K, Jiang Y, Xia B, Li P, Feng H, et al. Mirid bug outbreaks in multiple crops correlated with wide-scale adoption of *Bt* cotton in china. Science 2010; 328:1151-4 DOI: 10.1126/science.1187881.
2. Deguine JP, Ferron P, Russell D. Sustainable pest management for cotton production: A review. Agron Sustain Dev 2008; 28:113-37.
3. Wu KM, Guo YY. The Evolution of cotton pest management practices in China. Ann Rev Entomol 2005; 50:31-52.
4. Sun C, Xu J, Zhang Q, Feng H, Wang F, Song R, et al. Effect of transgenic *Bt* cotton on population of cotton pests and their natural enemies in Xinjang. Chinese J Biol Control 2002; 18:106-10.
5. Lu YH, Qiu F, Feng HQ, Li HB, Yang ZC, Wyckhuys KAG, et al. Species composition and seasonal abundance of pestiferous plant bugs (Hemiptera: Miridae) on *Bt* Cotton in China. Crop Prot 2008; 27:465-72.
6. Dutcher JD. A review of resurgence and replacement causing pest outbreaks in IPM. In: Ciancio A, Mukerji KG, Ed. General Concepts in Integrated Pest and Disease Management 2007; DOI: 10.1007/978-1-4020-6061-8-2.
7. Wu KM, Guo YY. The evolution of cotton pest management practices in China. Annu Rev Entomol 2005; 50:31-52.
8. Qiu J. GM crop use makes minor pests major problem. Pesticide use rising as Chinese farmers fight insects thriving on transgenic crop. Published online 2010. Nature; DOI:10.1038/news.2010.242.
9. Dale WS. Arthropod management using marked *Lygus hesperus* (Knight) (Hemiptera: Miridae) adults to evaluate sweep net sampling in cotton J. Cotton Sci 2009; 13:196-205.
10. Esquivel JF, Mowery SV. Host plants of the tarnished plant bug (Heteroptera: Miridae) in central Texas. Environ. Entomol 2007; 36:725-30.
11. Leonard R, Cook D. Insecticide use strategies in mid-south cotton fields for tarnished plant bug. Second International Lygus Symposium J. Insect Sci 2007; 7:49. http://www.insectscience.org/8.49.
12. Myers JH, Savoie A, van Randen E. Eradication and pest management. Annu Rev Entomol 1998; 43:471-91.
13. Sarjeet SG, Cowles EA, Pietrantonio PV. The mode of action of *Bacillus Thuringiensis* endotoxins. Annu Rev Entomol 1992; 37:615-34.
14. de Maagd RA, Bosch D, Stiekema W. *Bacillus thuringiensis* toxin-mediated insect resistance in plants. Trends Plant Sci 1999; 4:9-13.
15. Wang ZJ, Hai L, Huang JK, Hu RF, Rozelle S, Pray C. *Bt* Cotton in China: are the secondary benefits offsetting insect infestations in farmer fields? Agri Sci China 2009; 8:83-90.
16. Xu WH, Liu B, Wang RM, Zheng YP, Zhang Y, Li XG. Effects of transgenic *Bt* cotton on insect populations in cotton fields in coastal agricultural region of Jiangsu Province. J Ecol Rural Environ 2008; 24:32-8.
17. Meng Z. Effects of population dynamics of *Lygus lucorum* of two control *Helicoverpa armigera* measures on the transgenic *Bt* cotton fields. J Jilin Agricult Univ 2008; 30:128-32.
18. Harris FA, Furr RE Jr, Calhoun DS. Cotton insect management in transgenic *Bt* cotton in the Mississippi Delta 1992–1995. In: Proceedings Beltwide Cotton Conferences, Nashville, TN USA 1996; 2.
19. Stewart S, Reed J, Luttrell R, Harris FA. Cotton insect control strategy project: comparing *Bt* and conventional cotton management and plant bug control strategies at five locations in Mississippi 1995–1997. In: Proceedings of the Beltwide Cotton Conferences. San Diego, California, USA 1998; 2:1199-203.
20. Hardee DD, Bryan WW. Influence of *Bacillus thuringiensis*-transgenic and nectariless cotton on insect populations with emphasis on the tarnished plant bug (Heteroptera: Miridae). J Econ Entomol 1997; 90:663-8.
21. Uthamasamy S, Raguraman S. Transgenic cotton for insect resistance. In: Ignacimuthu S, Janarthanan ASS, Ed. Biotechnological Applications for Integrated Pest Management 2000.
22. Khadi BM. Impact of *Bt*-cotton on agriculture in India. In: Ninth International Symposium on Biosafety of Genetically Modified Organisms Biosafety Research and Environmental Risk Assessment. Jeju Island, Korea 2006; 96-100.
23. Wu K, Li W, Feng H, Guo Y. Seasonal abundance of the mirids, *Lybux lucorum* and Adelphocoris spp. (Hemiptera: Miridae) on *Bt* cotton in northern China. Crop Prot 2002; 21:997-1002.
24. Wilson LJ, Mensah RK, Fitt GP. Implementing integrated pest management in Australian cotton. In Horowitz AR, Ishaaya I, Ed. Insect Pest Management: Field and Protected Crops. Berlin, Heidelberg, New York: Springer 2004; 97-118.
25. Fitt GP. Implementation and impact of transgenic *Bt* cottons in Australia. In: Swanepoel A, Ed. Proc. World Cotton Conf-3, Cotton production for the new millenium, Cape Town ARC, Institute for Industrial Crops, Pretoria 2003; 371-2.
26. Layton MB. Biology and damage of the tarnished plant bug, *Lygus lineolaris*, in cotton. Southwestern Entomologist Suppl 2000; 23:7-20.
27. Wayland S, Mulkey M, Johnson S, Green J, Kearnes D, Barnes D, et al. Transmittal of the final report of the FIFRA scientific advisory panel subpanel on *Bacillus thuringiensis* (*Bt*) plant-pesticides and resistance management 1998; http://www.epa.gov/scipoly/sap/meetings/1998/february/finalfeb.pdf.
28. Rohini RS, Mallapur CP, Udekeri SS. Incidence of mirid bug, *Creontiades biseratense* (Distant) on *Bt* cotton in Karnataka. Karnataka J Agri Sc 2009; 22:3.
29. Wang Zi-jun, Lin H, Huang Jk, Hu Rf, Rozelle S, Pray C. *Bt* Cotton in China: Are secondary insect infestations offsetting the benefits in farmer fields? Agricultural Sciences in China 2009; 8:83-90.
30. Li HB, Wu KM, Xu Y,Yang XR, Yao J, Wang F. Population dynamics of pest mirids in cotton filed in Southern Xinjiang. Chinese Bull. Entomo 2007; 44:219-22.
31. Doyle B, Reeve I, Barclay E. The performance of Ingard cotton in Australia during the 2000/2001 season. In: Fifth Annual Report. Cotton Consultant Aqtralia Inc., CCA Ingard Cotton Survey 2000/2001. University of New England. Armidale NSW: Institute for Rural Futures 2001; http://www.ruralfutures.une.edu.au/cotton/resources/Ingard00-1.pdf.
32. Ruscoe JT, Andrews GL, Phelps JB, Bednarz CW. Efficacy and duration of early season insecticides on transgenic *Bt* cotton. Proceedings Beltwide Cotton Conferences, New Orleans LA, USA 1997; 2:888-91.
33. Layton MB, Stewart SD, Williams MR, Long JL. Performance of *Bt* cotton in Mississippi 1998; 942-5. *In* Proceedings of the Beltwide Cotton Conferences. Orlando, Florida USA 1999; 2.
34. Zhang ZQ, Guo TE, Wang W, Liu F, Mu W. Assessment of relative toxicity of insecticides to the green plant bug, *Lygus lucorum* Meyer-Dur (Hemiptera: Miridae), by two different bioassay methods. Acta Entomo. Sinica 2009; 52:9.
35. Guo JY, Zhou HX, Wan FH, Liu XJ, Han ZJ. Population dynamics and damage of *Lygus lucorum* Mayr in *Bt* cotton fields under two control measures. Chinese Bull. Entomol 2005; 42:4.
36. Ricroch A, Bergé JB, Kuntz M. Is the German suspension of MON810 maize cultivation scientifically justified? Transgenic Res 2010; 19:1-12.
37. Men X, Ge F, Edwards CA, Yardim EN. The influence of pesticide applications on *Helicoverpa armigera* Hübner and sucking pests in transgenic *Bt* cotton and non transgenic cotton in China. Crop Prot 2005; 24:319-24.
38. Hellmich RL, Calvin DD, Russo JM, Lewis LC. Integration of Bt Maize in IPM Systems: a US Perspective. In: Proceedings of the Second International Symposium on Biological Control of Arthropods (Davos, Switzerland) 2005; 1:356-61.
39. Wang SJD, Pinstrup-Andersen P, Babcock HE. Tarnishing Silver Bullets: *Bt* Technology Adoption, Bounded Rationality and the Outbreak of Secondary Pest Infestations in China. In: American Agricultural Economics Association Annual Meeting Long Beach 2006.
40. Smith RA, Nordlund DA. Mass rearing technology for biological control agents of Lygus spp. Southwestern Entomologist Suppl 2000; 23:121-7.
41. Joshi MD, Butani PG, Patel VN, Jeyakumar P. Cotton Mealy Bug, *Phenacoccus Solenopsis Tinsley*—A Review. Agricultural Reviews 2010; 31:2.
42. Mellet MA, Schoeman AS, Broodryk SW. Review of insect pest management strategies for the organic cultivation of cotton. Afr Plant Protect 2003; 9:61-86.
43. Meredith WR Jr. The role of host plant resistance in Lygus management. Proceedings Beltwide Cotton Conferences, San Diego, California USA 1998; 2.
44. Fitt G, Wilson L, Mensah R, Daly J. Advances with integrated pest management as a component of sustainable agriculture: the case of the Australian cotton industry. In: Fischer T, Ed. New directions for a diverse planet, Proc. 4th International Crop Science Congress, Brisbane, Australia 2004; www.cropscience.org.au.
45. Fan GH, Li DG, Li ZS, Gao FJ. Influence of ecological habitat on the occurrence and dynamics of *Lygus lucorum* Mayr and its natural predator. *Zhongguo Shengtai Nongye Xuebao*/Chinese J Eco-Agri 2009; 17:4.
46. Lundgren JG, Gassmann AJ, Bernal J, Duan JJ, Ruberson J. Ecological compatibility of GM crops and biological control. Crop Prot 2009; 28:1017-30.
47. Stewart SD, Layton MB. Cultural controls for the management of Lygus populations in cotton. Southwestern Entomologist Suppl 2000; 23:83-95.
48. CABI website. Protecting cotton from pests in China. 2010; http://www.cabi.org/default.aspx?site=170&page=1017&pid=2330.
49. Romeis J, Meissle M, Bigler F. Transgenic crops expressing *Bacillus thuringiensis* toxins and biological control. Nat Biotechnol 2006; 24:63-71.
50. Sisterson MS, Biggs RW, Olson C, Carrière Y, Dennehy TJ, Tabashnik BE. Arthropod abundance and diversity in *Bt* and non-*Bt* cotton fields. Environ Entomol 2004; 33:921-9.
51. Naranjo SE. Long-term assessment of the effects of transgenic *Bt* cotton on the function of the natural enemy community. Environ Entomol 2005; 34:1211-23.