New pests for old as GMOs bring on substitute pests

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In agroecological systems, one thing leads to another, often in unexpected ways. In the 1950s a single pesticide application per season was sufficient to control the jassid bug *Empoasca lybica*, the only major cotton pest in the Gezira of Sudan at the time (1). However, the spraying killed the natural enemies that had previously held populations of the cotton bollworm *Helicoverpa armigera* in check. Intensive spraying against the bollworm's larvae during the 1970s and 1980s led to the emergence from obscurity of whiteflies, *Bemisia tabaci*. They became primary pests in need of further control, and then there were also outbreaks of aphids, *Aphis gossypii*. Faced with crippling control costs and the development by the pests of resistance to the pesticides used against them (2, 3), the Sudanese eventually resorted to the integrated pest management approach. A similar but more complicated series of events is described for the cotton fields of China in PNAS by Zhang et al. (4), but in China it is not only trophic cascades leading to new pest upsurges but also effects of land-use alterations and climate change.

Protagonists of the use of genetically modified organisms (GMOs) for pest control argued that crops incorporating the *Bacillus thuringiensis* (Bt) toxins, such as Cry1Ac, would be a panacea, as they would obviate the need for pesticide sprays. Thus, Bt cotton was allowed to be planted in the United States in 1995, in China in 1997, in India in 2002, and is now predominant in these countries, as well as in Pakistan and elsewhere. However, experience has now shown, as with the deployment of conventional pesticides in Sudan, that Bt cotton also has unexpected side effects. In a reversal of the Sudanese situation, where release from natural predators and parasitoids—with the latter killed by pesticides—led to new pest outbreaks, with Bt cotton its supposed advantage of pesticide reductions has been to blame. Without being held in check by sprays against the bollworms, mirid bugs have thrived (5) and, to make matters worse, they have also been affecting additional crops, such as apples, grapes, peaches, Chinese dates, and pears. Fig. 1 illustrates potential mechanisms whereby new pests can emerge from the two contrasting approaches to pest control.

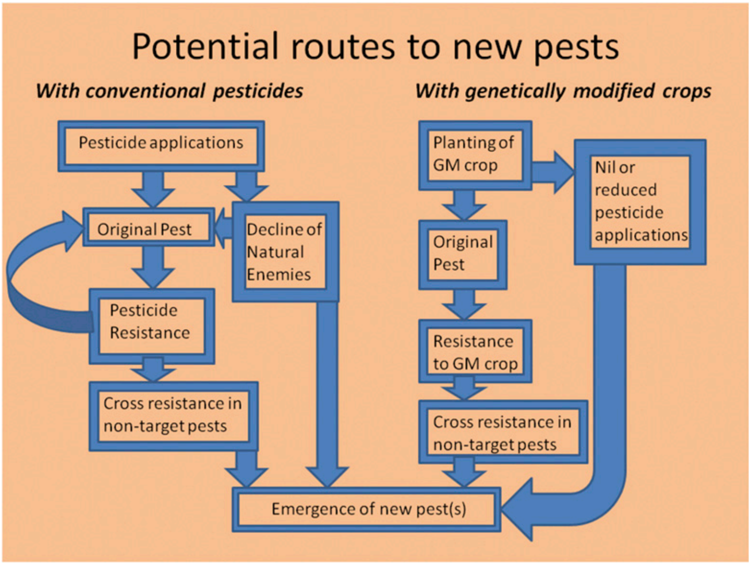

Fig. 1. Diagram of potential routes toward the emergence of new, often unexpected pests resulting from conventional pesticide use (*Left*) and plantings of genetically modified crops (*Right*).

The initial successes with Bt cotton led to more GM crops, including varieties of soya beans, potatoes, rice, tomatoes, sugar beet, apples, wheat, and many others. So Zhang et al.'s (4) findings, based on analyses of a huge dataset of secondary data derived from 51 counties in eight provinces of China from 1991 until 2015, have important implications for many different cropping systems. Lu et al. (5) had already pointed out the landscape-level effects of planting Bt cotton, but Zhang et al. (4) show that it is also interactions of Bt cotton with climate change and land-use changes that

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are driving the emergence of novel problems. In some cases it has been beneficial because the lack of spraying, aided by warmer temperatures in May, has reduced populations of the cotton aphid *A. gossypii*, as these succumb to recovering natural enemy populations in concert with reductions in the bollworms. But the mirid bugs (a mixture of *Apolygus lucorum*, *Adelphocoris suturalis*, *Adelphocoris lineolatus*, and *Adelphocoris fasciaticollis*) have increased threefold since 1997. Furthermore, these increases and those of the aphids were greatest where the diversity of the agroecosystem was lowest, although this was not so for the bollworms. Furthermore, the lack of a positive association between land-use diversity and mirid numbers contradicts the results from Lu et al.'s study (5).

The increases in mirid bugs led to farmers increasing their applications of pesticides against them, thereby negating one of the main benefits of Bt cotton planting. The news was not all bad because applications remain reduced against the bollworms and the aphids, but how long will this last? Bollworms showing resistance to the transgenic Bt cotton have already been identified in laboratory assays of populations from northern China (6). Such resistance is already problematic in the United States and Australia, where its management has involved planting of non-Bt cotton refuges to reduce the speed of resistance development. In China it may be necessary to introduce cotton expressing additional toxins, such as Cry2Ab, combined with increasing farmers' awareness of the value of natural enemies and the negative effects of unnecessary prophylactic spraying. Cotton is not the only crop involved in this manner because European corn borers, *Ostrinia nubilalis*, have developed resistance to Bt corn (maize), and at least 20% of an area planted with Bt corn in the United States must be growing non-Bt corn too, as part of integrated resistance management strategies insisted upon by the US Environmental Protection Agency and US Department of Agriculture (7).

In addition to human actions changing pest complexes in agriculture, similar phenomena occur with vector-borne diseases. Activities such as deforestation, afforestation with inappropriate species, and changes at forest/agriculture interfaces in South America have led to both malaria outbreaks and behavior changes from zoophilic to anthropophilic among leishmaniasis vectors, and to shifts in malaria epidemiology in Southeast Asia (8). Deforestation also changes the species of vector that transmits onchocerciasis in West Africa (9). Climate change is likely to have similar effects on the blackfly vectors (10) and on vectors of many other diseases, such as malaria, Lyme disease, and dengue fever (11). Uses of pesticides against such vectors has also led to resistance, exacerbated by migrations and hybridization, followed by replacements of one vector species by another (12), and a shift toward management with more ecologically friendly pesticides,

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such as Bt. Thus, given the recent approvals for releases of populations of *Aedes albopictus* mosquitoes with engineered self-limiting genes in Brazil, and of similar *Aedes aegypti* in Florida, for control measures aimed at reducing dengue fever and zika virus transmission, should the potential for unexpected outcomes be more carefully considered by authorities responsible for medical and veterinary issues, as well as the overseers of agriculture?

The Zhang et al. (4) study emphasizes the paramount importance of maintaining long-term datasets, without which the types of changes that they have documented would not be discernible. Long-term datasets are increasingly important, not only in agricultural science but also in conservation management, and where the two sciences impinge on each other. Thus, the major detrimental effects that agricultural intensification has had on British bird populations could not have been illuminated without the censuses of breeding bird populations collated for decades by the British Trust for Ornithology (13). Politicians and science administrators who curtail or stop the collection of the appropriate long-term information for short-term gains in their budgets do so at our and the planet's ecosystems' peril.

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