From insecticide resistance to Bt cotton: Is insect pest management sustainable in small-scale farming systems?

M. Vaissayre[1], *J.L. Hofs*[1] and *J.M. Vassal*[2]
[1]*CIRAD, Annual Crops Department, Cotton Program, Montpellier FRANCE*
[2]*CIRAD, AMIS Department, EntoTrop Laboratory, Montferrier/Lez FRANCE*
Correspondence author maurice.vaissayre@cirad.fr

ABSTRACT

Cotton farmers relied for many years on chemicals to control large number of a variety of pests. Environmental and cost considerations have today drastically reduced new chemistry on the agrochemical market. Pesticide resistance, and especially pyrethroid resistance, appears like a major issue for the cotton crop sustainability. An innovation such as the genetic transformation of cotton for insect resistance (Bt-Cotton) is raising considerable hope among farmers. In cropping systems in which insects are resistant to insecticides, the expression of a toxin (Cry1Ac) introduced into the cotton plant by genetic engineering, enables satisfactory control of bollworm populations. It is therefore natural to consider that the introduction of such cultivars may solve part of the pesticide resistance threat in many cotton-growing countries. However, there are two main reasons for tempering this point of view. The first is the fact that the Bt-toxin controls only a part of the pest spectrum (bollworms), and other insect pests, especially sucking ones, have to be handled still using pesticides. The second is related to the possible decrease in toxin efficacy resulting from the outbreak of a resistance mechanism inside bollworm populations. In cropping systems used by small-scale farmers, in which both the fields and decision-making are scattered, it is not easier to manage the prevention of resistance to Bt-toxins than to synthetic insecticides. Furthermore, the postulates allowing the dissemination of the innovation in large and intensive farming systems (toxin high doses + refuge) are not applicable to the situations observed in other continents. On one hand, results obtained in different laboratories show that the American bollworm (Helicoverpa armigera) *is less susceptible to the toxin Cry1Ac than* Heliothis virescens, *thus tempering the notion of strong expression of the toxin in the plant. On the other hand, the expression of the toxin is subordinate to the growing conditions of the cotton plant. Bt-cotton is not a "silver bullet" for handling pest pressure. The management of Bt-cotton must be accompanied - like traditional varieties - by a rational management of pest populations as a whole to limit the damage of the pest complex and to ensure the sustainability of cropping systems using cultivars modified for resistance to bollworms.*

Introduction

Cotton growing makes a substantial contribution to the incomes of small farms and to national economies in Asia, in Latin America and in West Africa. Through its stimulating effect on the cropping system, especially on food crops, it contributes to food self-sufficiency and the fight against poverty.

The use of chemicals is a much debated issue in cotton: it is essential for limiting pest damage and improving economic balance, but criticized for its impact on farmer health and environment. Cultural practices, resistant traits and beneficial fauna activity make it possible to reduce the damage of some components among the pest complex, but it is not enough to maintain the economic sustainability of the cotton crop. On the opposite, the massive use of pyrethroids to control bollworms led to insecticide resistance all over the world. After Australia, Turkey and Thailand, the problem reached the United States in 1985-86. Ten years after, pyrethroid resistance was reported from China, India and Pakistan and then more recently in West Africa (Martin *et al.*, 2000).

A failure in the control of pest populations as the result of insecticide resistance has serious economic repercussions for farmers and for the cotton sector. Health problems and environmental damage result from the increase in the amount of pesticides used to face resistance.

In the past, the problem of resistance was overcome by the introduction of new chemistry, whose target differed from that of the previous active ingredients. However, given the speed with which resistance appears, the registration of new, effective materials, respecting health and environment, seems doomed to failure in small cotton farming where the cost of inputs is a major limiting factor.

A major innovation

Many farmers consider a loss of effectiveness of the chemicals used for pest control as a major threat. An innovation such as the genetic transformation of cotton to make it resistant to insects raises great hope. For US farmers faced by pyrethroid-resistant Tobacco Budworms, Bt-cultivars (expressing a toxin produced by a gene of the bacterium *Bacillus thuringiensis*), gave a satisfactory control of noctuid populations (Perlak *et al.*, 2001). It is therefore natural to consider the introduction of such cultivars (Bt-cottons) to solve part of the cotton pest problem in small-scale farming situations elsewhere in the world. This hypothesis is confirmed by the success of Bt-cotton in China (Pray *et al.* 2001), South Africa (Ismael *et al.*, 2002) and India (Quaim and Zilberman, 2003).

There are nevertheless important points to keep in mind. The first is that the key pest in the "Old World" is *Helicoverpa armigera* (Hübner), and no more *Heliothis virescens*, like in North America. The second point is that the toxin controls only a part of the pest spectrum (bollworms), making it necessary to handle other pests, like on the one hand leafhoppers, aphids, whiteflies and bugs, and on the other hand also some leaf-eating caterpillars (Brickle *et al.*, 2001; Greene *et al.*, 2001). And last but not least is the loss of effectiveness of the toxin resulting from the selection of a resistance mechanism in bollworm populations (Roush and Shelton, 1997; Gould, 1998).

Will the rules of resistance management change?

In small-scale cropping systems, in which both the fields and decision-makers are scattered, it is no easier to build a strategy for the prevention of resistance to Bt-toxins than to synthetic insecticides. The postulates allowing the dissemination of the innovation in the United States are HD+R, that is to say high doses expression of the toxin inside the cotton plant, high enough to kill insects with intermediate level of resistance, associated with refuge providing large susceptible populations, refuges planted close enough to Bt-fields for emerging adult insects to mate with the few individuals surviving on Bt-cotton. Some observations temper the adoption of such a strategy for Bt-Cotton in the "Old World": data obtained in Australia (Fitt *et al.*, 1994) and France (Uraichuen *et al.*, 2001) show that *H. armigera* larvae are four or five times less susceptible to the toxin Cry1Ac than those of *H. virescens*, thus tempering the notion of high level of toxin expression with regard to this pest.

It seems that expression of the toxin is decreasing through the latter part of the season (Fitt *et al.*, 1994; Greenplate, 1999), leading to problems for cotton producing countries where the control of late season infestations of the bollworm is the key of the yield obtained. It seems that a variety of stresses, including water availability, temperature and light intensity, could affect toxin expression (Daly and Fitt, 1998; Botha-Oberholster and Hofs, personal communication).

It results from these points that the HR+R theory does not seem to be applicable to the situation observed in small farming in the Old World, as discussed in China (Ru-LiJun *et al.*, 2002).

Cirad works on resistance to Bt-toxins

CIRAD is currently involved in research programs on bollworm resistance to Bt-toxins, to help national research institutions willing to introduce Bt-cotton to build rational management programs. On one hand, experiments on *H. armigera* strains are conducted in the laboratory in Montpellier, on the other hand, observations are made on Bt-Cotton in the field and in controlled environment in South Africa, in collaboration with the University of Pretoria.

Selection of a laboratory strain of *H. armigera* in Montpellier led to an increase in resistance after 15 generations, the resistance level stabilizing around a 150-fold ratio (Uraichuen *et al.*, 2001). According to the number of insects used in the selection process, the frequency of mutations conferring resistance to Cry1Ac was estimated at 10^{-3}, a rather high but already cited value (Gould, 1998).

Cross mating between resistant and susceptible individuals and observations on the offspring indicated some dominance of the resistant trait, in contradiction with some lab results (Jurat-Fuentes *et al.*, 2000) and basic postulates for the management of resistance.

A third level of studies indicate cross resistance between Cry1Ac and other toxins like Cry1Aa and Cry1Ab, but not with Cry2A, results in accordance with other authors (Jurat-Fuentes *et al.*, 2000), which leads the way for gene pyramiding as a way to delay resistance, as far as Cry1Ac resistance is not already selected.

Among the issues of the research program performed by Cirad in cooperation with the University of Pretoria, are on one hand the impact of Bt-cotton on the insect fauna (pest complex as well as beneficial diversity and activity) and on the other hand a study of former "secondary" pests currently emerging as key-insects, (Fitt *et al.*, 1994; Greene *et al.*, 2001).

Another key point is the quantification of toxin expression along cotton growing, and how it could be affected by plant age, light intensity, drought or cold.

An economic and eco-toxicological balance has to be drawn up, considering as well the amount as the toxicology of the chemicals used for insect control in Bt-and conventional cotton crops.

Last but not least, detection and monitoring of individuals resistant to Cry1Ac toxin in South African populations of the noctuid *H. armigera* is high on the list of research topics set up in the field of entomology.

Bt-Cotton management in small scale farming systems

Are there special features of the management of Bt-cotton in comparison with that of resistance to pesticides for small farming?

The OECD Workshop on ecological implications of transgenic crop plants (Hokkanen and Wearing, 1994) gave a list of sixteen points to consider before introducing a Bt-crop in a new environment.

It is easy to answer to a first group of points for rainfed cotton in small farming: cotton is a crop of high economic value; the bollworms are of major importance; numerous wild or cultivated plants can act as refuges for polyphagous insects, like *H. armigera*; chemicals still remain a credible alternative; non- target insects seem unaffected by the toxin and cotton is generally grown with low risk of gene flow into wild relatives.

Some other points are not so easy to consider: will other Bt-crops be cultivated in the same area? Will growers be cooperative in resistance management? What will be the impact of "secondary" pests on yield? Some target species, like the red, the pink or the spiny bollworm are oligophagous species, and will be obliged to survive on cotton, accumulating resistance pressure; toxin expression level is not under control and resistance gene frequency in wild populations is unknown. The answer given to the last points is the key in the decision process.

Transgenic varieties are usually introduced from the United States. It means that they do not fit as well with the local conditions as the local cultivars. It is especially true for insect resistance. As an example, hairiness is broadly used through Africa and Asia as a resistance trait against jassids. As Bt-toxins do not control jassids, this hairiness has to be introduced in Bt-cultivars.

As less use is made of pesticides for bollworm control, increased activity of beneficials can be hoped for, diversifying the causes of mortality in the bollworm populations. But as Bt-toxins will not control cotton aphids, whiteflies and bugs, seed treatment for early control of homopteran species and pesticides to control Mirids and green bugs could be used, reducing therefore the impact of beneficials.

The exposure of larval populations to the toxin is permanent or practically permanent, thus increasing selection pressure. Reduction of such a selection pressure, as recommended for pesticides, could be only obtained only by promoter–controlled toxin expression in Bt-cultivars.

The notion of refuge is extremely debatable in a small-scale farming context. Is it enough for individuals to develop on host plants found in the eco-system, whether they are cultivated or not? The experience gained with pyrethroid resistance of *H. armigera* seems to indicate that it is not. Can it then be accepted that not all growers will adopt the innovation and that it will thus be possible to continue to provide classical pesticide protection of part of the area under cotton cultivation, or would it be necessary to set up small plots of conventional varieties in each village as refuges? The work of Cerda (2002) speaks in favour of the last proposal.

Should mixed seed be promoted, the first studies of which do not clearly demonstrate the advantage (Agi *et al*., 2001) or is it preferable to wait for cultivars expressing multiple toxins or antibiosis factors, before insect-resistant varieties are introduced?

Conclusion

This discussion is aimed at forming a reminder that there is no single response to the pressure exerted by cotton pests, but that it is necessary to set up rational management of all the weapons available to us in order to limit the impact of the pest complex on cotton production.

The need to use a number of practices to first of all avoid pests (grow healthy plants) and then to limit the economic effects (make observations for the appropriate action) has already been mentioned in relation to chemical control. These principles are valid for the cultivation of varieties transformed for resistance to bollworms. Knowledge of bollworm population dynamics should make it possible to choose cotton flowering and fruiting periods outside the main infestation periods by adapting the sowing date - when possible - to escape the phases of strongest pest pressure.

Two basic components of integrated protection making it possible to avoid leaf spraying of insecticides before the fruiting phase of cotton are a diversity of crops with the limiting of cotton in the agro-systems and the choice of a variety that is sufficiently hardy and also resistant to pests during the vegetative phase (hairiness vs. Typhlocybinae).

Cotton expresses the Bt-toxin in a satisfactory way during its vegetative growth phase only, as long as the plant is not affected by any stress - especially water stress. We should therefore work on the assumption of a weak toxin expression during the main bollworm infestation period. To increase gene flow between wild and toxin-exposed insect populations, it has been demonstrated that plots mixing transformed and non-transformed seeds are not very effective. The management of a cropping system enabling moth migrations (transfer?) between wild or cultivated host plants and the Bt-cotton fields is the first way to maintain susceptibility inside the *H. armigera* population. Furthermore, as it generally does not appear cross-resistance between Cry1Ac and Cry2Aa (Uraichuen *et al*., 2001; Gajendra Babu *et al*., 2002), gene pyramiding is a second step. And last, to fit with environmental conditions, it can be considered that, after backcrossing to introduce the Bt-genes, local hirsute Bt-cultivars would be better suited to small-scale farming cotton growing than the glabrous ones currently introduced. The CIRAD Cotton Program proposes to use such hypotheses to undertake preliminary studies for the introduction of cotton plants transformed for resistance to pests in small farming.

References

- Agi, A.L., Mahaffey, J.S., Bradley, J.R, Jr. and Van Duyn, J.W. (2001). Efficacy of seed mixes of transgenic Bt-and nontransgenic cotton against bollworm, *Helicoverpa zea* Boddie. *Journal of Cotton Science*, **5**: 74-80.
- Brickle, D.S., Turnipseed, S.G. and Sullivan, M.J. (2001). Efficacy of insecticides of different chemistries against *Helicoverpa zea* in transgenic *Bacillus thuringiensis* and conventional cotton. *Journal of Economic Entomology*, **94**: 86-92.
- Cerda, H. (2002). A high-dose refugia management strategy for Bt-transgenic crops: spraying the refugia ? *Antenna*, **26**: 124-126
- Daly, J.C. and Fitt, G.P. (1998). Efficacy of Bt-cotton plants in Australia: what is going on? Proceedings of the World Cotton Research Conference-2. Athens, Greece. 675-678.
- Fitt, G., Mares, C.L. and Llewellyn, D.J. (1994). Field evaluation and potential ecological impact of transgenic cottons in Australia. *Biocontrol Science & Technology*, **4**: 535-548
- Gajendra Babu, B., Udayasuriyan, V., Asia Mariam, M., Sivakumar, N.C., Bharathi, M. and Balasubramanian, G. (2002). Comparative toxicity of Cry1Ac and Cry2Aa delta-endotoxins of *Bacillus thuringiensis* against *Helicoverpa armigera*. *Crop Protection*, **21**: 817-822.
- Gould, F. (1998). Sustainability of transgenic insecticidal cultivars: integrating pest genetics and ecology. *Annual Review of Entomology*, **43**: 701-726.
- Greene, J.K., Turnipseed, S.G., Sullivan, M.J. and May, O.L. (2001). Treatment thresholds for stink bugs in cotton. *Journal of Economic Entomology*, **94**: 403-409.
- Greenplate, J.T. (1999). Quantification of *Bacillus thuringiensis* insect control protein Cry1Ac over time in Bollgard cotton fruit and terminals. *Journal of Economic Entomology*, **92**: 1377-1383.
- Hokkanen, H.M.T. and Wearing, C.H. (1994). The safe and rational deployment of Bt-genes in crop plants: conclusions and recommendations of the OECD Workshop. *Biocontrol Science & Technology*, **4**: 399-403.
- Ismael, Y., Bennett, R. and Morse, S. (2002). Farm-level economic impact of biotechnology: small-holder Bt-Cotton farmers in South Africa. *Outlook on Agriculture*, **31**: 107-111.
- Jurat-Fuentes, J.L., Gould, F.L. and Adang, M.J. (2000). High levels of resistance and cross resistance to *Bacillus thuringiensis* Cry1 toxins in *Heliothis virescens* are due to reduced binding and pore formation. *Resistant Pest Management*, **11**: 23-24.
- Martin, T., Ochou, G., Hala N'Klo, F., Vassal, J,M. and Vaissayre, M. (2000). Pyrethroid resistance in the cotton bollworm, *Helicoverpa armigera* (Hübner), in West Africa. *Pest Management Science*, **56**: 549-554.
- Perlak, F.J., Oppenhuizen, M., Gustafson, K., Voth, R., Sivasupramaniam, S., Heering, D., Carey, B., Ihrig, R. and Roberts, J.K. (2001). Development and commercial use of Bollgard cotton in the USA). early promises versus today's reality. *The Plant Journal*, **27**: 489-501.
- Pray, C., Ma, D.M., Huang, J,K. and Qiao, F.B. (2001). Impact of Bt-Cotton in China. *World Development,* **29**: 813-815.
- Quaim, M. and Zilberman, D. (2003). Yield effect of genetically modified crops in developing countries. *Science*, **299**: 900-902.
- Roush, R.T. and Shelton, A.M. (1997). Assessing the odds: the emergence of resistance to Bt-transgenic plants. *Nature Biotechnology,* **15**: 816-817.
- Ru-LiJun, Zhao-JianZhou, Rui-Chang Hui (2002). A simulation model for adaptation of cotton bollworm to transgenic Bt-cotton in northern China. *Acta Entomologica Sinica*, **45**: 153-159.
- Uraichuen, S., Vassal, J.M. and Vaissayre, M. (2001). *Helicoverpa* resistance and cross-resistance to *Bacillus thuringiensis* delta-endotoxins. Resistance 2001, 24-26 Sept. 2001, IACR Rothamsted, Harpenden, UK. Poster session, 2-38.