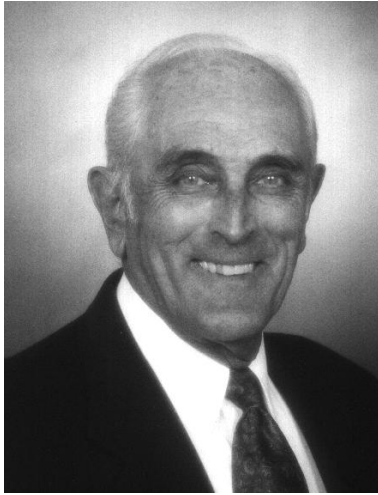


GUEST EDITORIAL



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Transgenic Cotton: The Quandary of Pink Bollworm Resistance Development in the Southwestern United States Growing Areas

The introduction of genetically modified cottons into agroecosystems in the southwestern United States has revolutionized pest management of the pink bollworm *Pectinophora gossypiella* (Saunders). Pink bollworm has been recorded from most cotton-growing countries of the world (15). Its early distribution and spread to various countries in the Middle East, in Australia and on the Indonesian and Malaysian Islands, after it was described from cotton in India in 1842, has been traced (15). The precise origin of the pink bollworm remains unknown. The preponderance of its parasites in Pakistan suggests it may be native to the Indo-Pakistan area (4).

Pink bollworm was first noted in the United States in Texas cotton in 1917. The source was traced to cottonseed shipped from Mexico in 1916 to Texas oil mills. Eradication of early infestations was followed by reinfestation in the lower Rio Grande Valley in 1936. By the mid-1950s, infestations were found in other areas in Texas, New Mexico, Oklahoma, Arizona, Arkansas and Louisiana. Infestations in eastern Arizona occurred in 1926 and at intervals thereafter in other parts of the state. Cooperative federal, state and industry programs suppressed the infestations and following the termination of programs in 1963, spread of pink bollworm throughout Arizona to the Imperial and Palo Verde Valleys of California had occurred by 1965.

Following spread of the pink bollworm, insecticide use on cotton increased in the invaded areas from one or two applications to ten to 15 applications. Resistance to DDT occurred in Mexico in the late 1950s after 11 to 12 years of selection pressure (20). DDT resistance was discovered in Texas in 1962 (16). By the mid-1970s, there were

reports of reduced effectiveness of some organophosphate and carbamate insecticides, but without documentation (20). By the mid-1980s pink bollworm tolerance to certain pyrethroid insecticides was documented (12,13). Losses in the Imperial Valley (California) alone ranged from 8% to 79% of the crop value from 1966 to 1980 (3). These losses and reduced cotton prices on the world market were major factors resulting in reduced cotton production, from 57,871 ha in 1977 to 3,713 ha in 1994 in the Imperial Valley. Heavy reliance on insecticides for pink bollworm control through the mid-1990s was only marginally effective and caused adverse environmental, social and economic problems. The mean cost of insecticides used in the Imperial Valley during 1978–88 rose to a high of \$640 per ha per year (8). Obviously the insecticide approach was not a long-term solution to the problem.

Although progress was made using conventional plant breeding techniques to identify plant traits for pink bollworm resistance (23), the major breakthrough for managing pink bollworm *via* host plant resistance occurred with the development of cottons carrying the gene that mediates production of one of the insect toxic proteins from *Bacillus thuringiensis kurstaki* (Berliner) (19). Evaluation of experimental transgenic cottons (23), advanced genetic lines (5), and finally commercially developed cultivars (6) showed >95% reduction in pink bollworm infestations. Enthusiastic grower acceptance followed with 50% or more of the acreage from 1997 to 2000 planted to *Bt* cottons in Arizona (21). Economic models suggest that pest control costs have been reduced by \$62 to \$136 per ha, with overall grower gains in excess of 10 million dollars per year (7). Adoption of *Bt* cotton and the use of insect growth regulators for sweetpotato whitefly, *Bemisia tabaci* (Gennadius), in Arizona has resulted in a 65% reduction in conventional insecticide use (21).

These outstanding successes have been clouded with concern that pink bollworm will become resistant to the *Bt* toxic protein(s) (9). The threat of loss of the positive impacts of *Bt* technology for cotton and other crops has stimulated substantial efforts to preserve the efficacy of *Bt* technology by reducing, delaying or preventing resistance. For cotton, this appeared to be a formidable long-term challenge. The long cotton-growing season exposes multiple pink bollworm generations annually to *Bt* toxic proteins. Exposures can be continuous for 5 to 7 months and laboratory selection of highly resistant strains has been easily achieved in four generations (2). Thus, most scientists agreed that there was a high risk of *Bt*-resistance development. The U.S. Environmental Protection Agency required a resistance management plan as a part of *Bt* registration. The high dose/refugia strategy was adopted (9) and implemented in Arizona with annual refinements beginning in 1997 (21). Non-*Bt* cotton refugia are grown in close proximity to *Bt* cottons that have high concentrations of toxic protein. Susceptible pink bollworms developed in the refugia mate with toxin-resistant individuals that survive in the *Bt* cotton. Progeny produced should have low or moderate toxin resistance; they should not be able to survive on the high-toxin-level *Bt* plants (10). Resistance monitoring has been conducted each year and a rapid response team established to investigate potential problems. After 6 years of commercial use, no failures in the field have been reported and high levels of efficacy have been maintained. Increased yields, reduced insecticide use and environmental compatibility have been documented (7).

The pink bollworm has the genetic ability to develop *Bt* resistance, as evidenced by several laboratory selection studies. There is no ready explanation for the lack of any measurable change in *Bt* susceptibility under field conditions for at least 24 generations.

Possibly, extremely low levels of resistant individuals occur that are not detected with current methodology and/or more extensive sampling is required for detection. The *Bt* technology appears recently to have been strengthened further with the introduction of a second gene producing a second toxic protein in cotton (22). The Bollgard® cottons containing two genes evinced tenfold better efficacy for pink bollworm control than cottons with the single genes only (17). The two-gene cottons also appear more efficacious for controlling other cotton pests (18). The concern regarding loss of *Bt* efficacy in late season also does not appear to be a significant threat. No differences in pink bollworm mortalities have occurred on late-season vs early-season bolls or in flower buds compared with 10-, 20-, 30- or 40-day-old bolls (14). The high degree of pink bollworm susceptibility to Cry1Ac protein (no survival of a susceptible strain on diets containing 0.005 $\mu\text{g}/\text{ml}$ of the toxic protein; ref. 2) may be a partial explanation. The lowest Cry1Ac level reported in *Bt* cotton fruiting forms was 6.7 $\mu\text{g}/\text{g}$ dry weight (11).

The threat of *Bt* resistance development remains a continuing concern. This takes on increasing significance in view of the western U.S. cotton producers' plan to eradicate the pink bollworm from 81, 162, 371 and 81 thousand hectares in west Texas, southern New Mexico, Arizona, and California and northern Mexico, respectively, while continuing to prevent pink bollworm establishment in California's San Joaquin Valley (1). The program will implement areawide short-season cultural control strategies and *Bt* cotton to reduce overall populations. The *Bt* management component is considered essential, since follow-up pheromone mating disruption and sterile pink bollworm releases are most effective at low population levels. The high dose refugia strategy is the only resistance management practice currently implemented, although alternate-year rotations have been discussed. We have no scientific measure of the refugia impact nor any detailed information on size, placement or configuration for optimum effects. Areawide pink bollworm suppression with the goal of eradication is a major undertaking. Although we have been unable to measure pink bollworm *Bt* resistance development or changes in susceptibility in the field and cannot explain the lack of resistance selection, there is no reason for complacency or diminished research effort to increase our knowledge of the system. Successful refugia resistance management impact assumes: genetically recessive resistance, rare resistance allele occurrences, and susceptible-resistant moth population mixing to achieve random mating (9). To assure areawide program success, our minimum needs are estimates of refugia effectiveness and a better understanding of the spatial, temporal and quantitative manipulation of refugias. Other needed information concerns pink bollworm behavior, dispersal and reproductive biology within and between *Bt* and non-*Bt* cotton cultivars. A concerted effort to define the mechanism of resistance may be necessary to reveal strategies to cope with or circumvent resistance if it occurs. Information on the more subtle, long-term concerns such as transgene flow to native plant species, potential effects on behavior and behavioral interactions of natural enemies and their hosts, and other environmental and ecological impacts, is also urgently needed and investigations of these subjects are at present in their infancy. These elements must be determined to facilitate and ensure efficient transition from conventional cotton cultures to the implementation of biotechnology advances not only with *Bt* toxic protein transgenes but also with additional useful transgene traits that may be on the horizon.



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