Managing pyrethroid- and Bt-resistant bollworm in southern U.S. cotton

By **Dominic Reisig**, North Carolina State University, Department of Entomology and Plant Pathology; **David Kerns**, Texas A&M University, Department of Entomology; and **Jeff Gore** and **Fred Musser**, Mississippi State University, Department of Biochemistry, Molecular Biology, Entomology, and Plant Pathology

Two- and three-toxin Bt cotton still provides a valuable service to integrated pest management in southern U.S. cotton. However, shifting patterns in resistance levels of a key pest, bollworm, have dictated changes in thresholds and foliar insecticide spray recommendations. **Earn 1 CEU in Integrated Pest Management** by reading this article and taking the quiz at www.certifiedcropadviser.org/education/classroom/classes/625.

Helicoverpa zea (Boddie), known as bollworm, corn earworm, and tomato fruitworm, is a pest that has likely plagued crops for millennia since they were first domesticated from their wild relatives. This pest is difficult to manage for many reasons:

1. It is polyphagous, meaning that it can eat a variety of different plant species. For example, in North Carolina, it can feed on at least 16 crops as well as many wild hosts (Neunzig, 1969). Hence, management of this insect in one crop can influence another crop.

2. It has multiple generations a year, and a single female can lay up to 2,500 eggs. As a result, although overwintering mortality is high (only ~1–9% of the population survive to the spring [Caron et al. 1978; Mueller et al., 1984]), populations grow exponentially by the time summer crops are attractive for moths to lay eggs.

3. It has facultative diapause. Diapause is a resting state, and in the case of bollworm, it diapauses as a pupa in the soil. Bollworm pupae can stay in the soil until

doi:10.2134/cs2019.52.0108

conditions are favorable for survival. Also, being facultative allows them to hedge their bets. For example, most emergence from overwintering takes place over two to three months (Dicke, 1939; Hardwick, 1965). However, a small subset of pupae can emerge as late as August from overwintering (Phillips and Barber, 1929).

4. It has excellent dispersal capabilities, meaning that bollworm management, or lack of management, and the availability of hosts in one area can influence bollworm management in another area. For example, adults can move distances of several hundred miles (Hendrix et al., 1987; Lingren, 1993), and larvae can move off plants (Terry et al., 1989) and between plants (Burkness et al., 2015).

5. Finally, it has a long history of insecticide resistance. Bollworm became resistant to organochlorines in the 1950s and 1960s, the organophosphates in the 1960s, the pyrethroids in the 1990s in the southern U.S. and in the 2000s in the Midwest, and the plant-produced Bt toxins (Cry toxins) in the 2010s. While insecticide resistance is the concern of this article, it is important to keep in mind the other factors that allow this insect to succeed.

The widespread planting of Bt corn and cotton, beginning in 1996, led to a changing pest complex in the system. In corn, the major targets of Bt were the southwestern corn borer [*Diatraea grandiosella* (Dyar)] and the European corn borer [*Ostrinia nubilalis* (Hübner)] (Storer et al., 2001). In cotton, the major targets of Bt cotton were bollworm, tobacco budworm [*Chloridea virescens* (Fabricius)], and pink bollworm [*Pectinophora gossypiella* (Saunders)] (USEPA, 1995). All of these reduced as major pests, largely due to the efficacy of Bt crops with the exception of bollworm. In corn, bollworm is typically not considered an economic pest because yields are rarely increased by Bt (Reay-Jones and Reisig, 2014; Reay-Jones et al., 2016; Bibb et al., 2018) and because foliar pesticide application would be cost prohibitive. Moreover, while bollworm feeding can be associated with aflatoxin and fumonisin contamination (Smith and Riley, 1992), environmental factors other than bollworm are much bigger drivers of mycotoxin levels (Bowen et al., 2014).

In contrast, bollworm is a major yield-limiting pest of both cotton (Bt and non-Bt) and soybean. In soybean, bollworm can currently be controlled using foliar insecticides. For example, a recent survey of bollworm populations across the southern U.S. found that they were very susceptible to diamide-class insecticides (Adams et al., 2016a) and that these could be effective, if used properly, in soybean (Adams et al., 2016b). While pyrethroid-resistant bollworm populations have been present since the 1990s, use of this class for bollworm in both cotton and soybeans was still widespread until the 2010s. Recent bioassay results have suggested that this selected for widespread pyrethroid resistance (Fig. 1). This reflects results experienced in the field.

Pyrethroid and Cry resistance

In Bt cotton, bollworm larvae that survive sublethal doses of the Bt grow more slowly and can be killed with pyrethroids or reduced rates of many other insecticides (Brown et al., 1998; Brickle et al., 2001). However, there is widespread resistance to cotton expressing Cry toxins in the southern U.S. (Yang et al. 2017; Reisig et al., 2018). As a result, pyrethroid- and Cry-resistant bollworm populations are now widespread, limiting the utility of pyrethroids for larval bollworm control in Bt cotton. Furthermore, new varieties of cotton have been introduced that express a non-Cry toxin, Vip3Aa19. This trait provides good control of bollworm in cotton but sometimes requires remedial oversprays. For example, in Midsouth trials during 2014, WideStrike 3 (Cry1Ac + Cry1F + Vip3Aa19) needed to be sprayed in one out of four locations that were tested to preserve yield (Fig. 2). Relative to Bollgard II and

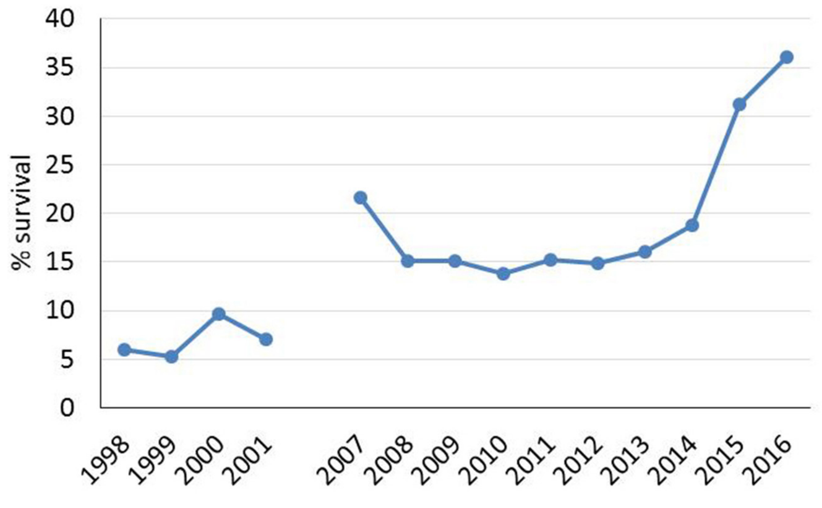

Fig. 1. Average percent survival of male adult bollworm in vials coated with 5 μg cypermethrin (corrected for control mortality) over time. Results from populations in Arkansas, Georgia, Louisiana, Mississippi, Missouri, North Carolina, South Carolina, Texas, and Virginia during most years (Musser et al. 2018 unpublished data).

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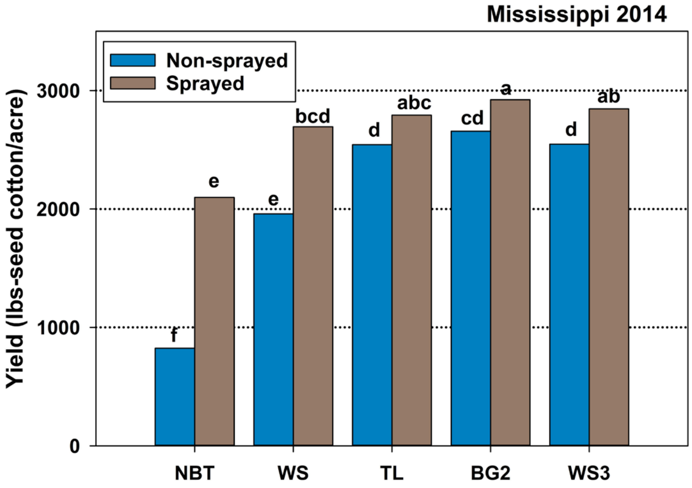

Fig. 2. Pounds of seed cotton per acre in a non-Bt (NBT), WideStrike (WS), TwinLink (TL), Bollgard II (BG2), and WideStrike 3 (WS3) variety during a 2014 trial in Mississippi. Plots were either left untreated for bollworm or treated preventatively with the full labeled rate of chlorantraniliprole (Prevathon) during the time that bollworm larvae were present.

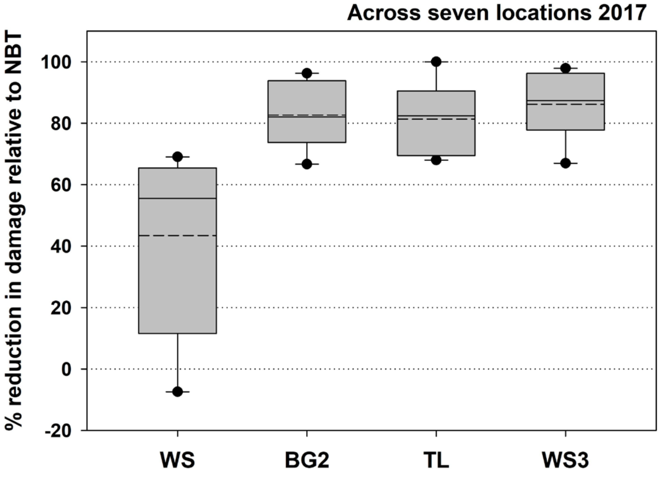

Fig. 3. Percent reduction in squares and bolls damaged by bollworm larvae from six Midsouth locations and one Texas location during 2017 in Bt cotton varieties relative to a non-Bt variety (NBT). WS= WideStrike, TL= TwinLink, BG2= Bollgard II, and WS3= WideStrike 3.

Twinlink, WideStrike 3 provides a modest improvement in protection of squares and bolls relative to non-Bt cotton (Fig. 3). However, the efficacy of each particular Bt cotton product relative to non-Bt will depend on the environment, particularly the Bt resistance profile of the bollworm population. Additionally, the prevalence of tobacco budworm is important since it is still well managed using all commercialized Bt cotton products.

Prior to widespread Cry resistance, most southern U.S. states recommended a larval or damaged reproductive structure-based threshold in Bt cotton. Thresholds ranged from three- to eight-second instar or larger larvae per 100 plants or 2 to 5% damaged reproductive structures (squares, bloom, and bolls). These thresholds are logical since Bt cotton completely controls tobacco budworm. Tobacco budworm and bollworm eggs are indistinguishable, and larvae must consume Bt tissue to die. Therefore, spray decisions could be made based on bollworm by scouting based on second-instar or larger larvae and damaged reproductive structures. Further advantages were relative ease of scouting and allowing more time for Bt and natural enemies to diminish bollworm populations.

However, the intersection of pyrethroid- and Cry-resistant bollworm populations made larval control increasingly difficult in Bt cotton without Vip3Aa19. Bollgard cotton (expresses one Bt toxin, Cry1Ac), which has not been commercially planted in the U.S. since 2009, required more frequent foliar insecticide intervention than pyramided Bt cotton (expresses two or more Bt toxins). While most states recommended a larval or damaged reproductive structure threshold for Bollgard cotton, there was some evidence that an egg-based threshold could be useful in Bt cotton (Sullivan et al., 1998). Egg-based thresholds were commonly used prior to the commercialization of Bt cotton, sometimes resulting in higher economic returns than larval-based thresholds (Bacheler and Bradley, 1989). However, in other cases, they were good, but no better than larval-based thresholds (Durant, 1991). Durant (1991) speculated that this was likely the case when tobacco budworms were present along with bollworms (as mentioned previously, tobacco budworm and bollworm eggs are indistinguishable).

Revival of an egg-based threshold?

A series of experiments conducted during 2017 in North Carolina demonstrated the potential for the revival of an egg-based threshold for bollworm in two-Bt-toxin cotton using the insecticide chlorantraniliprole. This technique was pioneered in the Midsouth and took advantage of the fact that this insecticide was xylem mobile (Lahm et al., 2007), translaminar, could move to newly grown vegetative tissue after application, and provided relatively extended residual (Adams et al., 2016b). The North Carolina experiments were initiated using foliar chlorantraniliprole (Prevathon) applications when bollworm eggs were deposited in Bt cotton, but larvae were not present, and when bollworm eggs were present, along with some larvae, in non-Bt cotton (despite Cry resistance, larvae still developed more slowly on Bt cotton during 2017). Additional treatments were chlorantraniliprole applications initiated weekly thereafter when fewer eggs were present and more larva were present. In all two-Bt-toxin cotton (Bollgard II, TwinLink, and WideStrike), yield and net returns were the highest when sprays were initiated when eggs were present before larvae. However, yields were not increased in three-Bt-toxin cotton (Bollgard 3, TwinLink Plus, and WideStrike 3) using chlorantraniliprole applications (Fig. 4).

These data support the use of an egg-based threshold for two-Bt-toxin cotton (Bollgard II, TwinLink, and WideStrike) but larval or damaged reproductive structure based thresholds for three-Bt-toxin cotton (Bollgard 3, TwinLink Plus, and WideStrike 3). At this time, there are little quantitative data to provide a good egg number for the threshold. The number of eggs that should trigger a chlorantraniliprole application will vary depending on factors such as growth stage of the cotton, Cry susceptibility of the bollworm population, and duration of the ovipositional (egg-lay) event, to name a few. Furthermore, scouting eggs is difficult. Most eggs are oviposited on leaves and bracts of reproductive structures (Braswell, 2018). Depending on the time of the season, these eggs can be laid throughout the canopy (harder to scout) or near the top of the plant (easier to scout; Braswell, 2018). Finally, the threshold will be most applicable to cases where tobacco budworm is relatively absent.

A valid criticism of the egg threshold it that it does not give the Bt technology the opportunity to demonstrate effectiveness. Thus, in areas where injury to Bt cotton is uncommon, the egg threshold should not be utilized. However, in areas where injury to Bt cotton is common, an egg-based threshold will be recommended for two-Bt-toxin cotton, and a larval or damaged reproductive structure based threshold will be recommended for three-Bt-toxin cotton (Bollgard 3, TwinLink Plus, and WideStrike 3). Insecticide choice and timing is important for these thresholds to be efficient. As previously mentioned, pyrethroid resistance in bollworm is common in much of the southern U.S. Many states no longer recommend pyrethroids for managing bollworms while some regions still find they are efficacious.

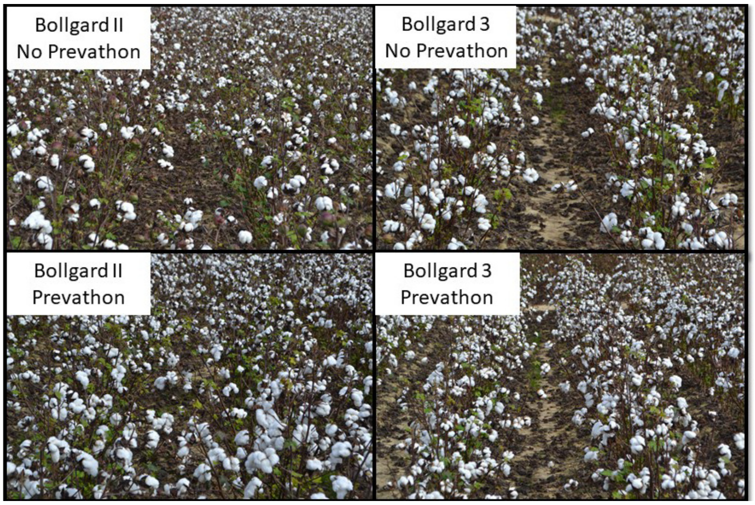

Fig. 4. Photos of representative plots at harvest time. Bollgard II and Bollgard 3 not sprayed with Prevathon (chlorantraniliprole) and sprayed with Prevathon weekly from the second through sixth week of bloom.

Overcoming insecticide control failures

Currently, diamide insecticides, such as chlorantraniliprole, are the most commonly recommended insecticides for managing bollworms in cotton. However, even these insecticides have experienced occasional control failures. Most control failures with diamide insecticides are thought to result from poor spray coverage, insufficient use rates, or poor timing. Timing insecticide application toward small larvae has proven to be most effective. Once the larvae reach second instar, they commonly move deeper into the plant canopy and burrow into fruiting structures, which greatly limits insecticide exposure. Managing crop growth to avoid excessive vegetative or rank growth can aid in minimizing problems with spray coverage. This means maintaining early-season fruit feeding pests such as plant bugs and cotton fleahoppers, avoiding excessive nitrogen fertilization, and proper utilization of plant growth regulators.

Other insecticides that are sometimes utilized for bollworm management in cotton include spinosad, indoxacarb, and methomyl, but these insecticides tend to be either less effective and/or exhibit shorter residual activity.

Conclusions

In conclusion, two- and three-toxin Bt cotton still provides a valuable service to integrated pest management in southern U.S. cotton. However, shifting patterns in resistance levels of a key pest, bollworm, have dictated changes in thresholds and foliar insecticide spray recommendations. These will no doubt continue to shift in the future as practitioners adopt these recommendations and exert selection pressure for the evolution of resistance to these management tactics. Therefore, practices that can reduce the selection pressure (i.e., planting non-Bt corn refuge and rotating foliar insecticides) will ensure the effective longevity of these management tactics.

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[continued from p. 33]

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