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The Conundrum of Chemical Boll Weevil Control in Subtropical Regions

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1. Introduction

Originally a Mesoamerican insect, the boll weevil, *Anthonomus grandis grandis* Boheman (Coleoptera: Curculionidae), has spread from the tropics, where it evolved on cotton, *Gossypium hirsutum* L., and other malvaceous plant species (Burke et al., 1986; Brubaker & Wendel, 1994; Showler, 2009b), north to temperate cotton producing areas of the United States and south to northern provinces of Argentina (Cuadrado, 2002; Showler, 2009b). The pest was first detected in United States cotton in 1892 (Parencia, 1978) and infested the Cotton Belt such that by 1917, every cotton-producing county in Georgia, for example, was infested (Hunter, 1917). Adults oviposit inside cotton buds or "squares" (usually one egg per square), and the hatched larva causes the square to abscise before it can flower (Showler and Cantú, 2005). If an egg is deposited within a young boll (older bolls become too hard to penetrate), or if mouthparts penetrate the rind of squares to the inner reproductive portion, fiber-producing locks can be injured or completely destroyed, but not necessarily all four locks (Showler, 2006a; Showler & Cantú, 2008). Boll weevil losses have been valued at $83.34 billion and insecticide-based control costs at $18.67 billion between 1893 and 1999, and infestations became so injurious that cotton-free winter periods were instituted by law in some areas (Haney, 2001). Later, insecticide-based eradication programs were launched in the United States and in Argentina (Dickerson & Haney, 2001; Haney et al., 2001; Johnson & Martin, 2001; Texas Department of Agriculture, 2002; Carmona et al., 2003).

Natural enemies indigenous to the United States are not considered to be important as mortality factors against boll weevils (Jones & Sterling, 1979; Showler & Greenberg, 2003), although the imported fire ant, *Solenopsis invicta* Buren, native to South America (Buren et al., 1974; Lofgren, 1986), can account for up to 58% of boll weevil mortality in relatively wet regions where the predator thrives (Sturm & Sterling, 1990). In one study imported fire ant predation on immature boll weevils averaged 84% compared with 0.14% and 6.9% mortality caused by parasitism and desiccation, respectively (Fillman & Sterling, 1983). But in drier cotton growing areas, lack of sufficient predation to help govern populations in some new habitats outside Mesoamerica (Showler, 2007) permitted rapid dispersal (Burke et al., 1986; Showler, 2009a). While certain cultural practices, such as early planting (Showler et al. 2005) can help avoid large populations that typically accumulate in the summer (Showler, 2003, 2005), chemical intervention against building infestations has been the chief control tactic.

In subtropical south Texas, before the boll weevil eradication program was re-instated in the fall of 2005 (after a halted attempt in 1995), crop protection against boll weevils was approached using three tactics: mandatory cotton stalk destruction before 1 September, prohibition on planting until 1 February and elimination of volunteer cotton during the cotton-free winter period (Texas Department of Agriculture, 2002). Insecticides were the only in-season control approach (Showler, 2007). Some growers sprayed 2–3 "pre-emptive" treatments starting at the "pinhead" square size (1–2-mm diameter) (Heilman et al. 1979) followed by insecticide applications (often azinphosmethyl, cyfluthrin, bifenthrin, or oxamyl) whenever 10% of randomly selected medium (3–5.4-mm diameter) or large (5.5–8-mm diameter) squares (Showler, 2005; Showler et al., 2005) had oviposition punctures (Showler et al., 2005). While Heilman et al. (1979) suggested that pre-emptive spraying delays insecticide applications later into the season, other research found no beneficial effect (Showler, 2004a) and the economic value of the practice is debatable. Pre-emptive sprays might kill some adult boll weevils that have entered the field after overwintering elsewhere, but the sparse numbers of weevils at that time and the presence of less-preferred and nutritionally inferior small squares contribute relatively little to field-level population buildups, and injury to such small squares has negligible impact on lint yield (Showler, 2004b; Showler et al., 2005). Late-season spraying for immediate crop protection (not eradication) purposes is also of questionable utility because, although feeding and oviposition punctures can be abundant on bolls, older bolls (≥14 days old) are less vulnerable to attack (because they harden) than younger (≤10 days old) bolls and bolls do not abscise in response to boll weevil oviposition (Showler, 2006a). When injury to a boll does occur, usually because of prior adult feeding during the square stage or larval infestation of the boll, damage is often limited to individual lint-bearing locks, of which there are four (Showler 2006a). Insecticides applied in the context of crop protection after cut-out (Guinn, 1986; Cothren, 1999), when bolls predominate, generally fail to measurably suppress boll weevil infestations (Showler & Robinson, 2005; Showler, 2008a).

When cotton is forming medium and large squares, which are most vulnerable to and useful for boll weevil reproduction (Showler, 2004b), the 10% spray intervention threshold is compromised by variability in total numbers of squares over time (Showler, 2007). Declining abundance of squares coupled with surges in boll weevil populations contribute toward the likelihood of triggering interventions based on randomly sampled squares; hence, spraying later protects fewer and fewer squares (Showler, 2007). A better estimate of infestation would involve comparing numbers of oviposition-punctured squares to total squares within, for example, three-meter (or some other length) sections of rows (Showler, 2007). In a study in south Texas, the standard approach, including three pre-emptive sprays, involved nine applications that failed to increase yield and economic return (Showler & Robinson, 2005). Once 10% of the squares harbor a boll weevil egg, protecting it from contact insecticides (Showler & Scott, 2004), it is too late to expect good control.

In temperate areas of the United States, the boll weevil eradication program has had remarkable successes since its beginning in North Carolina and Virginia in 1978 to Georgia to California (Dickerson et al., 2001) and the pest has been eradicated from northern and central regions of Texas as well (USDA-APHIS, 2007; Texas Boll Weevil Eradication Foundation, 2011). The boll weevil is "functionally" eradicated in other areas of Texas (USDA-APHIS, 2007), whereby <0.001 weevils/trap/week were found during the most recently completed growing season, indicating that boll weevils are not reproducing or causing economic damage in an area [*e.g.*, >1.5 million ha of cotton in 2010 (Texas Boll

Weevil Eradication Foundation, 2011)]. Eradication involves three techniques over a 4–5-year period: pheromone trap detection, reduction of boll weevil food supply, and malathion treatments (USDA-APHIS, 2007). The process starts with a series (often seven) of fall malathion applications that were once [and probably erroneously (Showler, 2010)] termed "diapause sprays" (McKibben et al., 2001). The aim is to reduce late season populations that will be further, and dramatically, reduced during cold temperate winters when food is unavailable and temperatures can be lethal (Showler, 2009b,c, 2010). Pheromone traps are then deployed around all cotton fields during the following spring planting and spraying of each field begins 5–6 weeks later based on trap captures; the process is repeated annually until the boll weevil is no longer found (USDA-APHIS, 2007). Still, there are ≈262,000 ha of cotton in east and subtropical south Texas where eradication has not been achieved (Texas Boll Weevil Eradication Foundation, 2011). While the chance of boll weevil dispersal from infested areas on wind and in hurricane systems exists (Texas Boll Weevil Eradication Foundation, 2011), particularly from nearby Mexico where eradication efforts are not underway, there are other overriding factors contributing to the pest's persistence in the subtropics (Showler, 2007, 2009b). Misconceptions relating to boll weevil ecology and biology (Showler, 2009c), while immaterial in cold temperate areas, appear to underlie the challenges to eradication efforts under subtropical conditions (Showler, 2009b, 2010).

2. Misunderstandings

There have been misconceptions pertaining to fundamental aspects of boll weevil survival outside its native Mesoamerican region that involve dietary habits, overwintering, and diapause, all of which interrelate (Showler, 2007, 2009b,c, 2010), presenting obstacles to temperate eradication approaches when used in the subtropics. Ultimately, the problem resides in numbers of boll weevils (including offspring from overwintering weevils) that can survive cotton-free winters to feed and reproduce in large cotton plantings of the following season. In south Texas, large end-of-season populations can be observed by trapping at the edges of cotton fields that are disrupted by defoliant application, consequent host plant desiccation, harvest, and stalk shredding (Showler, 2003). Those populations move into surrounding habitats where, under temperate winter conditions, the boll weevils that survived the first-year series of late-season eradication program sprays must survive frequently severe and extended cold conditions for which the tropical insect had not evolved, as well as starvation due to lack of viable winter plant hosts (Showler, 2009b,c). Boll weevils have long been assumed to feed solely on pollen of certain malvaceous plants (Burke & Earle, 1965; Cate & Skinner, 1978), and later, pollens of other plants were recognized (Jones et al., 1992, 1993; Hardee et al., 1999), but recent research has revealed that adult boll weevils can consume cotton leaves and bracts, citrus and cactus fruit, and likely nectar (Showler & Abrigo, 2007; Showler, 2009b). In the subtropics, adult boll weevils can survive and reproduce during the winter on small patches of volunteer cotton that, despite surveillance, are overlooked, and adults can be trapped in substantial numbers around grapefruit, *Citrus paradisi* Macfad., and orange, *C. sinensis* (L.) Osbeck., orchards (Showler, 2006b). The edible endocarps of grapefruits and oranges of those citrus species can sustain up to 25% of adult boll weevils in nonreproductive condition for longer than five months (completing the cotton-free period); the maximum longevity (246 days) was only seven days less than boll weevils fed large cotton squares (Showler & Abrigo, 2007). The fruit of prickly pear cacti, *Opuntia* spp. [114 species in Mexico alone (Vigueras & Portillo, 2001)], which is

widespread and abundant in south Texas, can support 10% of adult boll weevils over the winter period, and there are likely other as yet unreported food sources (Showler, 2009b). Hence, in subtropical areas of North and South America where cotton is grown in proximity with citrus, persistent boll weevil populations have been reported even after cotton growing was eliminated or where eradication programs have begun (Cuadrado, 2002; Carmona et al., 2003; Mas et al., 2007; Texas Boll Weevil Eradication Foundation, 2011). Despite the availability of *Opuntia* spp. and other host plants in Mexico and south Texas (Gaines, 1935; Lukefahr, 1956; Lukefahr & Martin, 1962; Stoner, 1968; Cross et al., 1975; Vigueras & Portillo, 2001), cotton in the Lower Rio Grande Valley remained free of boll weevils for 30 years of commercial production beginning ≈1860 (Garza & Long, 2001) even though cotton around Monclova, Coahuila, Mexico, ≈45 minutes latitude north and 220 km west of the Lower Rio Grande Valley, was so heavily infested that the crop was abandoned in 1862 (Howard, 1897). Boll weevil food sources under orchard conditions are concentrated and support substantial active populations through winter (Showler, 2006b) because endocarps are accessible through cracks, holes, or lesions while the fruit is attached to the plant or fallen (Showler, 2007; Showler & Abrigo, 2007). Establishment of boll weevils in Lower Rio Grande Valley cotton during the early 1890s (Parencia, 1978; Haney, 2001) may have been connected to a simultaneous citrus industry boom (Waibel, 1953). The author has witnessed, in mid January, large flying populations of boll weevils in and around nonsanitized (fallen fruit on the orchard floor not removed) orange and grapefruit orchards in south Texas that were so abundant that they were a nuisance. Boll weevils are also known to reproduce in volunteer cotton during Lower Rio Grande Valley winters (Summy et al., 1988), which also contradicts widely accepted, but apparently erroneous, dogma regarding the existence of winter diapause (Showler, 2009c, 2010).

For more than 50 years, boll weevils have been assumed to enter a state of winter diapause (Brazzel & Newsom, 1959), but diapause-induction studies involved weak experimental methods and dubious interpretations of results, and recent research in the subtropics indicates that boll weevils, being of tropical origin, did not evolve a diapause mechanism for surviving temperate winters (Showler, 2007, 2009c, 2010). Sterling and Adkisson's (1966) finding that boll weevils in the Texas High Plains "diapause" earlier and in greater percentages than in Central Texas (at a lower latitude) implies that boll weevil dormancy is not seasonal (a criterion for diapause), but it is instead responsive to dormancy-triggering conditions whenever they occur (Showler, 2010). Brazzel and Newsom (1959), however, claimed that, in the instance of boll weevils, diapause could be a "facultative" response to harsh, unfamiliar, conditions such as cold temperate winters. It is more likely, however, that the response is merely a metabolic and locomotory slowing caused by declining temperature (Fye et al., 1969; Jones & Sterling, 1979; Watson et al., 1986), giving the appearance of being facultative. As winter temperatures cool, a threshold for quiescence (Koštál, 2006; Guerra et al., 1984) or some other nondiapause expression of dormancy is reached first, followed later, if temperatures become sufficiently cold, by mortality (Showler, 2010). Whatever words are employed to describe the insect's response to temperate winters, eradication strategy involving "diapause spraying" has been effective where temperate winter attrition is substantial even if "diapause" might not be the technically correct term (Showler, 2010).

The inescapable point is that under subtropical conditions, particularly in the presence of relatively large plantings of citrus throughout the agricultural landscape, boll weevil mortality is not as great as in cold-winter temperate areas because winters are generally

warm and can support populations with food until the spring (Showler, 2009b). In February, when cotton can be planted, boll weevil numbers near south Texas citrus orchards were found to be substantial (Showler, 2006b). Loss of major winter attrition as an eradication tool will likely require adjustments to the customary approach. Chance movement of boll weevils on wind or farm vehicles into active eradication program areas might cause setbacks to eradication, but the ecological reasons for the boll weevil's persistence in subtropical areas presents broader and more difficult challenges.

3. Chemical tactics: no easy answers

3.1 Insensitive trigger

The spray regimen for cotton crop protection against boll weevils and the reasons it was sometimes not sufficient across all growing areas have been discussed, but aspects of eradication involving insecticide application are also weakened in the subtropical context. Monitoring in-season boll weevil populations, for example, is important for determining whether to intervene and to assess efficacy. It is surprising that boll weevil surveillance fails to account for in-season changes in adult boll weevil response to grandlure largely predicated by cotton plant phenology and associated volatiles. One change occurs as cotton begins to square; then, even while boll weevils are accumulating in cotton fields, few are collected in the traps (Parajulee et al., 2001), presumably a result of competing plant volatiles from large fields of cotton versus a point pheromone source. Further, the trap's physical design presents a series of obstacles that boll weevils must negotiate before finding their way into a plastic cap on top where the weevils are counted (Showler, 2007). At low ambient populations in south Texas, differences in numbers of boll weevils captured in the conventional trap versus a sticky board trap were not detected, both traps using the same pheromone lure, but at higher populations sticky board traps collected ≥9-fold more weevils than the conventional trap, and 30% of the conventional traps collected no boll weevils when corresponding sticky boards accumulated from 82 to 511 weevils at the same locations and time; on one occasion, the conventional trap had two boll weevils compared with 2,228 on a sticky board (Showler, 2003). This is not to suggest that sticky board traps should replace the conventional trap unless their deployment can be made less labor intensive, but a more sensitive trap design would refine spray timing for greater effect as a result of more accurate population detection.

3.2 Spray timing

Because the boll weevil's life cycle includes ≈18 days in immature life stages protected within squares (Showler & Cantú, 2005), commonly-used insecticides with relatively short residual effects (≤4 days) can miss that cohort (Showler & Scott, 2004). To ensure lethal exposure to a larger proportion of the population, such insecticides would have to be sprayed *at least* once every four days. Yield increases in experimental plots were reported where some were sprayed "proactively" every 7–8 days starting when ≈2% of randomly selected squares were large (Showler & Robinson, 2005). It is unlikely, however, that the proactive spray regime would be as effective in larger commercial fields on an area-wide scale; in the study, applications were meticulous and tractor-mounted drop nozzles provided complete coverage even when the plants were high. For large boll weevil populations likes those encountered in the Lower Rio Grande Valley (Showler 2003), insecticides would have to be applied every three or four days from the time medium-sized

squares (3–5.4-mm- diameter) first develop (before 2%) until cut-out when square production declines rapidly (Guinn, 1986; Cothren, 1999).

Under subtropical field conditions, feeding on pinhead- and match-head-sized squares is negligible, and large squares are preferred to medium-sized squares regardless of planting date (Showler, 2005). Boll weevil feeding punctures on large squares were 7.8- and 25-fold more abundant compared with match-head squares and bolls, respectively (Showler, 2004b). In terms of nutritional value, medium and large squares promote greater egg production and longevity of adult boll weevils than any other stage of cotton fruiting body (Showler, 2008b), and in terms of providing enough food and space for the immature stages of the boll weevil to develop, pinhead and match-head squares are generally too small (Showler, 2004b). Hence, spraying insecticides well before medium and large square sizes are available is of little value to crop protection and for impeding boll weevil reproduction, which agrees with the recommendation by Norman and Sparks (1998) for beginning boll weevil control in the Lower Rio Grande Valley when one-third-grown squares appear. Once large squares blossom and form post-bloom, young, and hardened older bolls, the nutritional value for longevity and egg production declines to nil when the rind can no longer be penetrated (Showler, 2004b). This explains why adult boll weevil populations plateau following cut-out through harvest (Showler et al., 2005). While spraying during the late season, particularly the series of late season eradication program sprays that occur in the first year (USDA-APHIS, 2007), can likely reduce boll weevil numbers, warm winters with plentiful food can ensure the survival of many until after spring cotton planting.

Scott et al. (1998) reported that, in the Lower Rio Grande Valley, early- and medium-maturing cotton varieties produce the best yields. In a similar vein, square production in early-planted cotton is lower than in later plantings and avoids the high numbers of weevils occurring in later-planted cotton (Showler et al., 2005). Although late-planted cotton produces more squares than early-planted cotton, this advantage is off-set by losses from heavy boll weevil infestations (Showler et al., 2005). The best time for planting was found to be intermediate between early and late for an optimal balance between increasing square production while avoiding the greatest accumulations of boll weevils, thereby reducing insecticide applications as well (Showler et al., 2005).

Harvest timing can also influence insecticide use. From a crop protection perspective, although harvesting late (at 75% boll splitting) rather than earlier (at 40% boll split) can require an extra insecticide application where using the proactive approach, particularly when boll weevil populations were relatively large, but harvesting late captures greater quantities of lint when more bolls have matured, resulting in better economic return, even if the late season insecticide treatment is superfluous (Showler & Robinson, 2008). Mixing the defoliant with an insecticide was found to be relatively ineffective and unreliable (Showler, 2008a).

3.3 Resistance

Boll weevil tolerance to organophosphorus, carbamate, and pyrethroid insecticides was reported by Kanga et al. (1995), but analyses of field populations have not detected resistance to malathion. It is conceivable, however, that under continual insecticide pressure from malathion only, resistance might develop (Bottrell et al., 1973), and because the boll weevil eradication program relies exclusively upon malathion, exposed boll weevil populations should be assessed intermittently for signs of resistance. For the time being, malathion remains toxic to boll weevils, even at reduced rates (Showler et al., 2002).

4. Possibilities

There are a number of ways in which chemical boll weevil control might be improved. First, a more sensitive trap would permit increasingly timely responses to the early in-season presence of adult boll weevils (but not while squares are still match-head size). At that point, spraying should provide continuous protection of vulnerable and nutritious medium- and large-sized squares. Even if sprays occur weekly, achieving acceptable control on an area-wide scale is improbable, which suggests that using a more sensitive trap design could result in more appropriately-timed, and likely increased, spray applications for the subtropics (unless spraying is conducted at ≤4-day intervals between late match-head to cut-out stages) where overwintering populations are relatively large (Showler, 2007). Both crop protection strategies and the eradication approach should evolve to incorporate emerging information on boll weevil ecology to find tactics that can help mitigate population buildups, such as avoiding late planting, use of earlier-maturing varieties, and development of longer-residual insecticides to reduce numbers of applications and to enhance protection of squares. Because subtropical boll weevil populations are active during winter and can sustain themselves on citrus, removal of such plentiful food through post-harvest orchard sanitation would augment the ban on cotton. Another overlooked tactic is plant resistance. While cotton has been bred for a variety of traits, no cultivars have been developed to resist boll weevil attack. Efforts in this direction might include altering square rind thickness or consistency to make the inner portion, where the immature weevil stages develop, less accessible, or changing the availability of certain nutrients that can affect egg production (Showler, 2009a). Eradicating a tropical pest like the boll weevil in temperate areas was achievable, but the subtropics are more akin to the insect's native habitat in terms of temperature and host plants. For this reason, adjustments to the temperate eradication strategy might have to involve tailoring insecticides, application timing, and the circumstances under which they are applied (*e.g.*, as influenced by planting dates and phenological stages of the crop) for extending prophylactic crop protection and decimating boll weevil populations as selectively as possible to avoid the possibility of for secondary pest outbreaks.

However, even were all of the issues surrounding subtropical boll weevil eradication to be resolved, the feasibility of remaining boll weevil-free in areas along international borders is compromised by boll weevil populations breeding on the other side of the border where attention to eradication, for a complex of reasons, may not be in synchrony. Hence, the success of eradication in subtropical border areas depends to a great extent on the coordinated efforts of both countries. In the instance of a somewhat analogous pest, the desert locust, *Schistocerca gregaria* (Forskål), which can move long distances as massive swarms in Africa and the Middle East, breeding in one country can put crops in neighboring countries at risk, resulting in perpetually reactive and increasingly insecticide-based, rather than preventive maintenance strategies (Steedman, 1988; Showler & Potter 1991; Showler, 1995).

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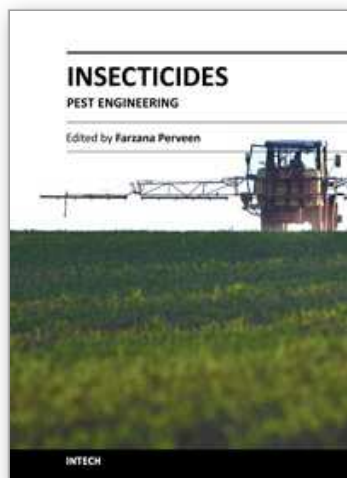
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Insecticides - Pest Engineering

Edited by Dr. Farzana Perveen

This book is compiled of 24 Chapters divided into 4 Sections. Section A focuses on toxicity of organic and inorganic insecticides, organophosphorus insecticides, toxicity of fenitrothion and permethrin, and dichlorodiphenyltrichloroethane (DDT). Section B is dedicated to vector control using insecticides, biological control of mosquito larvae by Bacillus thuringiensis, metabolism of pyrethroids by mosquito cytochrome P40 susceptibility status of Aedes aegypti, etc. Section C describes bioactive natural products from sapindacea, management of potato pests, flower thrips, mango mealy bug, pear psylla, grapes pests, small fruit production, boll weevil and tsetse fly using insecticides. Section D provides information on insecticide resistance in natural population of malaria vector, role of Anopheles gambiae P450 cytochrome, genetic toxicological profile of carbofuran and pirimicarp carbamic insecticides, etc. The subject matter in this book should attract the reader's concern to support rational decisions regarding the use of pesticides.

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