



## Biology and Management of the Pecan Weevil (Coleoptera: Curculionidae)

Phillip G. Mulder, Jr.,<sup>1,2</sup> Marvin K. Harris,<sup>3</sup> and Richard A. Grantham<sup>1</sup>

<sup>1</sup>Department of Entomology and Plant Pathology, Oklahoma State University, 127 Noble Research Center, Stillwater, OK 74078.

<sup>2</sup>Corresponding author, e-mail: phil.mulder@okstate.edu.

<sup>3</sup>Department of Entomology, Texas A&M University, College Station, TX 77843-2475.

J. Integ. Pest Mngmt. 3(1): 2012; DOI: <http://dx.doi.org/10.1603/IPM10027>

**ABSTRACT.** The pecan weevil, *Curculio caryae* (Horn), and its primary host, pecan, *Carya illinoensis* (Wagenheim) K. Koch are indigenous to North America east of the Rocky Mountains. This review is presented to describe the biology, life stages, crop injury, monitoring approaches, and primary control strategies currently used for pecan weevil in pecan. Suggested economic thresholds are extrapolated from several sources and the utility of current monitoring information is presented to aid in management and quarantine decisions.

**Key Words:** *Curculio caryae*, *Carya illinoensis*, pecan, integrated orchard management, weevil monitoring

Horn (1873) first described pecan weevil, *Curculio caryae* (Horn) (Coleoptera: Curculionidae) from specimens captured under hickory, *Carya* spp. Ring et al. (1991) determined that the host range of the pecan weevil included all North American *Carya* species as Gibson (1969) suggested. Harris et al. (2010) used DNA analyses to confirm a natural infestation of *Juglans regia* L. (Persian walnut) in Missouri that added credence to the only other report of *C. caryae* on *J. regia* from Ontario, Canada (Foott and Timmins 1984). Pecan weevil adults damage pecan each year just before and after initiation of kernel development by feeding directly on the nuts and by oviposition (Boethel and Eikenbary 1979). Nuts infested with larvae result in complete destruction of the kernel (Calcote 1975). Although feeding and oviposition activities have been studied on other tree nuts, contrary to reports by Mulder et al. 1997 and Mulder and Grantham 2007, confirmed hosts for pecan weevil currently are comprised of *Carya* sp. and *J. regia* (Ring et al. 1991, Collins et al. 1998). The pecan weevil is a key pest where it occurs on commercial pecan and inevitably requires multiple insecticide applications each year to prevent economic damage (Harris 1983).

The greatest risk to pecan occurs where commercial production is highly concentrated, spanning the indigenous range of pecan in Texas to the Atlantic coast of the United States except for a few pockets where this pest is inexplicably absent (Harris 1979). Though increasingly expensive, eradication efforts have successfully forestalled the threat of pecan weevil expanding westward into new pecan-growing regions of New Mexico (Nielsen and Harris 1992). Arizona and California have also expanded pecan production, posing a risk to these geographically isolated areas if this pest were introduced. The recent confirmation of pecan weevil using *J. regia* as a host (Harris et al. 2010) indicates the much larger walnut industry of California would be at risk as well.

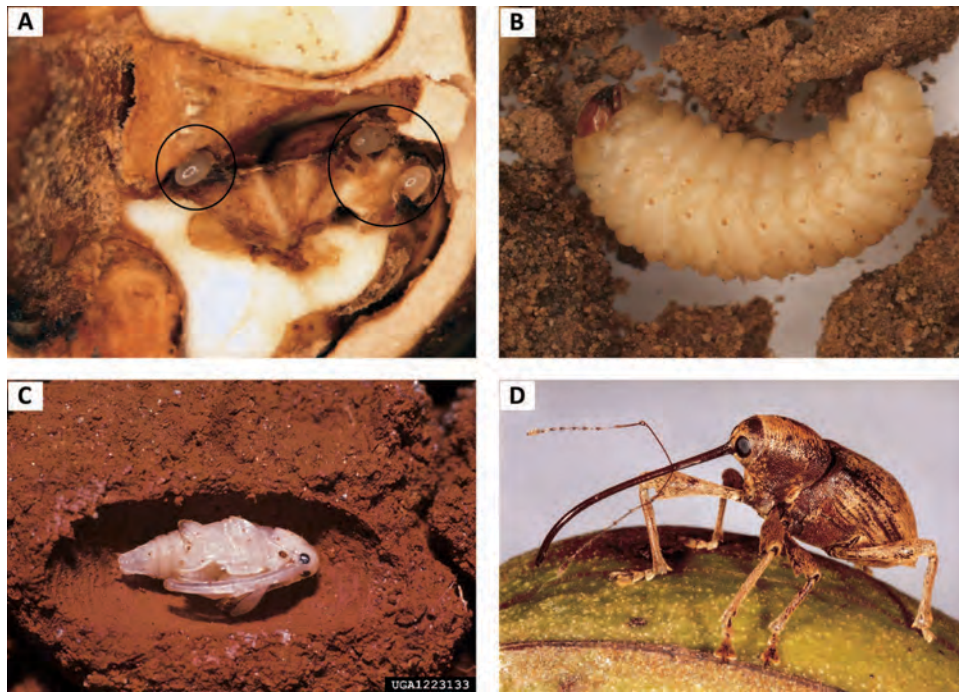
The pecan weevil has been associated with North American hickory for millions of years (Mynhardt et al. 2007), which is reflected in the synchrony observed in their complex plant–insect interaction today (Harp 1970). Management of pecan weevil is confounded by many factors acting together or separately that result in varying weevil densities across locations and time. This variation can be because of rainfall (Hinrichs and Thomson 1955); onset of crop maturity (Moznette et al. 1931, Van Cleave and Harp 1971, Harris 1976a, Harris and Ring 1979); cultivar selection (Criswell et al. 1975, Harris 1976b); surrounding topography (Mulder and Grantham 2007); and soil type (Alverson et al. 1984, Harris et al. 1998). In addition, fruit development (i.e., phenology, crop load, or both) in one area of an orchard or grove can influence weevil dispersal to neighboring areas.

An appreciation for pecan weevil biology, life cycle, fruit injury, and pest management methods on pecan provided here present an historical perspective for practices used in managing, monitoring, avoiding this pest, or both.

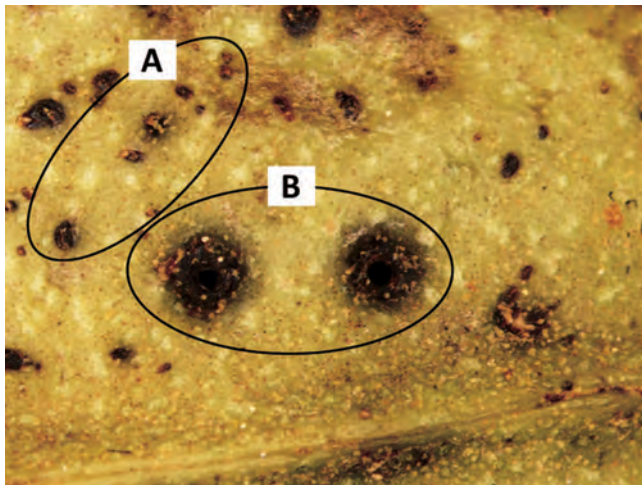
### Pecan Weevil Life Cycle and Biology

The pecan weevil passes through four life stages: egg, larva, pupa, and adult (Fig. 1) and requires two or 3 yr to complete one generation. Generally, August through November is spent infesting nuts in the canopy and the remaining period is spent in diapause (in either the larval or adult stages) in the soil. The pupal stage is also soil dwelling but represents a transition stage, it does not involve diapauses. Details associated with this development are described under the subsequent four sub-headings.

**Egg Deposition.** Pecan weevil females generally begin laying eggs in pecan about 5 d after emergence, when the fruit is nearly hardened and contains a developing lignified pericarp (i.e., onset of dough stage) (Moznette et al. 1931, Van Cleave and Harp 1971, Criswell et al. 1975, Harris 1976a, Ree et al. 2000). Rarely, female weevils oviposit in pecans in the water stage (noncellular endosperm). When they do, larvae do not survive, and if the seed coat is penetrated the fruit is dehisced within 15 d (Woodroof and Woodroof 1927, Calcote 1975, Hall et al. 1981). Before oviposition, the female chews a hole through the pecan shuck and shell (involucre) and completely inserts her snout inside the fruit to reach the developing kernel. After penetrating the shuck, she withdraws her snout and turns around to probe through the hole with her ovipositor until she reaches the shell (pericarp) (Smith and Mulder 2009). A great deal of effort is involved in chewing through the shuck and subsequently penetrating the hard shell, so the female must grip tightly onto the shuck and rotate around the initial penetration site. This process creates tracking marks on the shuck (Fig. 2) (Ree et al. 2000, Smith and Mulder 2009). The tiny eggs are generally deposited on the distal end of maturing pecan, where development of the seed embryo and cotyledon begin (Harris and Ring 1979, Harris 1983, Smith and Mulder 2009). Once the shell has been penetrated, female weevils can extend their ovipositor into various regions of the developing kernel (Fig. 3) (Smith and Mulder 2009). Aguirre (1979) notes the female chews a single oviposition hole into the kernel but excavates several cavities within the pecan where eggs will be placed. She then inserts her ovipositor, deposits one egg, turns around and places the egg in a cavity with her snout, and repeats the sequence until 2–4 eggs are in place. She then uses her snout to plug the oviposition hole with shell and shuck materials and gustatory fluids. The entire process requires approximately 2 hr (Shen 1973, Aguirre 1979). In the laboratory, eclosion from the egg occurs within 6–14 d after deposition (Harp 1970, Van Cleave and Harp 1971) and



**Fig. 1.** Four life stages of the pecan weevil. (A) Eggs, circled, photo credit, R.A. Grantham, OSU; (B) fourth-instar larva, photo credit R.A. Grantham, OSU; (C) Pupa inside earthen cell, photo credit, Jerry Payne, USDA/ARS, Bugwood.org and (D) Adult female on pecan, photo credit Kevin Coblentz, Tulsa, OK.



**Fig. 2.** Tracking marks (A) created by female pecan weevil. (B) Holes created by female weevil chewing and subsequently inserting her ovipositor through the shuck and shell. Photo credit, R.A. Grantham, OSU.

averaged nearly 9 d in a noninvasive field study (Harris and Ring 1979). Several earlier studies show that each infested nut arose from a single female, one oviposition event, and that previously infested nuts were rarely attacked a second time (Aguirre 1979, Harris and Ring 1979). Subsequent research by Smith and Mulder (2009), however, revealed that when weevil population densities were extremely high and fruit density limited in a given location, multiple oviposition events in a single nut were more common.

**Larval Description and Development.** Pecan weevils exhibit four larval instars (Sterling et al. 1965). Development times for instars 1–3 average 3.9, 3.7, and 6.5 d, respectively, and fourth instars may feed for 5–9 d but do not emerge from the nut until an average of 20.3 d have passed (Fig. 1b) (Harris and Ring 1979). This disparity between emergence and when feeding ceases among fourth-instar larvae may



**Fig. 3.** Female weevil with ovipositor extending through the shuck and into the nut. Photo credit, Jerry Payne, USDA/ARS, Bugwood.org.

be because of physiological changes needed to prepare for a 1- to 2-yr diapause spent in the soil without feeding (Harp 1970, Van Cleave and Harp 1971). During diapause, larvae, pupae, and preemergent adults will rely on their stores of fat body and exhibit an eight-fold decrease in oxygen consumption compared with active stages (Harp and Van Cleave 1976a). Weevils in diapause are well protected, do not feed, and can essentially “sip” oxygen to conserve themselves and their air supply even under flood conditions (Mulder and Grantham 2007). Fully grown larvae have a creamy white body measuring  $\approx 19$  mm long with a reddish-brown head capsule (Mulder and Grantham 2007). After feeding on the kernel for  $\approx 4$ –5 wk, larvae chew exit holes measuring  $\approx 3$  mm in diameter in the shell, emerge from the nuts, and drop to the ground (Fig. 4) (Raney et al. 1970, Boethel and Eikenbary 1979). Larvae burrow into the soil to various depths depending on the type and condition of the soil below the host tree. Most healthy larvae descend to a depth of 10–31 cm (Moznette et al. 1931, Osburn et al. 1966, Van Cleave and Harp 1971) where they construct a hard,



**Fig. 4.** Fourth-instar pecan weevil larva exiting a nut. Photo credit, Jerry Payne, USDA/ARS, Bugwood.org.

earthen cell, and remain in diapause until they pupate in late summer of the next year or the year after that. Most weevil larvae exhibit little to no lateral movement upon entering the soil and hence, occur primarily within the drip line associated with the host tree (Bissell 1931, Chau 1949, Tedders and Osburn 1971).

**Pupal Description and Development.** Approximately 90% of the larvae entering the soil spend 1 yr within the earthen cell before pupating (Fig. 1C) (Boethel and Eikenbary 1979). The remaining 10% pupate the next year (Harp and Van Cleave 1976b,c). Laboratory studies by Harp and Van Cleave (1976b,c) revealed that the duration of the pupal stage ranged from 14 to 23 d, averaging  $\approx 18$ –19 d for both sexes. After pupation, adult weevils remain in diapause within the earthen cell until emerging a year later.

**Adult Description, Development, Dispersal, and Mating Behavior.** The adult pecan weevil is a light-brown to grayish snout beetle, measuring  $\approx 1.5$  cm in body length (Fig. 1) (Mulder and Grantham 2007). The male's snout is about three-fourths the length of the body, and slightly enlarged at the apex. The apical one-third of the snout appears to curve suddenly or moderately at the tip (Chittenden 1927). Antennae of the male attach to the snout half the distance from the face (Mulder and Grantham 2007, Fig. 5A). Female pecan weevils possess a snout slightly longer than the body and it also curves sharply at the apex (Chittenden 1927). Their antennae attach to the snout about

one-third the distance from the face (Mulder and Grantham 2007, Fig. 5B). Snout length and attachment point of the antennae generally suffice to distinguish the sexes; however, Chittenden (1927) also provides definitive genital characters for discerning weevil gender.

Adult weevils in diapause remain within their earthen cells until midsummer of the year after pupation when metabolic activity increases followed by emergence from the soil (Harp and Van Cleave 1976b,c). Throughout the native range of pecan weevil, peak emergence generally occurs from August to September (Dupree and Bissell 1965, Boethel 1978) when maturing fruit are converting liquid endosperm to form the kernel (Payne et al. 1974, Boethel and Eikenbary 1979). However, earlier accounts suggested this timing was affected by soil moisture because weevil emergence was observed to increase 3–4 d after a 1–2 inch rainfall (Moznette et al. 1931, Price 1939, Hinrichs 1948, Nickels 1950, Hinrichs and Thompson 1955, Raney et al. 1970, Tedders 1974). Subsequent studies showed that when drought conditions persist in clay soils, weevil emergence can be delayed until late September or even October (Neel et al. 1975, Harris 1978, Harris and Ring 1980). Finally, Alverson et al. (1984) and Schraer et al. (1998) showed delayed emergence was related to soil hardness with a threshold of  $\approx 60$  kg/cm<sup>2</sup> forming a physical barrier that prevented emergence from the soil cell to the surface. Taken together, these findings show that the emergence pattern of the adult pecan weevil can vary widely over a 3-mo period. Management of the pecan weevil depends on killing adults in the pecan canopy after they emerge from the soil but before they can deposit eggs inside nuts. Therefore, to properly detect when and if treatments are needed, regular monitoring for weevil emergence is suggested from the liquid endosperm stage of fruit development until shuck split (Harris 1983).

Pecan weevils start laying eggs in early-maturing nuts and early-emerging weevils are capable of surviving until the crop is suitable for oviposition (Criswell et al. 1975). The average longevity of postemergent adults is 15–30 d (Harris et al. 1981a); however, female weevils emerging beneath large-seeded cultivars can live for up to 56 d (Van Cleave and Harp 1971, Criswell et al. 1975). Generally, females live longer than males and those that emerge early in the season live longer than those that emerge later (Criswell et al. 1975, Harris et al. 1981a). After emergence, pecan weevils enter the tree by either crawling up the bole or flying directly to the canopy or bole (Raney and Eikenbary 1968, Mulder et al. 2003). Raney and Eikenbary (1968) showed in a capture–release study that the majority of weevils flew to the bole. Cottrell and Wood (2008) found that newly-emerged weevils predominantly crawl up the bole to enter the canopy and search for viable fruit. This explains why traps affixed to the bole are more efficient at capturing weevils than other trap types (Mulder et al. 2003). Weevils initially enter the canopy to search for food and oviposition sites; if no pecans are found or if many nuts are already infested within the orchard where the beetles emerged, they may fly to adjacent trees or



**Fig. 5.** Pecan weevil adults showing insertion point of antennae on rostrum. (A) Male; (B) Female. Photo credit, R.A. Grantham, OSU.

emigrate from the orchard to more suitable areas (Raney and Eikenbary 1968; Eikenbary and Raney 1973; Boethel et al. 1976a,b; Eikenbary et al. 1978; Harris et al. 1981).

### Fruit Injury and Damage

Pecan weevils cause different kinds of damage, depending on the stage of fruit development at the time of attack:

- 1) Adult weevils feeding on the kernel during the water stage typically cause the fruit to abort and fall to the ground (Calcote 1975, Boethel and Eikenbary 1979). On average, a male or female weevil destroys 0.23 or 0.29 nuts per day, respectively (Calcote 1975). Such feeding can result in crop losses of 30.5% (Hall et al. 1981) to 80% (Swingle 1935). The amount of damage because of adult feeding is directly related to their density, time of emergence, and adult longevity (Van Cleave and Harp 1971, Harris et al. 1981a). In addition to fruit loss during the water stage, adult feeding that reaches or penetrates the cotyledon layer after shell hardening causes black spots to form on the kernel (Fig. 6a), or may introduce molds that degrade the gel resulting in “sticktights” (Fig. 6b) (shuck adheres to the shell), respectively (Calcote 1975, Boethel and Eikenbary 1979). Black spots, similar to those created by stink bug feeding on pecan late in the season, can make each affected kernel taste bitter and thereby decrease marketability (Mulder and Grantham 2007). Shallow feeding by male weevils after shell hardening may impart slight scarring on the shell but generally results in no damage to the nut meat (Calcote 1975).
- 2) Larval feeding coincides with kernel formation. Immature pecan weevils can be found within a nut for  $\approx 36$ –51 d, with the greatest amount of time spent in the fourth instar ( $\approx 20$  d) (Harris and Ring 1979). During this time, weevil grubs damage the maturing fruit, which remains in the canopy as the larvae continue to feed. Some infested nuts will not separate the shuck from the shell. Two to four larvae within each infested nut easily destroy the entire kernel and kill the embryo (Fig. 7).
- 3) Oviposition damage by female weevils leads to an unmarketable product and continued proliferation of the population throughout the orchard. Oviposition has been observed as early as 2 d after emergence; however, the average preovipositional period is  $\approx 5$ –6.5 d (Van Cleave and Harp 1971, Criswell et al. 1975). Peak egg production occurs 10–12 d after emergence (Criswell et al. 1975). Delays in mating, egg maturation, and oviposition have been observed in late-maturing, large-seeded cultivars, or both (Criswell et al. 1975). Each female weevil can oviposit 26–79 (average  $\approx 45$ ) eggs during her lifetime; therefore, one weevil could affect as many as 20–40 fruits, assuming two to four larvae per nut (Harp and Van Cleave 1976). Transport of infested in-shell pecans may disperse the pecan weevil into previously uninfested areas.

Female weevils typically avoid attacking previously infested nuts (Aguirre 1979, Harris and Ring 1979), however, Smith and Mulder



**Fig. 7.** Destruction of the entire pecan kernel from inside the nut by larval pecan weevils. Photo credit, HC Ellis, University of Georgia, Bugwood.org.

(2009) show that if infestations exceed 90% of the nuts then multiple egg-laying events may occur on individual fruit.

### Monitoring and Factors in Managing Pecan Weevil Populations

Many techniques have been developed and reviewed to monitor pecan weevil (Neel and Shepard 1976, Mulder et al. 1997). Mulder et al. (2003) evaluated these methods to determine their utility for integrated pest management (IPM) of pecan weevil. The ultimate purpose of monitoring for pecan weevil is to determine if and when management is needed to prevent economic damage. The ideal method would detect adults from the onset of emergence until death and determine their absolute density at any point in the process; in addition, managing pecan weevil must still allow the grower a profitable economic gain when all inputs are considered.

**Limb Jarring.** The first method described for sampling and to some extent controlling pecan weevil is limb jarring (Swingle 1935, Bissell 1939). With this labor-intensive approach, tarps are set within the drip line and limbs are beaten with a padded pole to dislodge, capture, and count adult weevils. Swingle (1935) reported that five men using two sheets could jar 15–30 trees per hour for three to 10 cents per tree, depending on tree configuration (low spreading versus high top-worked trees). The process would be repeated three more times at a cost of 12–40 cents per tree per season to obtain 60–85.8% control (Swingle 1935). The advent of insecticides and application equipment after WWII allowed jarring to be used as a monitoring tool to signal treatment. Several authors suggested, but did not experimentally prove, that jarring five or more weevils from a tree constituted an action level that warranted an insecticide application (Phillips et al.



**Fig. 6.** Pecan weevil damage after the liquid endosperm has begun to harden results in; A) black spots on the kernel indicative of pecan weevil feeding or B) degradation of the gel resulting in “sticktights”. Photo credit, Jerry Payne, USDA/ARS, Bugwood.org.

1952, Hinrichs and Thomson 1955, Osburn et al. 1963, Johnson 1969). Jarring is effective in detecting pecan weevil but labor costs prohibit use in commercial orchards. Jarring may be useful to homeowners with a few isolated pecan trees, especially because insecticide applications are not always practical for pecan trees in urban environments. Jarring may be useful in reducing weevil damage; however, reaching the tops of large trees remains a significant challenge for most homeowners.

**Tree Bands.** Scientists seeking less labor-intensive approaches to pecan weevil sampling than limb jarring explored using behavioral orientation of postemergent pecan weevils to monitor, control the pest, or both. Where pecan orchard floors are used for grazing livestock, banding methods avoid interference by grazers (Mulder et al. 1997). Tree banding includes sticky tree bands using Tanglefoot (Tanglefoot Company, Grand Rapids, MI) placed on the tree trunk to capture weevils climbing up the bole (Beckham and Dupree 1954, Hinrichs and Thomson 1955, Nash and Thomas 1972, West and Shepard 1974); cloth and burlap bands fastened around the trunk (Polles and Payne 1973, Harris 1974, Tedders 1974, West and Shepard 1974); and perforated Tygon tubing tied around the tree trunk at  $\approx 40$  inches aboveground (West and Shepard 1975). Neel and Shepard (1976) compared the advantages and disadvantages of these various systems for monitoring pecan weevil and found them to be effective, but labor intensive and impractical for commercial orchards.

**Pyrethrum Sprays.** Several studies have provided estimates of pecan weevil density in an orchard using polyethylene collecting sheets placed under heavily infested trees and applying “knockdown” mixtures of Pyrethron spray into the canopy (Raney and Eikenbary 1971, Polles and Payne 1973, West and Shepard 1975). This strategy has merit in research, but the high costs preclude widespread adoption of this approach for use in IPM (Neel and Shepard 1976).

**Wire-Cone Emergence and Pyramid Traps.** Variations of the cone trap initially developed for monitoring pink bollworm, *Pectinophora gossypiella* (Saunders) have been adapted for use with pecan weevil (Shiller 1946). Wire cone emergence traps (Fig. 8) have been used and modified to improve durability and ease of use (Raney and Eikenbary 1969, Polles and Payne 1972, West and Shepard 1974). Boethel et al. (1976a,b) used similar traps to establish a viable treatment threshold

for pecan weevil; however, this approach requires extensive and dedicated monitoring using 120 cone traps placed in the understory of 10 trees within an orchard. This method is labor intensive and incompatible with livestock grazing and has resulted in limited use by some growers (Mulder et al. 2003). Tedders and Wood (1994) introduced dark-colored pyramid traps (Fig. 9), also placed on the orchard floor, as an alternative to wire cone emergence traps. This approach was less expensive, required fewer traps, was relatively simple to construct, and was effective at attracting and trapping weevils. Pyramid traps still involved potential problems with grazing livestock. In addition, this trap type required painting or whitewashing the nearest tree to mask the visual cue of the tree bole for emerging weevils (Tedders and Wood 1994). Also, no treatment threshold has been developed for use with pyramid traps.

**Circle Traps.** In an attempt to bring trapping back to the tree bole and reduce or eliminate the inherent problems associated with using ground-cover traps (livestock grazing, haying, or both) Mulder et al. (1997) suggested the modified Circle trap (Fig. 10). This trap, initially designed by Edmond Circle (a Kansas pecan grower), is attached directly to the tree where it is out of harm’s way from equipment and grazing livestock. Mulder et al. (1997) modified the trap to include a boll weevil trap top with an enlarged opening. They also presented step-by-step directions on how to construct the trap and provided comparisons and designs of previous trapping devices. Mulder et al. (2003) further evaluated the trapping efficiency of the modified Circle trap compared with wire-cone emergence and pyramid traps and subsequently extrapolated a threshold based on these comparisons. In conjunction with estimates from Eikenbary et al. (1978) and information from Harris et al. (1981b) Circle traps provide growers with an effective detection method for assessing damaging pecan weevil populations while allowing them to use the orchard floor for haying, livestock grazing, or both. Research by Mulder et al. (2003) showed the efficiency of the Circle trap in comparison to wire-cone emergence traps or pyramid traps and also elucidated the utility (under field conditions) of a relatively new pheromone for pecan weevil (Hedin et al. 1997). While the efficacy of the pheromone looked promising in the laboratory, field evaluations were not positive and subsequent trials to enhance efficacy also failed. The Circle trap has been widely adopted on pecan and other crops (Akotsen et al. 2010) and according to Mulder et al. (2003) provided greater confidence in detecting and accurately timing treatments for pecan weevil, particularly as the pecan weevil emergence season progressed. In comparison to earlier trunk trapping methods, this approach provides a simpler, less expensive, and effective means of detecting weevil emergence in pecan.

**Orchard History Infestation Records.** The biology and population dynamics of pecan weevil provides a method to assess current-season



Fig. 8. Wire cone emergence traps. Photo Credit: P.G. Mulder, OSU.



Fig. 9. Pyramid trap. Photo credit, P.G. Mulder, OSU.



**Fig. 10.** Pecan Circle trap. In this picture, two traps encircling the tree are used to trap all weevils crawling up the pecan trunk. Photo credit, P.G. Mulder, OSU.

risk. The pecan weevil increases  $\approx$ five-fold per generation and disperses very little unless trees in the immediate vicinity are devoid of fruit (Raney and Eikenbary 1968, 1971; Calcote 1975; Harp and Van Cleave 1976b; Harris et al. 1981a). Maintaining good harvest records, including data on yield and percent infestation by pecan weevil, allow a ballpark estimate ( $\pm 25\%$ ) of pecan weevil risk for future harvests. By multiplying the number of infested nuts per unit area that occurred 2 yr ago by five you can estimate the number of nuts expected to be at risk in the same orchard or grove in the current season. The value of the nuts at risk is dependent on the current price they are expected to bring at harvest and this is compared with the expected costs of pecan weevil management to assess whether treatment is warranted.

### Other Management Considerations

Insecticide control is generally targeted at adult pecan weevils. Many attempts have been made to control weevils in the soil using insecticides (Hinrichs 1951, Nickels 1952, Tedders and Osburn 1971). This has not been successful because of several factors including:

- 1) Weevils are in diapause with reduced respiratory or other physiological activity that would hasten intoxication under normal metabolic conditions.
- 2) Penetrating the soil profile to a depth of 15–30 cm with a lethal dose of insecticide has not been demonstrated for any chemical.
- 3) Weevils are protected within their hardened earthen cell.
- 4) Killing weevils in the soil does nothing to prevent weevil immigration into the orchard from adjacent unprotected orchards or native trees.

**Biological Control, the Organic Challenge, or Both.** Because of the subterranean nature of the pecan weevil, a prolonged life cycle, susceptibility to current organically-approved materials, and the challenges associated with anticipating peak emergence of adults, managing pecan weevil larvae, adults, or both using biological control agents is a monumental task. Swingle and Seal (1931) when attempting to rear larvae under controlled conditions, first reported on two fungi causing up to 100% mortality of pecan weevil. These fungi were identified as *Metarrhizium anisopliae* (Metschnikoff) Sorokin and *Sporotrichum bassiana* (Balsamo). The latter species is synonymous with *Beauveria bassiana* (Balsamo) Vuillemin. Subsequent laboratory experiments by Neel and Sikorowski (1972) indicated that low concentrations of the latter organism could kill larvae and adults of the pecan weevil. Field surveys of entomopathogenic nematodes and fungi endemic to pecan orchards within the southeastern United States and their virulence to the pecan weevil have been conducted by

Shapiro-Ilan et al. (2003). These surveys revealed that entomopathogenic fungi appeared to be relatively common, being recovered in 76% of orchards surveyed, whereas nematodes were evident in only 28% of orchards sampled. These studies also revealed how soil micronutrients may affect fungal infection levels and further showed that pecan weevil larvae were not strongly susceptible to entomopathogenic nematodes recovered in the samples. Field experiments revealed the efficacy of the entomopathogenic nematode, *Neoplectana dutkyi* Jackson, and two fungi; *M. anisopliae* and *B. bassiana* to be up to 67%, 59.3% and 61.5%, respectively Tedders et al. (1973). More extensive evaluations by Shapiro-Ilan (2001) tested the virulence of nine species and 15 strains of entomopathogenic nematodes on fourth-instar pecan weevil larvae. He found no significant difference in virulence among the various species or strains. In addition, only three of the nine species tested caused mortality of pecan weevil greater than untreated larvae. His data also suggested that as pecan weevil larvae mature, they become less susceptible to infection with entomopathogenic nematodes. In subsequent research, Shapiro-Ilan et al. (2004) found that some species of entomopathogenic nematodes, particularly *Steinernema carpocapsae* (Weiser) were highly virulent on adult pecan weevils. Shapiro-Ilan et al. (2005) later examined the recycling potential and fitness of two species of nematodes and based on these results predicted that under “normal” field conditions continued recycling of nematode populations in pecan weevil would diminish based on reduced reproduction in the host. When examining the additive effects of biological organisms (nematodes, fungi, or bacterium) that can impinge on pecan weevil populations Shapiro-Ilan et al. (2004) concluded that combinations of pathogens were unlikely to improve on suppression of pecan weevil beyond what could be expected from a single organism with a high range of virulence. Using a commercially available product alone but testing different application methods seemed to be the next logical step in seeking a viable candidate for control of pecan weevil. Therefore, Shapiro-Ilan et al. (2008) examined soil and tree trunk applications of *B. bassiana* for suppression of adult pecan weevil. Trunk applications yielded the greatest levels ( $>75\%$ ) of mortality on pecan weevil. Unfortunately, because mortality of weevils using this material may take more than 7 d, the beetles can still cause some level of feeding or oviposition damage to the nuts before the fungus takes effect (Shapiro-Ilan et al. 2008). Furthermore, authors of this latter study acknowledge that weevil mortality may have been influenced by bringing the beetles back to the laboratory and keeping them in controlled conditions. In subsequent studies, Shapiro-Ilan et al. (2009a) showed similar levels of control of pecan weevil using the entomopathogenic fungus *M. anisopliae*; however, field applications using this organism have yielded poor or variable results at best (Tedders et al. 1973, Shapiro-Ilan et al. 2009b). With the many environmental influences, variable rates of control, economic levels of crop protection gained, and organism interactions, much work remains to be done in seeking biological control organisms that will effectively, efficiently, and economically manage pecan weevil populations in field situations.

**Pecan Culture and Grazing Livestock.** Regarding the issue of livestock grazing in pecan orchards, this practice is used to varying degrees in different regions of the country, and generally used more often in the native pecan range than in orchards consisting primarily of improved cultivars. This difference is likely attributable to the economic return associated with smaller, native pecans than with larger-seeded and higher priced, improved cultivars. For several years, livestock grazing in pecan orchards has surfaced as a “potential” food safety issue that can affect marketability of pecan harvested from the orchard floor. Preharvest or postharvest contamination of in-shell nuts or the final end product by bacterial organisms, such as *Salmonella* sp. can occur anywhere in the harvest and handling process (Beuchat and Heaton 1975) and some states have adopted guidelines for reducing the likelihood of contamination (Oklahoma Department of Health 1991). These guidelines include; cleaning and sanitizing of the prod-

uct, the holding and drying areas, equipment, and displaying proper signage in exempt situations (i.e., custom pecan cracking operations). To reduce contamination many states have recommended removal of cattle from the orchard well in advance of harvest; thereby, allowing appreciable time (90–120 d) to degrade manure that may be harboring suspect bacteria, such as *Escherichia coli* Escherich. Pecan processors are generally encouraged to use hot water (194° F for 80 s) or chlorinated water (200 ppm, for 1 min followed by soaking in water for 2 h at 70° F and treating in water at 185° F for 10 min) to decontaminate pecans (Beuchat and Mann 2010, 2011). Equipment can be cleaned using the same approach or using hot air or steam. Although not all states have specific guidelines for sanitation of pecan, many of the cited guidelines are generally taken from the USDA National Organic Program (seven CFR, Part 205, section 203). If increased incidences of bacterial contamination become more commonplace, particularly where Good Agricultural Practices are conducted, modification of mandates under the relatively new Food Safety Modernization Act (U.S 111<sup>th</sup> Congress 2011) will be constructed to address these issues. Until this is done, it is more likely that retailers and processors (shellers) will impose defacto standards first (W. McGlynn, Horticulture Products Processing Specialist, Oklahoma State University, personal communication).

### Pecan Weevil Management

**Management Decision Making.** The essential elements in efficiently managing pecan weevil involve monitoring pecan phenology, initial pecan weevil emergence from the soil, and activity of adults in the canopy. Monitoring data should be combined with information on pecan cultivar, price estimates, and treatment costs to aid in making management decisions. Nuts become susceptible to oviposition with the onset of the gel stage and various traps can detect emergence of pecan weevil. Pecan cultivar and price affect the economic risk posed by pecan weevil and Harris et al. (1981a) show that the static economic threshold ranges from an end-of-season density of 500–3600 adults/ha depending on nuts/kg and price. Mulder et al. (2003) suggest that the Circle trap may be deployed before adult emergence and a dynamic economic threshold of 0.3 weevils per trap per day be used when weevils are detected among a minimum set of two traps per tree on 10 trees (20 traps total). By their own admission, the threshold of Mulder et al. (2003) represents a rough extrapolation comparing the capture rates of wire-cone emergence traps with Circle traps. No studies have confirmed that this threshold represents an accurate approach to pecan weevil pest management. Practically speaking, postemergent adult pecan weevils cause economic damage at low densities and their mere detection at or shortly after the gel stage is a strong indication that treatment is warranted. This is particularly true for improved cultivars sold at retail prices. To protect the harvestable crop and lower the carrying capacity in the orchard, early control measures may be required to reduce infestation of the crop 2 yr later and beyond. Thus, a treatment is usually suggested after detection at this susceptible stage, followed by continued monitoring to determine if subsequent emergence of adults occurs after residual effects of the insecticide have dissipated (typically 5–10 d depending on the material and the weather). Detection of continued emergence triggers another treatment, and so on until shuck-split occurs. Using this scenario typically results in 2–3 treatments in infested areas.

**Treatment Application.** Once a threshold is reached in an orchard or grove, treatment should be applied with an airblast sprayer calibrated to deliver 75–100 gallons of spray mixture per acre (Fig. 11). Airblast sprayers come in a range of sizes. Large sprayers can allow deposition to the tops of trees in excess of 60 feet and provide excellent coverage to the entire canopy, provided the grower takes specific application precautions (Sumner 2004). To ensure penetration and thorough coverage, commercial growers are encouraged to treat both sides of each tree while traveling at the proper speed (1.5 mph). Even large air blast sprayers may have their limitations when address-



**Fig. 11.** Air-blast sprayer used for treating pecan orchards for pecan weevil and other pests. Photo credit, B. Savage, Savage Equipment, Madill, OK.

ing trees with a massive canopy; in particular the top-center portion of the tree will typically be the area where chemical deposition may be compromised (Sumner 2004). Pesticide compatibility must be considered for grazing livestock. Consult university guidelines for a complete listing of insecticide recommendations on pecan. For more detailed information on other factors affecting the pecan crop, a list of pesticides, and label information see <http://pecan.ipmpipe.org/>, a website developed to improve communication among stakeholders in the pecan industry (Harris et al. 2008).

### Eradication and Quarantine Considerations

The expansion of commercial pecan production in the El Paso Valley of far West Texas, the adjacent Mesilla Valley of New Mexico, the region near Tucson, AZ, and California separates the crop from native production to the east by natural barriers posed by deserts and mountains. Nevertheless, pecan weevil has been found infesting pecans on three separate occasions in three different counties in New Mexico and successful programs were conducted to eradicate them. Presumably, these infestations arose from inadvertent human transport of larvae either in infested nuts that were discarded near pecan trees in the area or in harvesting materials moved from infested to uninfested areas. Pecan weevil is a tractable target for eradication because of numerous factors: 1) diagnosis of a new infestation is likely to occur rapidly when nuts are found to contain emergence holes, larvae, or both; 2) established populations appear to spread slowly when nuts remain available to be infested at the original site of introduction; 3) the 2- or 3-yr life cycle and modest fecundity limit the weevil's rate of increase; 4) the reproductive period ranges from the onset of the gel stage in the crop to the completion of shuck split, a period of  $\approx 8$  wk in the fall; 5) effective insecticides with different modes of action are available for prophylactic treatment using air blast sprayers in areas where eradication is needed; and 6) monitoring traps like the Circle, pyramid and cone traps can aid treatment timing and combined with intensive inspection of harvested nuts, determine a successful eradication attempt—typically four consecutive years with no weevils detected. Limitations to tractability and eradication efforts in uninfested areas could be homeowner trees in yards, where treatment efforts, in particular airblast sprayers would likely not be used. This limitation represents a reason to advocate for an effective monitoring approach and educational effort in marginal production areas such as homeowner trees.

Obviously, avoiding new introductions of pecan weevil through human transport is preferable to a retrospective eradication program. Therefore, pecan-growing states and regions free of pecan weevil have developed quarantines to govern the movement of nuts, trees, har-

vesting machinery and equipment, etc. to prevent the introduction of pecan weevil (e.g., see <http://www.nmcpr.state.nm.us/nmac/parts/title21/21.017.0028.htm> for New Mexico). Protocols for preventing transport of infested nuts rely on freezing (Harris 1973), hot water, or steam treatments (Payne and Wells 1974) before shipment from infested to uninfested areas; the use of traditional fumigants using methyl bromide, phosphine, or both are not recommended because they are ineffective or impractical for killing larvae in nuts (Leesch and Gillenwater 1976). However, Arizona currently has methyl bromide fumigation listed as a viable treatment <http://www.azda.gov/PSD/NutTreePests.htm>. Under both state regulations, any regulated article must be quarantined and treated or otherwise disposed of as necessary to prevent spread or establishment in their respective states. The Global commerce in pecan nuts has exploded during the last decade and expanding markets may not be aware of the risk of pecan weevil transport or treatments needed to minimize that risk.

### Acknowledgments

Thanks are extended to Tom Royer and Eric Rebek for constructive comments on this publication. We also recognize the support of the Oklahoma Cooperative Extension Service (OCES) and the Southern Regional IPM Program for support in publishing this work.

### References Cited

- Aguirre, L. A. 1979. Biology of the immature stages of the pecan weevil, *Curculio caryae* (Horn) and oviposition habits of the adult weevil. Ph.D. dissertation, Texas A&M University, College Station.
- Akotsen-Mensah, C., R. Boozer, and H. Fadamiro. 2010. Field evaluation of traps and lures for monitoring plum curculio (Coleoptera: Curculionidae) in Alabama peaches. *J. Econ. Entomol.* 103: 744–753.
- Alverson, D. R., M. K. Harris, C. E. Blanchard, and W. G. Hanlin. 1984. Mechanical impedance of adult pecan weevil (Coleoptera: Curculionidae) emergence related to soil moisture and penetration resistance. *Environ. Entomol.* 13: 588–592.
- Beckham, C. M., and M. Dupree. 1954. Pecan weevil control investigations. *Proc. S.E. Pecan Growers' Assoc.* 47: 93–96.
- Beuchat, L. R., and E. K. Heaton. 1975. *Salmonella* survival on pecans as influenced by processing and storage conditions. *Appl. Microbiol.* 29: 795–801.
- Beuchat, L. R., and D. A. Mann. 2010. Survival and growth of *Salmonella* in high-moisture pecan nutmeats, in-shell pecans, inedible nut components and orchard soil. *J. Food Prot.* 73: 1975–1985.
- Beuchat, L. R., and D. A. Mann. 2011. Inactivation of *Salmonella* on in-shell pecans during conditioning treatments preceding cracking and shelling. *J. Food Prot.* 74: 588–602.
- Bissell, T. L. 1931. Experiments on controlling larvae of the pecan weevil by cultural methods. *J. Econ. Entomol.* 24: 861–866.
- Bissell, T. L. 1939. Fighting the pecan weevil. *Proc. S.E. Pecan Growers' Assoc.* 33: 36–41.
- Boethel, D. J. 1978. Unpublished data. Shreveport, LA.
- Boethel, D. J., and R. D. Eikenbary. 1979. Status of pest management programs for the pecan weevil, pp 81–119. *In* Pest management programs for deciduous tree fruits and nuts. D. J. Boethel and R. D. Eikenbary, (eds.), Plenum, New York.
- Boethel, D. J., R. D. Eikenbary, R. D. Morrison, and J. T. Criswell. 1976a. Pecan weevil *Curculio caryae* (Coleoptera: Curculionidae). Comparison of adult sampling techniques. *Can. Entomol.* 108: 11–18.
- Boethel, D. J., R. D. Morrison, and R. D. Eikenbary. 1976b. Pecan weevil *Curculio caryae* (Coleoptera: Curculionidae). Estimation of adult populations. *Can. Entomol.* 108: 19–22.
- Calcote, V. R. 1975. Pecan weevil: feeding and initial oviposition as related to nut development. *J. Econ. Entomol.* 68: 4–6.
- Chau, K. M. 1949. Study of feeding habits and investigating soil fumigation as a means of control for pecan weevil. M.S. thesis, Oklahoma State University, Stillwater.
- Chittenden, F. H. 1927. Classification of the nut Curculios (formerly *Balaninus*) of boreal America. *Entomol. Am.* 7: 129–207.
- Collins, J. K., P. G. Mulder, R. A. Grantham, W. R. Reid, M. W. Smith, and R. D. Eikenbary. 1998. Assessing feeding preferences of pecan weevil (Coleoptera: Curculionidae) adults using a Hardee olfactometer. *J. Kans. Entomol. Soc.* 70: 181–188.
- Cottrell, T. E., and B. W. Wood. 2008. Movement of adult pecan weevils *Curculio caryae* within pecan orchards. *Agric. For. Entomol.* 10: 363–373.
- Criswell, J. T., D. J. Boethel, R. D. Morrison, and R. D. Eikenbary. 1975. Longevity, puncturing of nuts, and ovipositional activities by the pecan weevil on three cultivars of pecans. *J. Econ. Entomol.* 68: 173–177.
- Dupree, M., and T. L. Bissell. 1965. Observations on the periodic emergence of the pecan weevil. *Proc. S.E. Pecan Growers Assoc.* 58: 50–51.
- Eikenbary, R. D., and H. G. Raney. 1973. Intratree dispersal of the pecan weevil. *Environ. Entomol.* 2: 927–930.
- Eikenbary, R. D., R. D. Morrison, G. H. Hedger, and D. B. Grovenburg. 1978. Development and validation of prediction equations for estimation and control of pecan weevil populations. *Environ. Entomol.* 7: 113–120.
- Foott, W. H., and P. R. Timmins. 1984. Occurrence of the pecan weevil, *Curculio caryae* (Coleoptera: Curculionidae), in Persian walnut, *Juglans regia*. *Can. Entomol.* 116: 107.
- Gibson, L. P. 1969. The genus *Curculio* in the United States. *Entomol. Soc. Am. Misc. Publ.* 6: 239–285.
- Gill, J. B. 1924. Important pecan insects and their control. *USDA Farmers Bull.* 843. 1–48.
- Hall, M. J., G. H. Hedger, R. D. Eikenbary, and R. W. McNew. 1981. Impact of pecan weevil on pecan production in a pest-managed commercial orchard. *Environ. Entomol.* 10: 668–672.
- Harp, S. J. 1970. The biology and control of the pecan weevil, *Curculio caryae* (Horn), in Texas. Ph.D. Dissertation, Texas A&M University, College Station.
- Harp, S. J., and H. W. Van Cleave. 1976a. Evidence of diapauses in the pecan weevil. *Southwest. Entomol.* 1: 35–37.
- Harp, S. J., and H. W. Van Cleave. 1976b. Biology of the subterranean life stages of the pecan weevil in two soil types. *Southwest. Entomol.* 1: 31–34.
- Harp, S. J., and H. W. Van Cleave. 1976c. Biology of the pecan weevil. *Southwest. Entomol.* 1: 21–30.
- Harris, E. D., Jr. 1974. Pecan weevil. Georgia Cooperative Extension Service, EFS-3N-1 Revised: Leaflet No. 26.
- Harris, M. K. 1973. Pecan weevil larval response to some temperatures while in the nut. *Tex. Agric. Exp. Stn. Prog. Rep.* 3176.
- Harris, M. K. 1975. Pecan weevil distribution in some Texas soils. *Environ. Entomol.* 4: 849–853.
- Harris, M. K. 1979. Pecan weevil distribution across the pecan belt. *Southern Cooperative Series Bulletin No.* 238.
- Harris, M. K. 1976a. Pecan weevil adult emergence, onset of oviposition and larval emergence from the nut as affected by the phenology of the pecan. *J. Econ. Entomol.* 69: 167–170.
- Harris, M. K. 1976b. Pecan weevil infestations of pecan of various sizes and infestations. *Environ. Entomol.* 5: 248–250.
- Harris, M. K. 1978. Annual report of cooperative regional project S-88. Bionomics and control of the pecan weevil.
- Harris, M. K., and D. R. Ring. 1979. Biology of pecan weevil from oviposition to larval emergence. *Southwest. Entomol.* 4: 73–85.
- Harris, M. K., and D. R. Ring. 1980. Adult pecan weevil emergence related to soil moisture. *J. Econ. Entomol.* 73: 339–343.
- Harris, M. K., D. R. Ring, L. A. Aguirre, and J. A. Jackman. 1981a. Longevity of post-emergent adult pecan weevil in the laboratory and field. *Environ. Entomol.* 10: 201–205.
- Harris, M. K., J. A. Jackman, and D. R. Ring. 1981b. Calculating a static economic threshold and estimating economic losses for pecan weevil. *Southwest. Entomol.* 6: 165–173.
- Harris, M. K. 1983. Integrated pest management of pecans. *Annu. Rev. Entomol.* 28: 291–318.
- Harris, M. K., B. Ree, J. Cooper, J. Jackman, J. Young, R. Lacewell, and A. Knutson. 1998. Economic impact of pecan integrated pest management implementation in Texas. *J. Econ. Entomol.* 1011–1020.
- Harris, M. K., M. Nesbitt, R. Luttrell, R. Mizell, J. Dutcher, M. Hall, B. Reid, P. Mulder, B. Lewis, B. Ree, and A. Knutson. 2008. Pecan ipmPIPE: aiding communications among pecan stakeholders Belt-Wide. *Pecan Grower* 4: 58–59.
- Harris, M. K., K. L. Hunt, and A. I. Cognato. 2010. DNA identification confirms pecan weevil (Coleoptera: Curculionidae) infestation of Carpathian walnut (*Juglans regia* L.). *J. Econ. Entomol.* 103: 1312–1314.
- Hedin, P. A., D. A. Dollar, J. K. Collins, J. G. Dubois, P. G. Mulder, G. H. Hedger, M. W. Smith, and R. D. Eikenbary. 1997. Identification of male pecan weevil pheromone. *J. Chem. Ecol.* 23: 965–977.
- Hinrichs, H. A. 1948. Pecan scab and pecan weevil control. *Proc. Okla. Pecan Growers Assoc.* 19: 41–48.
- Hinrichs, H. A. 1951. Soil fumigation to control pecan weevil. *Proc. 13<sup>th</sup> Annual Texas Pecan Growers Assoc.* 43–47.
- Hinrichs, H. A., and H. J. Thomson. 1955. Insecticide tests for pecan weevil control. *Oklahoma Agric. Exp. Stn. Bull.* 450: 1–12.
- Horn, G. H. 1873. Contributions to a knowledge of the Curculionidae of the United States. *Proc. Am. Philos. Soc.* 13: 457–461.

- Johnson, W. T. 1969. Plant pests, pp. 67–156. In R. A. Jaynes (ed.), Handbook of North American nut trees. W.F. Humphrey Press, Inc., Geneva, New York.
- Langston, J. M. 1930. Some experiments with the pecan weevil. *Quart. Bull. State Plant Board Miss.* 9: 1–12.
- Leesch, J. G., and H. B. Gillenwater. 1976. Fumigation of pecans with methyl bromide and phosphine to control the pecan weevil. *J. Econ. Entomol.* 69: 214–44.
- Moznette, G. F., T. L. Bissell, and H. S. Adair. 1931. Insects of the pecan and how to combat them. USDA Farmers Bull. 1654: 1–59.
- Mulder, P. G., B. D. McCraw, W. Reid, and R. A. Grantham. 1997. Monitoring adult weevil populations in pecan and fruit trees in Oklahoma. Oklahoma Coop. Ext. Serv. Fact Sheet No. 7190. 8 pp.
- Mulder, P. G., W. Reid, R. A. Grantham, S. Landgraf, L. Taliaferro, M. E. Payton, and A. Knutson. 2003. Evaluations of trap designs and a pheromone formulation used for monitoring pecan weevil, *Curculio caryae*, pp. 85–99. In J. D. Dutcher, M. K. Harris, and D. A. Dean (eds.), Integration of chemical and biological insect control in native, seedling, and improved pecan production. Southwest. Entomol. Supplementary Issue No. 27.
- Mulder, P. G., and R. A. Grantham. 2007. Biology and control of the pecan weevil in Oklahoma. Oklahoma Coop. Ext. Serv. Fact Sheet No. EPP-7079.
- Mynhardt, G., M. K. Harris, and A. I. Cognato. 2007. Population genetics of the pecan weevil (Coleoptera: Curculionidae) inferred from mitochondrial nucleotide data. *Ann. Entomol. Soc. Am.* 100: 582–590.
- Nash, R. F., and C. A. Thomas. 1972. Adult pecan weevil emergence in the Upper Coastal Plains of South Carolina. *J. Econ. Entomol.* 65: 908.
- Neel, W. W., H. R. Sterling, N. V. Mody, and L. B. Gray. 1975. Pecan weevil: late seasonal emergence in Arkansas. *Pecan Quart.* 9: 20–21.
- Neel, W. W., and M. Shepard. 1976. Sampling adult pecan weevils. *Southern Coop. Ser. Bull.* 208: 1–17.
- Nickels, C. B. 1950. Experiments in the control of the pecan weevil in Texas. *J. Econ. Entomol.* 43: 552–554.
- Nickels, C. B. 1952. Control of the pecan weevil in Texas. *J. Econ. Entomol.* 45: 1099–1100.
- Nielsen, G., and M. Harris. 1992. Pecan weevil eradication-Tularosa, New Mexico. *Southw. Entomol.* 17: 183–184.
- Oklahoma Department of Health. 1991. Good manufacturing practice regulations – pecan processing. Chapter 260, subchapter 5.
- Osburn, M. R., W. C. Pierce, A. M. Phillips, J. R. Cole, and G. L. Barnes. 1963. Controlling insects and diseases of the pecan. USDA Agric. Handbook. 240: 1–52.
- Osburn, M. R., W. C. Pierce, A. M. Phillips, J. R. Cole, and G. E. Kenbright. 1966. Controlling insects and diseases of the pecan. USDA Agric. Handbook. 240: Rev. 1–55.
- Payne, J. A., and J. M. Wells. 1974. Postharvest control of the pecan weevil in in-shell pecans. *J. Econ. Entomol.* 67: 789–790.
- Payne, J. A., S. G. Polles, and E. J. Wehunt. 1974. Pecan weevil: biology and control. *Ann. Rep. North. Nut Growers Assoc.* 65: 134–144.
- Phillips, A. M., J. R. Cole, and J. R. Large. 1952. Insects and diseases of the pecan in Florida. *Univ. of Florida Agric. Exp. Stn. Bull.* 499: 1–75.
- Polles, S. G., and J. A. Payne. 1972. An improved emergence trap for adult pecan weevils. *J. Econ. Entomol.* 65: 1529.
- Polles, S. G., and J. A. Payne. 1973. Pecan weevil: An improved method of sampling populations in pecan trees. *J. Econ. Entomol.* 66: 519–520.
- Price, W. S. 1939. Observations on the pecan weevil. *Proc. Texas Pecan Growers Assoc.* 19: 30–31.
- Raney, H. G., and R. D. Eikenbary. 1968. Investigations on flight habits of the pecan weevil, *Curculio caryae* (Coleoptera: Curculionidae). *Can. Entomol.* 100: 1091–1095.
- Raney, H. G., and R. D. Eikenbary. 1969. A simplified trap for collecting adult pecan weevils. *J. Econ. Entomol.* 62: 722–723.
- Raney, H. G., R. D. Eikenbary, and N. W. Flora. 1970. Population density of the pecan weevil under Stuart pecan trees. *J. Econ. Entomol.* 63: 697–700.
- Raney, H. G., and R. D. Eikenbary. 1971. Ecological research involved in controlling pecan weevils. *Proc. Southeastern Pecan Growers Assoc.* 64: 115–130.
- Ree, B., A. Knutson, and M. Harris. 2000. Controlling the pecan weevil. *Texas Agric. Ext. Serv. L-5362*: 1–6.
- Ring, D. R., L. J. Grauke, J. A. Payne, and J. W. Snow. 1991. Tree species used as a host by pecan weevil (Coleoptera: Curculionidae). *J. Econ. Entomol.* 84: 1782–1789.
- Schraer, S. M., M. Harris, J. A. Jackman, and M. Biggerstaff. 1998. Pecan weevil (Coleoptera: Curculionidae) emergence in a range of soil types. *Environ. Entomol.* 27: 549–554.
- Shapiro-Ilan, D. I. 2001. Virulence of entomopathogenic nematodes to pecan weevil larvae, *Curculio caryae* (Coleoptera: Curculionidae), in the laboratory. *J. Econ. Entomol.* 94: 7–13.
- Shapiro-Ilan, D. I. 2003. Microbial control of the pecan weevil, *Curculio caryae*, pp. 101–114. In J. D. Dutcher, M. K. Harris, and D. A. Dean (eds.), Integration of chemical and biological insect control in native, seedling, and improved pecan production. Southwest. Entomol. Supplement No. 27.
- Shapiro-Ilan, D. I., W. A. Gardner, J. R. Fuxa, B. W. Wood, K. B. Nguyen, B. J. Adams, R. A. Humber, and M. J. Hall. 2003. Survey of entomopathogenic nematodes and fungi endemic to pecan orchards of the southeastern United States and their virulence to the pecan weevil (Coleoptera: Curculionidae). *Environ. Entomol.* 32: 187–195.
- Shapiro-Ilan, D. I., M. Jackson, C. C. Reilly, and M. W. Hotchkiss. 2004. Effects of combining an entomopathogenic fungi or bacterium with entomopathogenic nematodes on mortality of *Curculio caryae* (Coleoptera: Curculionidae). *Biol. Control* 30: 119–126.
- Shapiro-Ilan, D. I., J. D. Dutcher, and M. Hatab. 2005. Recycling potential and fitness of steinernematid nematodes cultured in *Curculio caryae* and  *Galleria mellonella*. *J. Nematol.* 37: 12–17.
- Shapiro-Ilan, D. I., W. A. Gardner, T. E. Cottrell, R. W. Behle, and B. W. Wood. 2008. Comparison of application methods for suppressing the pecan weevil (Coleoptera: Curculionidae) with *Beauveria bassiana* under field conditions. *Environ. Entomol.* 37: 162–171.
- Shapiro-Ilan, D. I., W. A. Gardner, T. E. Cottrell, J. Leland, and R. W. Behle. 2009a. Mortality and mycosis of adult *Curculio caryae* (Coleoptera: Curculionidae) following application of *Metarrhizium anisopliae*: laboratory and field trials. *J. Entomol. Sci.* 44: 24–36.
- Shapiro-Ilan, D. I., T. E. Cottrell, W. A. Gardner, R. W. Behle, B. Ree, and M. K. Harris. 2009b. Efficacy of entomopathogenic fungi in suppressing pecan weevil, *Curculio caryae* (Coleoptera: Curculionidae), in commercial pecan orchards. *Southwest. Entomol.* 34: 111–120.
- Shiller, I. 1946. A hibernation cage for the pink bollworm. *USDA Bur. Entomol. Plant Quart.* ET-226: 1–6.
- Smith, M. W., and P. G. Mulder. 2009. Oviposition characteristics of pecan weevil. *Southwest. Entomol.* 34: 447–455.
- Sterling, W. L., S. G. Wellso, P. L. Adkisson, and H. W. Dorough. 1965. A cottonseed-meal diet for laboratory cultures of the boll weevil. *J. Econ. Entomol.* 58: 867–869.
- Sumner, P. E. 2004. Experiences with pecan air blast sprayers. Society of Engineering in Agriculture, Food, and Biological Systems. and Canadian Society of Engineering in Agriculture, Food and Biological Systems. Paper No. 041089: 1–12.
- Swingle, H. S. 1935. Control of the pecan weevil. *J. Econ. Entomol.* 28: 794–795.
- Swingle, H. S., and J. L. Seal. 1931. Some fungous and bacterial diseases of pecan weevil larvae. *Scientific Note: J. Econ. Entomol.* 24: 917.
- Tedders, W. L., and M. R. Osburn. 1971. Emergence and control of the pecan weevil. *J. Econ. Entomol.* 64: 743–744.
- Tedders, W. L., D. J. Weaver, and E. J. Wehunt. 1973. Pecan weevil: Suppression of larvae with the fungi *Metarrhizium anisopliae* and *Beauveria bassiana* and the nematode *Neoplectana dutkyi*. *J. Econ. Entomol.* 66: 723–725.
- Tedders, W. L. 1974. Bands detect weevils. *Pecan Quarterly.* 8: 24–25.
- Tedders, W. L., and B. W. Wood. 1994. A new technique for monitoring pecan weevil emergence (Coleoptera: Curculionidae). *J. Entomol. Sci.* 29: 18–30.
- U.S. 111<sup>th</sup> Congress. 2011. Food and Drug Administration Food Safety Modernization Act. Public Law 111–353. Enacted January 4, 2011.
- Van Cleave, H. W., and S. J. Harp. 1971. The pecan weevil: Present status and future prospects. *Proc. Southeastern Pecan Growers Assoc.* 64: 99–111.
- West, R. P., and M. Shepard. 1974. A comparison of trapping methods for the pecan weevil. *Proc. Southeastern Pecan Growers Assoc.* 67: 67–69.
- West, R. P., and M. Shepard. 1975. Analysis of sampling techniques for the pecan weevil, *Curculio caryae*. *Proc. Southeastern Pecan Growers Assoc.* 68: 55–61.
- Woodroof, J. G., and N. C. Woodroof. 1927. The development of the pecan nut (*Hicoria pecan*) from flower to maturity. *J. Agric. Res.* 34: 1049–1063.

Received 21 December 2010; accepted 13 December 2011.