PECAN WEEVIL[1] MANAGEMENT: PAST, PRESENT AND TOWARD A FUTURE STRATEGY

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ABSTRACT

The pecan weevil, *Curculio caryae* (Horn) (Coleoptera: Curculionidae), is an indigenous pest of the native North American pecan, *Carya illinoensis* Wang K (Koch). Before the era of broad-spectrum chemical insecticides, management of the pecan weevil was attempted with cultural methods, but control was generally poor. Chemical insecticides offered efficacious foliar sprays and a few soil treatments. Most of these chemicals are no longer available. Carbaryl has emerged as the predominant insecticide presently used to manage pecan weevils but foliar applications disrupt natural enemies thus leading to secondary pest outbreaks. We tested various rates of carbaryl, applied to pecan trunks, against pecan weevils that were exposed to those trunks for a single, brief interval. If effective, future pecan weevil management programs may include such a strategy since natural enemies in the canopy would be less-affected and applications would be targeted to a specific site. We exposed groups of weevils 1, 4, 8 and 13 days after treating trunks; each individual was evaluated as healthy, moribund or dead at 3, 6, 12, 24, 48 and 72 h after exposure. Probit analysis was used to estimate effective rates that resulted in 95% non-feeding weevils (i.e., ER_{95}) for the four test dates after application and six time periods after exposure. A regression equation in terms of days since insecticide application and hours since exposure was fit to those estimates and used to construct a response surface plot. Brief exposure to the insecticide affected pecan weevils. To achieve an ER_{95} by 12 h after exposure and through 13 days after treating trunks, carbaryl would need to be applied at 7.9X the rate normally applied to foliage. It is likely that other insecticides may provide similar results when used in this manner.

INTRODUCTION

The pecan weevil, *Curculio caryae* (Horn) (Coleoptera: Curculionidae), is indigenous to North America and is capable of using all *Carya* spp. found in the U.S. as hosts (Ring et al. 1991). This includes the economically important native pecan, *Carya illinoensis* (Wang) K. Koch, and its improved cultivars. Thus the pecan weevil can be a serious direct pest of pecan nuts in most pecan-producing regions of the U.S. When left uncontrolled, the pecan weevil can cause substantial direct damage to pecan and has long been recognized as an economic pest. Bissell (1942) reported that uncontrolled pecan weevils take an increasingly heavier toll over subsequent seasons and can damage 50 to 75% of the crop. Dupree and Beckham (1953) similarly noted that >90% of the crop could be damaged.

[1] Coleoptera: Curculionidae

Early control efforts, before the common use of broad-spectrum insecticides, included cultural practices such as removing adult weevils from orchards through limb jarring (Swingle 1935; Bissell 1939, 1942), removing larvae from orchards by harvesting nuts early (Bissell 1930), and attempted destruction of subterranean stages by tilling the orchard floor (Bissell 1930). Nickels and Pierce (1947) even tested flooding soil with water to control larvae but obtained low mortality. Generally, cultural manipulations provided poor control compared with levels of control that would be obtained with chemical insecticides.

During the majority of the pecan weevil life cycle, eggs, larvae, pupae and adults are inadvertently well-protected from chemical control. Eggs are inaccessible within the nut as are developing larvae. Even when fourth instars exit nuts, only a relatively short interval is needed for larvae to drop to the orchard floor, burrow into soil and become inaccessible again. Once in the ground and settled within a newly-constructed cell, larvae, pupae, and yet-to-emerge adults are relatively safe from chemical control. Nevertheless, attempts have been made to chemically control subterranean pecan weevils. Carbofuran and ethylene dibromide (EDB) were reported to cause higher larval mortality compared with other soil insecticides and nematicides but pecan weevil control was not achieved (Hinrichs 1951, 1952; Nickels 1952; Tedders and Osburn 1971; Polles et al. 1973). Thus, pecan weevil management has primarily focused on management of adult weevils in the canopy.

Many broad-spectrum insecticides have been used or tested as foliar treatments against adult pecan weevils. Some of these insecticides include benzene hexachloride, carbofuran, chlordane, DDT, EPN, heptachlor, lead arsenate, monocrotophos, phosalone, parathion, and toxaphene (Nickels 1950, 1952; Dupree and Beckham 1953; Osburn and Tedders 1966; Polles and Payne 1973a). Options for chemically controlling the pecan weevil have dwindled because candidate materials have been banned, not labeled for pecan or have been ineffective.

Current control recommendations for the pecan weevil rely predominantly upon foliar applications of carbaryl, 1-naphthyl methylcarbamate (Ellis et al. 2001). In fact, it was reported that carbaryl was used on 96% of pecan acreage that required treatment for pecan weevil and provided superior control compared with other insecticides (Payne and Dutcher 1985). Even after > 30 years of use, pecan weevil resistance to carbaryl has not been documented or even suspected. Other insecticides used include pyrethroids and organophosphates but these are generally better-suited for orchards with low weevil populations (Ellis et al. 2001). Various microbial control agents (e.g., fungi, bacteria and nematodes) have been studied as pathogens of the pecan weevil (Tedders et al. 1973; Sri-Arunotai et al. 1975; Smith et al. 1993; Shapiro-Ilan 2001) but are not included in current control recommendations for commercial orchards.

Although carbaryl is highly efficacious against the pecan weevil, the period of adult emergence exceeds foliar residual activity of carbaryl, necessitating repeated applications. Thus pecan weevil management has tended to focus on monitoring adult emergence and refining timing of carbaryl application. To this end, different methods have been developed to monitor weevil emergence and include limb jarring, knockdown insecticide sprays, cone emergence traps, pheromone traps, ground cover traps, an assortment of trunk banding schemes (Raney and Eikenbary 1969; Polles and Payne 1973a; Neel and Shepard 1976) but more recently malaise traps (Dutcher et al. 1986), pyramidal traps (Tedders and Wood 1994) and trunk traps (Mulder et al. 1997). Boethel et al. (1976a, 1976b) compared some of these trapping methods and used the data to develop prediction equations for weevils in trees. In addition, identification of pecan weevil pheromones (Mody et al. 1973; Hedin et al. 1979, 1997) may help to improve detection of pecan weevils. Harris and Ring (1980) and Schraer et al. (1998) also studied effects of soil penetrability, as affected by soil type and drought, on weevil emergence. Schraer et al. (1998) reported that drought conditions resulting in soil penetrability ≥65 kg/cm^2 delayed weevil emergence; whereas, unhindered emergence occurred when soil penetrability was less.

Whether future pecan weevil management is achieved by biological control agents, semiochemicals, resistant cultivars, new insecticidal chemistry or exploitation of weevil behavioral tendencies, the goal will still be to maintain populations below an economic threshold. Given the benefits of carbaryl (e.g., high efficacy against the pecan weevil, low mammalian toxicity and relative low cost to pecan producers), it likely will remain a vital component of a pecan weevil management program.

Use of carbaryl in pecan production does have drawbacks. It is harsh on natural enemies and has been documented to cause outbreaks of aphids and mites (Dutcher 1983; Dutcher and Payne 1983). In addition, availability of this insecticide could be affected by regulatory action of the Environmental Protection Agency (EPA) since the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) and the Federal Food, Drug and Cosmetic Act (FFDCA) were amended with the Food Quality Protection Act (FQPA) in 1996. This amendment changed the way the EPA regulates pesticides such that new safety standards of 'reasonable certainty of no harm' must be applied to all pesticides used on foods (Tomerlin 2000). Because safety considerations are based on groups of pesticides that have the same mode of action, the fate of carbamates as a whole may significantly impact the future of carbaryl for pecan weevil management. Yet it may be possible to avoid destruction of natural enemies and secondary pest outbreaks by using carbaryl in applications targeting the pecan trunk.

Newly-emerged pecan weevil adults seek entry into the pecan canopy by flying or crawling. Those weevils flying into the canopy either fly directly into the canopy from the orchard floor or fly to the pecan trunk and then crawl up into the canopy. Crawling weevils enter the canopy by moving across the orchard floor and up the pecan trunk. Quantification of undisturbed, naturally moving pecan weevil adults to the host tree is lacking but Raney and Eikenbary (1968) used field-collected pecan weevils to show that when released on the orchard floor about 85% went to the pecan trunk. The pecan trunk can serve as a bottleneck for pecan weevil entry into the canopy and may allow for their targeted control at that site. If efficacious, such an approach could be incorporated into current weevil management strategy.

The objective of this study was to determine if pecan weevil adults were affected by exposure to insecticide-treated trunks. We treated pecan trunks with various rates of an insecticide and briefly exposed pecan weevils as would occur when weevils traverse the trunk. Data on efficacy and residual activity of the treatments was collected.

MATERIALS AND METHODS

This study was done at the USDA-ARS, Southeastern Fruit and Tree Nut Research Laboratory in Byron, GA. We used approximately 75-yr-old 'Stuart' pecans in a mixed-variety pecan orchard. The experimental design was a randomized complete block with three replications. Treatments consisted of a water-only control and four rates (2.88, 5.76, 14.40 and 28.80 g [AI]/ liter H_2O) of carbaryl (Sevin® 80S, Rhône-Poulenc Ag Company, Research Triangle Park, NC). Treatments were representative of 0, 1, 2, 5, and 10X the recommended rate of 2.69 kg [AI] / ha for pecan orchards, respectively. Treatments were applied to pecan trunks using a handgun applicator and sprayed to runoff. Trunks were treated from the soil to a height of approximately 4.5 m. Before treatments were applied, an 8.5-cm diameter hole saw was used to cut 1-cm deep circles into bark of test trees. Four of these circles were cut into each tree and were located 1.5 m above ground and spaced equidistant around the trunk. Adult pecan weevils were collected from pyramidal traps (Tedders and Wood 1994) in a pecan orchard and also by jarring pecan trees (Bissell 1939). Twenty adult pecan weevils, five per circle, were caged on trees for 10 min at 1, 4, 8, and 13 days after carbaryl treatments had been applied to trunks. Cages were made from collared lids of 450-ml fonda cartons. The top of the lid was removed and replaced with 0.32-cm mesh hardware cloth. The collar of the 8.5-

cm diameter lid fit snugly into the circle cut into the tree. A nail was driven into the bark on each side of the circle and a rubber band was stretched between the nails (i.e., crossing over the cage) to insure cage attachment to the trunk. After being caged on the trunk for 10 min, weevils were then removed from cages and placed into 9-cm diameter petri dishes. No food source was provided, but water was provided in a 2-dram shell vial stoppered with a cotton dental wick. Weevils were held in the laboratory at approximately 25 °C with a 14:10(L:D)h photoperiod. Behavior of weevils was monitored and recorded as normal, moribund or dead at 3, 6, 12, 24, 48 and 72 h after removal from trunks. Data for weevils recorded as moribund and dead were combined as non-feeding weevils.

Probit analysis (PROC PROBIT, SAS 1996) was done on counts of non-feeding weevils and the effective rate (ER_{95}) with lower and upper fiducial limits was estimated for six time periods (3, 6, 12, 24, 48 and 72 h) after exposure within the four test dates (1, 4, 8 and 13 days) after carbaryl application to trunks (i.e., 24 estimates). A regression equation in terms of days after treatment and hours after exposure was fitted to the ER_{95} estimates and a response surface plot was created using the equation.

RESULTS AND DISCUSSION

Trunk circumference ($\bar{x}$ ± SE) of test trees 1 m above ground was 2.3 ± 0.1 m. Handgun application of treatments required approximately 23 liters per tree to cover the trunk (from ground to 4.5 m above ground) to beginning of runoff. This resulted in approximately 66.2, 132.5, 331.2, and 662.4 g (AI) carbaryl per tree for 1, 2, 5 and 10X treatments respectively.

Because weevils naturally occur on the trunk for only a brief period while moving to the pecan canopy, we exposed weevils to trunks for 10 min. This exposure interval was chosen primarily due to time required for experimenters to perform the test but also from observations of weevils that were released on soil at pecan trunks during the day. Some weevils that climbed the trunk were observed to climb to 4.5 m in 5 to 10 min while others that climbed onto the trunk stopped climbing and did not reach 4.5 m after 20 min (T. Cottrell, personal observation). It is likely that handling and time of day affected climbing behavior of these weevils.

Many species of Curculionidae generally feign death if disturbed; weevils drop from the substrate and remain immobile for a period of time (Borror et al. 1989) as with some test weevils in petri dishes. To overcome this problem, we used forceps to apply slight pressure to the weevils' proboscises. A normal weevil readily responded to this stimulus by immediately attempting to free its proboscis by pushing with its legs against the forceps. The criterion for pecan weevil death used by Polles and Payne (1973b) was based on the inability of weevils to move when the ventral surface of the thorax was pressed with a pencil. Our method allowed for quickly assaying behavior with little contact and no need for positioning weevils. Moribund weevils most often continued erratic body and appendage movements and did not respond to pressure applied to the proboscis. We combined data for moribund and dead weevils because these weevils were not capable of causing damage to pecans.

Estimates of ER_{95} were obtained for each of the 24 day/hour combinations using probit analysis (Table 1). These estimates were regressed on functions of days after treatment and hours after exposure to obtain the following regression equation: $y = 11.6311 + ([d_i][-1.0019]) + ([d_i^2][0.0723]) + ([f(h)][-1.4780])$, where y = estimated ER_{95}, d_i = number of days since carbaryl application to trunks, $f(h) = log(h/3)/log\ 2$ (i.e., function to linearize time intervals), and h = hours since 10 min exposure to trunks. All parameter estimates in this equation were highly significant ($\alpha < 0.01$) and $R^2 = 0.74$ (Table 2).

The regression equation was used to create a response surface plot of estimated ER_{95} on days after treatment (1 to 13 days) and hours after exposure (3 to 72 h) (Fig. 1). The ER_{95}

decreased, for all times after exposure, from day 1 to day 7, and then increased from day 7 to day 13. It is possible that by-products of carbaryl degradation (e.g., through photodecomposition) on the trunk were more toxic to pecan weevils than the parent compound as evidenced by the decrease in the estimated rates from 1 to 7 days after application but continued degradation over time decreased toxicity, as seen in an increase in rates from 7 to 13 days after application.

TABLE 1. Estimated Effective Rate that Results in 95% Non-feeding Pecan Weevils After Weevils were Exposed for 10 min to Pecan Trunks Sprayed with Various Rates of Carbaryl

Days after Application	Hours after Exposure	ER_{95}	Fiducial Limits Lower	Fiducial Limits Upper
1	3	14.40	12.19	17.97
1	6	8.67	7.46	10.47
1	12	6.21	5.32	7.57
1	24	4.44	3.75	5.51
1	48	2.67	2.28	3.33
1	72	2.50	2.13	3.10
4	3	10.97	9.36	13.46
4	6	7.42	6.28	9.20
4	12	6.54	5.53	8.11
4	24	6.02	5.06	7.52
4	48	5.01	4.18	6.33
4	72	3.97	3.31	5.03
8	3	6.38	5.46	7.80
8	6	4.65	3.91	5.83
8	12	4.57	3.81	5.78
8	24	1.83	1.58	2.21
8	48	1.84	1.59	2.24
8	72	1.89	1.60	2.35
13	3	11.04	9.73	12.91
13	6	8.59	7.50	10.17
13	12	7.44	6.40	9.01
13	24	6.72	5.61	8.53
13	48	6.34	4.92	9.32
13	72	5.08	4.03	7.13

TABLE 2. Regression Analysis for ER_{95} = Days (d_i), Days × Days (d_i^2) and Hours $f(h)$

Parameter	df	Coefficient	Standard Error	t-value	P
Intercept	1	11.63	1.05	11.05	<0.0001
Days (d_i)	1	-1.00	0.33	-3.06	0.0062
Days × Days (d_i^2)	1	0.07	0.02	3.23	0.0042
Hours $f(h)$	1	-1.48	0.22	-6.76	<0.0001

$R^2 = 0.74$

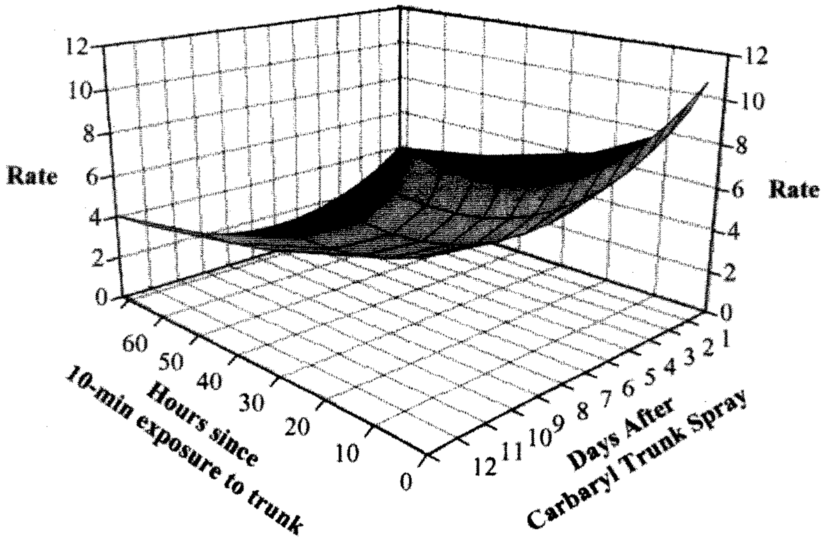

FIG. 1. Estimated rates of carbaryl to provide 95% control of pecan weevils when weevils were exposed to trunks for 10 min. Standard 1X rate = 2.88 g [AI] / liter applied ate 2.69 kg [AI] / ha.

Crosby et al. (1965) reported that carbaryl (i.e., Sevin®) exposed to sunlight or weak ultraviolet light gave rise to one cholinesterase-inhibiting decomposition product but exposure to intense ultra violet light resulted in five cholinesterase-inhibitors. Polles and Payne (1973b) tested residual activity of carbaryl, applied to petri dishes, against pecan weevils in the laboratory and found that percentage mortality decreased from 100% on the first day to 26% on the fifth day. This is in stark contrast to our results; however, those authors reported the concentration of the carbaryl solution used to coat petri dishes (i.e., 600 ppm) but not the volume of the solution used. Thus, a comparison of g [AI]/unit area between studies is not possible. Residual activity of carbaryl can be greatly decreased by a basic pH (Larkin and Day 1985) and Polles and Payne (1973b) did not report the pH of their 600 ppm carbaryl solution nor do we in this study.

Nevertheless, carbaryl can have considerable residual activity as shown by Werner et al. (1986). Those authors tested carbaryl on white spruce boles, *Picea glauca* (Moench) Voss, against spruce beetles, *Dendroctonus rufipennis* Kirby (Coleoptera: Scolytidae), and reported that a single application of 1 and 2% carbaryl to runoff still provided 89 and 96% protection, respectively, from *D. rufipennis* through three growing seasons. More relevant to our study was the use of carbaryl applied as trunk bands to elms, *Ulmus* spp., by Hall et al. (1988) and Dreistadt and Dahlsten (1990) for control of elm leaf beetles, *Pyrrhalta* (=*Xanthogaleruca*) *luteola* (Müller) (Coleoptera: Chrysomelidae). After *P. luteola* larvae feed in the canopy, late third instars migrate down the trunk to pupate at, or near, the base of the trunk. When third-instar *P. luteola* were released on elm trunks and allowed to migrate down and across a 1-m wide band of 2% carbaryl, applied two weeks earlier, larval mortality was 100% but at six and eight weeks after application, mortality was 37 and 53%, respectively (Hall et al. 1988).

Dreistadt and Dahlsten (1990), however, reported that carbaryl bands on elms lasted for at least 15 weeks and killed most *P. luteola* larvae that naturally traversed the bands.

Our results show that as early as 12 h after exposure, including all test dates, a high percentage ($\bar{x} \pm$ SE) of weevils from the 2, 5 and 10X treatments were assessed as non-feeding, 77.9 ± 10.6, 93.1 ± 2.8 and 96.1 ± 1.2, respectively. At this same time, percentage of non-feeding weevils in control and 1X treatments were 11.1 ± 0.9 and 36.1 ± 10.6, respectively. Moribund weevils in the control, 1, 2, 5, and 10X treatments accounted for most of these non-feeding weevils (85.6, 88.4, 87.2, 83.9 and 87.3%, respectively). At 72 h after exposure, a high percentage of weevils from the 2, 5 and 10X treatments were again assessed as non-feeding, 88.3 ± 4.7, 98.8 ± 1.3 and 99.5 ± 0.5, respectively; whereas, percentage of non-feeding weevils in control and 1X treatments were 28.3 ± 8.6 and 57.6 ± 6.3, respectively. Unlike non-feeding weevils at 12 h after exposure that were mostly moribund, most weevils in the control, 1, 2, 5, and 10X treatments at 72 h after exposure were dead and accounted for 88.1, 88.9, 92.2, 94.5 and 95.7% of these non-feeding weevils, respectively.

Mortality data alone would indicate that more time after exposure is needed for weevils to be affected. By including moribund data with mortality data, a truer estimate for the propensity to alter weevil behavior and decrease damage to nuts was obtained since moribund weevils were not likely to recover and rarely did so in this study. With this in mind, our response surface graph indicates that to achieve an ER_{95} by 12 h after exposure and through 13 days after treatment, carbaryl would need to be applied at a rate of 7.9X; a lower rate could be used if a longer interval (e.g., 24 or 48 h) could be sustained before the initiation of nut damage by weevils.

Application of high rates of carbaryl to trunks and the potential for runoff of carbaryl onto the orchard floor could be of concern when pecans are harvested from the orchard floor. In fact, on days 14 and 15 after carbaryl application, we recorded 13.2 cm of rain; whereas, no rainfall was recorded from the day of application to 13 days after application. In their review of carbaryl stability in soil, Kuhr and Dorough (1976) report on a study where application of carbaryl to soil at 3.37, 10.10 and 30.31 kg/hectare produced carbaryl half-lives of 8 days for each rate and by 40 days after application, total destruction of the parent molecule was completed for each rate. In another study, application of carbaryl to apple trees at 3.37 kg / hectare left residues on the orchard floor of 14 ppm the day of application, 3 ppm 1 to 2 days after application and <1 ppm 14 days after application. Payne et al. (1985) compared weevil control using carbaryl applications to soil under pecan trees or to the pecan canopy. Given the fast degradation of carbaryl in soil, it is not surprising that those authors obtained superior weevil control with foliar-applied carbaryl than soil-applied carbaryl. In fact soil-applied carbaryl was superior to untreated controls only during 2 of the 4 yr the study was done. Considering that weevil sprays are completed at least 4 wk before harvest, carbaryl residues on the orchard floor should not pose a problem.

This study was done to determine whether a short exposure to carbaryl would be sufficient to control weevils. McVay (1999) commented that there was a need for research on alternative methods of weevil control and questioned if trunk-applied insecticides might be a method. Our results show that a short exposure to carbaryl can affect pecan weevils and our regression equation estimates rates of carbaryl required. We do not advocate this approach as a management option since more information is required concerning natural flight activity of weevils and their propensity to immediately infest trees different from the one under which the adults emerge. In addition, field tests must be done to confirm whether this methodology is capable of providing economic control of the pecan weevil.

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