Potential of Contact Insecticides to Control *Xyleborus glabratus* (Coleoptera: Curculionidae), a Vector of Laurel Wilt Disease in Avocados

DANIEL CARRILLO,[1] JONATHAN H. CRANE, AND JORGE E. PEÑA

Tropical Research and Education Center, University of Florida, 18905 SW 280 Street, Homestead, FL 33031

ABSTRACT *Xyleborus glabratus* Eichhoff (Coleoptera: Curculionidae: Scolytinae) is an invasive ambrosia beetle that vectors laurel wilt, a new disease that threatens avocado and other species in the Lauraceae Family. The lethal concentrations ($LC_{50 \& 90}$) of nine commercial insecticides to *X. glabratus* were determined by using a bolt-dip bioassay. Different formulations of bifenthrin, permethrin, fenpropathrin, z-cypermethrin + bifenthrin, l-cyhalothrin + thiamethoxam, malathion, chlorpyrifos, carbaryl, and methomyl were tested. Four concentrations of each insecticide were tested (0.5, 0.1, 0.03, and 0.01 of the label rate) and with water as a control. Beetles were exposed to treated bolts and mortality registered 48 h later. After 2 wk, bolts were destructively sampled to determine the number of beetles that constructed galleries and were alive inside the wood. Probit analysis was used to determine the $LC_{50 \& 90}$. Six pesticides were applied directly to the trunk and limbs of avocado trees in a commercial grove. Limbs of treated trees were cut weekly after the application and exposed to *X. glabratus* to determine the number of beetles boring into the logs. The toxicity of pesticides to *X. glabratus* was greatly reduced 2 wk after application. Among the tested pesticides, malathion and z-cypermethrin + bifenthrin provided the best suppression of *X. glabratus*. Among the insecticides registered for use in avocado, fenpropathrin and malathion were the most effective in protecting trees from attack by *X. glabratus*. Other pesticides that are currently not registered for use in avocados could be useful for managing this ambrosia beetle.

KEY WORDS redbay ambrosia beetle, exotic insect, insect–disease complex, Lauraceae, chemical control

The redbay ambrosia beetle, *Xyleborus glabratus* Eichhoff (Coleoptera: Curculionidae: Scolytinae), is an invasive species that vectors a phytopathogenic fungus, *Raffaelea lauricola* T.C. Harr., that causes laurel wilt, a lethal disease of several plant species within the Lauraceae, including avocado (*Persea americana* Miller), redbay (*Persea borbonia* (L.) Spreng), swampbay (*Persea palustris* (Raf.) Sarg.), and sassafras (*Sassafras albidum* (Nutt.) Nees; Fraedrich et al. 2008, Peña et al. 2012). The spread of *X. glabratus* has affected large areas of native Lauraceae trees in the southeastern United States (Fraedrich et al. 2008) and is now threatening the avocado industry in south Florida (Crane et al. 2008; Carrillo et al. 2012, 2013). Most studies about the life history of *X. glabratus* have been conducted in natural areas with large stands of Lauraceae trees, primarily redbay and swampbay. In a 2-yr study in South Carolina and Georgia, *X. glabratus* adults were active throughout the year, with peak activity in September (Hanula et al. 2008). In north Florida conditions, Brar et al. (2012) reported that largest number of beetles was trapped at heights of 35–100 cm above the ground, mostly between 1600 and 1800 hours, and observed two peaks of trap catches (March–April and October). Maner (2012) reported that symptoms characteristic of laurel wilt develop in redbay trees with as few as two *X. glabratus* entry holes. Little is known about the life history of *X. glabratus* in avocado. Mayfield et al. (2008) evaluated young potted avocado trees in no-choice tests and found boring of *X. glabratus* and transmission of the laurel wilt pathogen. Kendra et al. (2011) found that avocado wood volatiles were attractive to dispersing female *X. glabratus* in natural areas infested with this beetle. In addition, Brar et al. (2013) studied the life cycle of *X. glabratus* in logs of avocado, redbay, and swampbay. They found comparable rates of development in the three hosts, but fewer progeny produced in avocado.

The detection of *X. glabratus* in commercial avocado groves is quite recent, and it is unclear if it will follow the same life-history patterns observed in hosts in natural areas. Miami–Dade County is the main (>95%) commercial avocado production area in Florida. During February 2010, one *X. glabratus* female was collected by FDACS-CAPS (Florida Department

[1] Corresponding author, e-mail: dancar@ufl.edu.

of Agriculture and Consumer Services, Cooperative Agricultural Pest Survey) personnel from a trap in Miami–Dade County. The trap was placed in a natural area ≈11 miles north of the avocado production area. One year later, laurel wilt was detected in native swampbay trees only a few miles from the initial beetle detection. In February 2012, the first avocado tree in a commercial grove located in the northeastern quadrant of the avocado growing area was diagnosed with *R. lauricola* (Florida Department of Agriculture and Consumer Services [FDACS] 2012). As of July 2013, 90 trees have been have diagnosed *R. lauricola* positive, and >1,900 symptomatic trees have been removed as part of a suppression and sanitation strategy (J. H. Crane, personal communication). Interestingly, only six *X. glabratus* individuals have been captured in commercial avocado groves (A. Derksen and D. Carrillo personal observation). Because of the lack of alternative pest management strategies (e.g., biological control, repellents, etc.), private landowners and avocado producers rely on applications of chemical insecticides to complement sanitation practices and protect trees in groves affected by this beetle–disease complex.

Most chemical control strategies against scolytines have focused on those species that are pests of conifers or ornamental plants. Carbaryl, permethrin, cyfluthin, esfenvalerate, fenitrothion, chlorpyrifos, and/or bifenthrin have been used to manage pine bark beetles (Hall et al. 1982, Shea et al. 1984, Haverty et al. 1998, Hastings et al. 2001, DeGomez et al. 2006, Fettig et al. 2006, 2013). Pyrethroid insecticides and chlorpyrifos have been proposed to manage the native elm bark beetle, *Hylurgopinus rufipes* (Eichhoff; Coleoptera: Curculionidae), and the smaller European elm bark beetle, *Scolytus multistriatus* (Marsham), vectors of the Dutch elm disease (Gardiner and Web 1980, Lanier et al. 1984, Phillipsen et al. 1986, Pajares and Lanier 1989, Jin et al. 1996, Jin and Webster 1997, Oghiakhe and Holliday 2011). Much less is known about insecticide efficacy for management of bark and ambrosia beetles in fruit crops. Saeed et al. (2011) evaluated the toxicity of several insecticides against the mango bark beetle, *Hypocryphalus mangiferae* Stebbing, and found that among the contact insecticides tested, chlorpyrifos had greater efficacy than deltamethrin and bifenthrin. Lozano et al. (2001) suggested that deltamethrin can provide effective protection to olive trees from attack by the olive bark beetle, *Phloeotribus scarabaeoides* (Bernard).

Very few studies have investigated chemical control of ambrosia beetles. Mizell and Riddle (2004) reported that high rates of bifenthrin provided better suppression of the granulate ambrosia beetle, *Xylosandrus crassiusculus* (Motschulsky), than other tested insecticides. Reding et al. (2013) reported that permethrin and bifenthrin provided better protection to nursery plants from attack by *Xylosandrus germanus* (Blandford) and *X. crassiusculus*. In addition, endosulfan has been used against the coffee berry borer, *Hypothenemus hampei* (Ferrari; Damon 2000). Peña et al. (2011) initiated efforts to identify effective pesti-

cides against *X. glabratus;* their first approach used a "hanging bolt" technique to test insecticides applied as a barrier treatment to prevent beetles from boring into avocado bolts. In that study, the contact insecticides z-cypermethrin + bifenthrin and l-cyhalothrin + thiamethoxam provided the most consistent suppression of Scolytinae in areas infested by *X. glabratus.* The hanging bolt technique is limited in that it does not allow identification of beetles attacking the bolt. Thus, a detailed study to determine the effectiveness of different insecticides specifically on *X. glabratus* is needed.

In the current study, controlled laboratory bioassays and a field trial were conducted to test the efficacy and persistence of several insecticides applied as barriers to prevent *X. glabratus* from boring into host trees. A range of insecticides from different chemical groups were tested against *X. glabratus*, including insecticides that are registered for use on avocado or recommended for management of other wood-boring insects. The specific objectives were 1) to determine the lethal concentrations ($LC_{50 \& 90}$) of commercial insecticides to *X. glabratus*, and 2) to determine the persistence of selected insecticides to manage *X. glabratus* in avocados, under normal field conditions during the summer rainy season in south Florida.

Materials and Methods

Insects. All *X. glabratus* used in the bioassays emerged from logs cut from swampbay (*P. palustris*) trees affected by laurel wilt. Collection sites were swampy natural areas in Flagler County (29° 36′47.48″ N–81° 13′39.41″ W) during November 2011, Miami–Dade County (25° 43′37.96″ N–80° 28′36.16″ W) during February 2012, and Highlands County (27° 12′53.94″ N–81° 20′49.38″ W) during August 2012. In these sites, trees showing signs of *X. glabratus* infestation (small strings of compacted sawdust protruding from the bore holes along the trunk of the tree) were cut and measured, and wood >10 cm in diameter was stored inside emergence chambers (165 liters, Brute container 2643–60, Rubbermaid, Peoria, IL) with a mason jar placed in a hole in one of its sides to collect emerging beetles. Wood collected from Flagler County was transported and held at the Department of Entomology and Nematology, University of Florida, Gainesville, FL, whereas the wood collected from Miami–Dade and Highland Counties was transported and held at the Containment Facility of the University of Florida, Tropical Research and Education Center (TREC), Homestead, FL. Wood was kept at photoperiod of 14:10 (L:D) h, 80% relative humidity (RH), and 25°C. *X. glabratus* adult females that emerged from the wood were collected daily and placed inside petri dishes (5 cm in diameter) provided with a moistened filter paper. All healthy *X. glabratus* female beetles used in the bioassays had less than 2 d of emergence from the wood.

Host Plant Material. Limbs (7–10 cm in diameter) of healthy and nonsprayed 'Lula' avocado trees from an avocado orchard at TREC were cut with a chainsaw

and divided into smaller bolts (7–9 cm in diameter by 10 cm in length) by using a table saw (DeWalt DW713). All plant material was cut 1 d before each bioassay.

Lethal Concentration of Contact Insecticides on *X. glabratus*. Nine insecticides, including products registered for use in avocado, and others recommended for use against other wood boring insects, were tested in the bioassays (Mizell and Riddle 2004; Reding et al. 2013). Each insecticide was tested in a serial dilution where the starting solution was half the recommended label rate for field applications, assuming a standard volume of water of 935 liters/ha. For each pesticide, five concentrations (treatments) were tested: 0.5, 0.1, 0.03, 0.01, and 0 (control) of the label concentration. Each treatment was replicated five times. The full label rates for field applications were not included in the lethal concentration determinations because these are usually higher than the concentrations used in laboratory toxicological bioassays. The tested pesticides (including trade name, manufacturer, chemical class, active ingredient, application rate, label rate, and bioassay concentrations) are listed in Table 1. Avocado bolts were dipped for 5 s in the different pesticide solutions or in water (control) and air-dried at ambient temperature for 24 h. Treated bolts were placed individually inside plastic containers with a screen lid for ventilation (11 cm in diameter by 14.5 cm in height, Instawares APCTR32) and stored at the TREC Containment Facility (26°C, 70 ± 10% RH, 14:10 [L:D] h). Ten *X. glabratus* females were placed on the bark of each bolt and allowed to interact with the treated bolts. After 48 h, the numbers of dead and live beetles, and the number of beetles that bored into the bolts, were recorded. Two weeks later, bolts were opened to determine the number of beetles that constructed galleries and alive or dead inside the bolts.

Persistence of Selected Insecticides Against *X. glabratus* Under Field Conditions. Six insecticides were selected to test their residual efficacy protecting avocado from *X. glabratus* infestations under field conditions. The trunk of 'Peterson' avocado trees were sprayed (May 2012). The insecticide solutions were prepared by using the highest label concentration of each pesticide (Table 2) and a standard application volume of 935 liters H_2O/ha. The treatments were applied with a handgun sprayer calibrated to deliver 3.8 liters of solution per tree, directing the application to the tree trunk and limbs. Twenty-one trees were treated; three with each insecticide and three with water (control). Each treated tree was separated by at least three untreated trees.

On days 4, 8, 15, and 22 after application, five randomly selected limbs per tree (≈50 cm in length and 7–10 cm in diameter) were cut with a chainsaw and subsequently cut into two smaller bolts (8–9 cm in diameter by 10 cm in length). The bolts were placed inside a plastic container with a screen lid for ventilation (11 cm in diameter by 14.5 cm in length) and kept at the TREC Containment Facility. Ten *X. glabratus* females were placed on the bark of each bolt. After 48 h, the numbers of dead and live beetles were re-

Table 1. Commercial pesticides tested against *X. glabratus* (including class/a.i., trade name, manufacturer, label rate, label concentration, and bioassay concentrations)

Class/a.i.	Trade name	Manufacturer	Label rates (liter/ha)	Label concn (ml/liter)	Bioassay concn (ml/liter)
Pyrethroid/bifenthrin (25.1%)	Brigade 2EC	FMC Corporation, Philadelphia, PA	0.88–2.3	0.94	0.47, 0.1, 0.03, 0.001, 0
Pyrethroid/permethrin (36.8%)	Permethrin 3.2AG*	Arysta LifeScience North America Corporation, Cary, NC	0.6	0.62	0.31, 0.06, 0.020, 0.001, 0
Pyrethroid/fenpropathrin (30.9%)	Danitol 2.4 EC*	Valent USA Corporation, Walnut Creek, CA	1.2–1.6	1.25	0.62, 0.13, 0.04, 0.001, 0
Pyrethroid/z-cypermethrin (3.75%) + bifenthrin (11.25%)	Hero	FMC Corporation, Philadelphia, PA	0.75	0.87	0.44, 0.09, 0.026, 0.001, 0
l-Cyhalothrin (9.48%) + thiamethoxam (12.6%)	Endigo ZC	Syngenta Crop Protection, Greensboro, NC	0.37–0.44	0.43	0.21, 0.04, 0.01, 0.0004, 0
Organophosphate/malathion (56%)	Malathion 5EC*	Micro Flo Company, Memphis, TN	1.7–5.2	1.88	0.94, 0.19, 0.06, 0.002, 0
Organophosphate/chlorpyrifos (44.9%)	Lorsban 4E	Micro Flo Company, Memphis, TN	3.5	1.88	0.94, 0.19, 0.06, 0.002, 0
Carbamate/carbaryl (44.1%)	Sevin XLR	Bayer CropScience, Research Triangle Park, NC	2.3–11.7	2.50	1.25, 0.25, 0.075, 0.003, 0
Methomyl (99.3%)	Lannate LV*	DuPont, Wilmington, DE	1.7–3.5	1.88	0.94, 0.19, 0.06, 0.002, 0

For each pesticide, five concentrations (treatments) were tested: 0.5, 0.1, 0.03, 0.01, and 0 (control) of the label concentration.
Trade names followed by asterisks (*) are registered for use in avocado.

Table 2. **Insecticides applied to avocado trees at the highest label rate to determine the persistence of *X. glabratus* control under field conditions**

a.i.	Trade name	liter/ha	ml/liter H_2O
Bifenthrin	Brigade 2EC	1.8	1.87
Permethrin	Permethrin 3.2AG*	0.6	0.62
Fenpropathrin	Danitol 2.4 EC*	1.6	1.66
z-cypermethrin + bifenthrin	Hero	0.8	0.87
l-cyhalothrin + thiamethoxam	Endigo ZC	0.4	0.43
Malathion	Malathion 5EC*	5.6	5.63

Trade names followed by asterisks (*) are registered for use in avocado.

corded. Fifteen days later, the bolts were destructively sampled to determine the number of beetles that bored through the bark and were found alive. Each treatment was replicated five times. Rainfall during this experiment was recorded through the Florida Automated Weather Network (FAWN), which has a meteorological station located ≈200 m away from the experimental site.

Data Analysis. Lethal concentrations 50 and 90 ($LC_{50\ \&\ 90}$) were calculated 48 h after beetles were exposed to each pesticide by using the SAS-PROBIT procedure (SAS Institute 2012). Abbott's transformation was used to correct for control mortality (Abbott 1925), which was usually <10%. Significant differences between lethal concentrations were indicated when the 95% fiducial limits (FLs) of one pesticide did not overlap with the FLs of the other pesticides. Because of variance heterogeneity and non-normality of data, beetle mortality and beetle boring into bolts treated with the various concentrations of each pesticide were analyzed with Kruskal–Wallis tests (SAS Institute 2012).

Beetle mortality and boring values in the insecticide persistence field trial were normally distributed (Kolmogorov $P > 0.005$) and analyzed through repeated-measures analysis of variance. Differences among the treatments were detected through Tukey's range tests (SAS Institute 2012).

Results

Lethal Concentration of Contact Insecticides on *X. glabratus*. Chlorpyrifos showed the lowest LC_{50} compared with the other insecticides, and therefore had

the highest acute toxicity on *X. glabratus* among the tested insecticides (Table 3). The LC_{50} of chlorpyrifos was similar (as indicated by 95% FLs overlap) to z-cypermethrin + bifenthrin and fenpropathrin but was significantly lower than malathion, permethrin, bifenthrin, and l-cyhalothrin + thiamethoxam (Table 3). Carbaryl and methomyl had significantly higher LC_{50}s; consequently, these two insecticides had the lowest acute toxicity on *X. glabratus*. Similarly, the LC_{90} of chlorpyrifos was significantly lower than the other insecticides, followed by malathion and z-cypermethrin + bifenthrin. The estimated LC_{90}s of malathion and z-cypermethrin + bifenthrin were similar to those of fenpropathrin, permethrin, and bifenthrin, but significantly lower than l-cyhalothrin + thiamethoxam (Table 3). Carbaryl and methomyl had the highest LC_{90}s. The $LC_{50\ \&\ 90}$ of chlorpyrifos, malathion, z-cypermethrin + bifenthrin, bifenthrin, permethrin, fenpropathrin, and l-cyhalothrin + thiamethoxam were within the range of the tested concentrations (Tables 1 and 3). By contrast, the estimated lethal concentrations of carbaryl and methomyl were out of the range of the tested concentrations and were higher than the label concentrations (Tables 1 and 3).

Contact with fresh residues of most insecticides caused death on *X. glabratus* in a concentration-dependent fashion (Fig. 1). Contact with chlorpyrifos resulted in significantly higher mortality of beetles exposed to the three highest concentrations ($\chi^2 = 20.81$; $P < 0.001$) compared with all others tested. Exposure to the two highest concentrations of malathion caused significantly higher mortality than beetles exposed to the two lowest concentrations, which had mortality rates similar to the untreated control ($\chi^2 = 19.07$; $P < 0.001$; Fig. 1). Contact with fresh residues of bifenthrin, permethrin, fenpropathrin, z-cypermethrin + bifenthrin, and l-cyhalothrin + thiamethoxam at the highest tested concentration (i.e., $0.5 \approx$ half of the label rate) resulted in 100% death of *X. glabratus* within 48 h (Fig. 1). However, beetle mortality decreased significantly ($\chi^2 = 22.16$, $\chi^2 = 20.77$, $\chi^2 = 14.69$, $\chi^2 = 21.86$, $\chi^2 = 19.37$; $P < 0.001$; respectively) when exposed to lower insecticide concentrations (Fig. 1). No effect of the insecticide concentration was observed in the mortality of beetles exposed to fresh residues of carbaryl ($\chi^2 = 4.21$; $P = 0.37$). Exposure to the two highest concentrations of methomyl

Table 3. **Lethal concentrations ($LC_{50\ \&\ 90}$) at 48 h after *X. glabratus* adults were exposed to avocado bolts treated with nine pesticides at four different concentrations**

Pesticide	LC_{50} (ml/liter)	LC_{50} FL (ml/liter)	LC_{90} (ml/liter)	LC_{90} FL (ml/liter)	χ^2	Slope
Bifenthrin	0.08	0.03–0.42b	0.25	0.11–91.2bcd	9.15	2.59
Permethrin	0.07	0.03–0.26b	0.23	0.1–12.41bc	8.19	2.60
Fenpropathrin	0.06	0.02–0.35ab	0.19	0.08–44.6cb	29.54	2.27
z-cypermethrin + bifenthrin	0.03	0.02–0.04ab	0.1	0.08–0.14b	3.25	2.60
l-cyhalothrin + thiamethoxam	0.08	0.07–0.10b	0.22	0.18–0.30c	2.72	3.01
Malathion	0.03	0.03–0.04b	0.1	0.08–0.13b	1.15	2.84
Chlorpyrifos	0.02	0.01–0.02a	0.07	0.05–0.07a	0.97	2.28
Carbaryl	23.6	3.6–12360c	1607	56.6–1.4 by 10^8d	2.72	0.70
Methomyl	2.71	1.1–17.38c	126.3	19.05–6550d	1.94	0.77

Fiducial limits (FL) = 95%. The LC_{50} and LC_{90} of each pesticide followed by the same letter are not significantly different because of FL overlap.
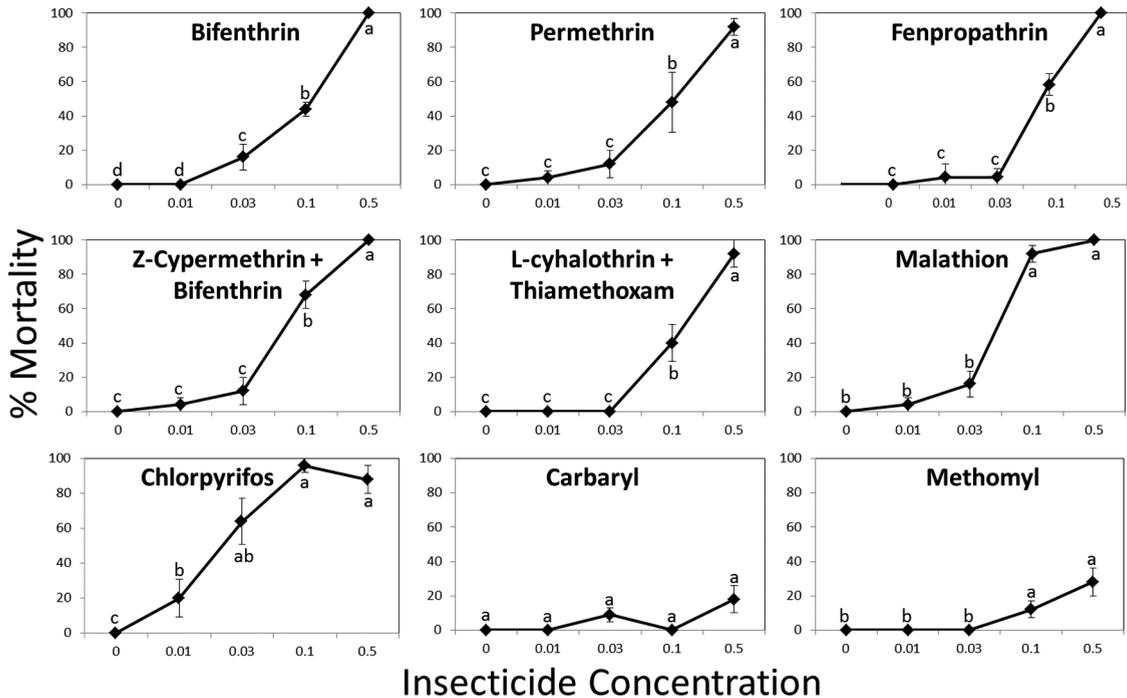
Fig. 1. Percent mortality of *X. glabratus* 48 h after exposure to five different concentrations of pesticides on avocado bolts. The insecticide concentration "0" represents the no-insecticide control treatment. Error bars represent the SEM.

caused significantly higher mortality than beetles exposed to the two lowest concentrations ($\chi^2 = 10.49$; $P < 0.001$); however, mortality rates were <40% even after exposure to the highest concentration of methomyl (Fig. 1).

The percentage of beetles that bored into the bolts and were found alive inside galleries after 15 d was affected by the pesticide concentration of all insecticides but carbaryl and methomyl (Fig. 2). There was significantly less boring and survival of beetles exposed to the three highest concentrations of chlorpyrifos compared with the control ($\chi^2 = 17.28$; $P < 0.002$). Exposure to the two highest concentrations of malathion, fenpropathrin, and permethrin resulted in little beetle boring and survival, but exposure to the two lowest concentrations resulted in beetle boring and survival rates similar to the untreated control ($\chi^2 = 19.59$, $\chi^2 = 17.10$, $\chi^2 = 19.28$; $P < 0.001$, respectively; Fig. 2). Contact with fresh residues of z-cypermethrin + bifenthrin resulted in significantly less boring and survival than the control treatment across all the tested concentrations; the two highest concentrations resulted in less beetle boring and survival ($\chi^2 = 21.97$; $P < 0.001$). The bifenthrin and l-cyhalothrin + thiamethoxam treatments showed a concentration-dependent effect with significantly less boring and survival at the highest concentrations ($\chi^2 = 21.48$, $\chi^2 = 18.40$; $P < 0.001$, respectively; Fig. 2). No beetle boring was recorded in the bolts treated with the three pyrethroid insecticides at the highest rates (z-cypermethrin + bifenthrin, permethrin, bifenthrin). By contrast, no effect of the in-

secticide concentration was observed in the percentage of boring and surviving beetles in the carbaryl ($\chi^2 = 5.73$; $P = 0.21$) and methomyl ($\chi^2 = 8.85$; $P = 0.06$) treatments (Fig. 2).

Persistence of Selected Insecticides Against *X. glabratus* Under Field Conditions. Evaluation of the efficacy of the tested insecticides 4 d after the application showed that all insecticides but permethrin caused a significant reduction in the number of beetles boring in avocado wood ($F = 13.86$; df = 6, 34; $P < 0.001$; Fig. 3). Few beetles bored through the bark of bolts treated with bifenthrin, fenpropathrin, z-cypermethrin + bifenthrin, l-cyhalothrin + thiamethoxam, and malathion (Fig. 3). Contact with permethrin residues caused significantly less beetle mortality than the other insecticides ($F = 17.59$; df = 6, 34; $P < 0.001$) and more beetles were found alive 15 d later inside galleries constructed within the wood. Beetles exposed to the water control treatment had a low mortality and more boring through the bark. No rain was recorded during the first 4 d after application.

Eight days after application, only the z-cypermethrin + bifenthrin and malathion treatments caused significantly higher beetle mortality than the control treatment ($F = 3.50$; df = 6, 34; $P = 0.01$; Fig. 3). Consequently, fewer beetles bored through bark treated with these two insecticides compared with the other treatments ($F = 5.72$; df = 6, 34; $P < 0.001$). The number of beetles that died 48 h after exposure to l-cyhalothrin + thiamethoxam was higher than the number of beetles that bored and were found alive 15 d later (Fig. 3). In the rest of the treatments, the
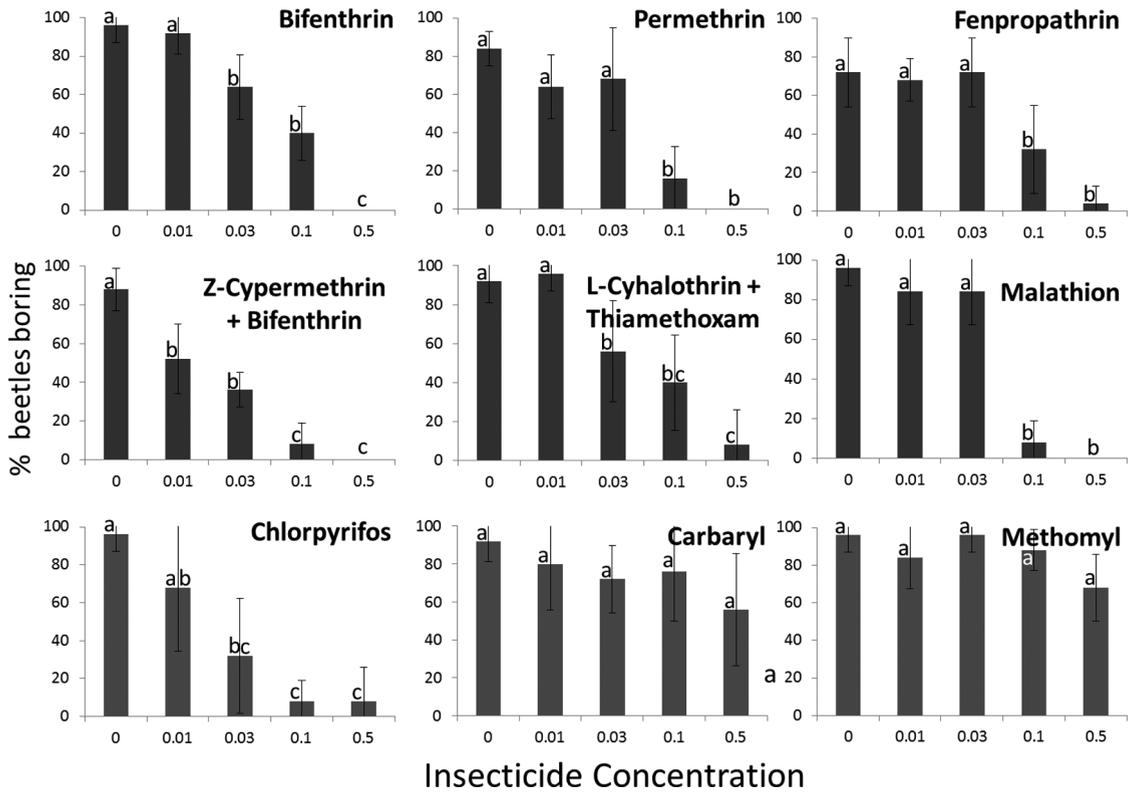
Fig. 2. Percent of *X. glabratus* that bored through the bark and were found alive inside galleries 15 d after exposure to five different concentrations of insecticides. The insecticide concentration "0" represents the no-insecticide control treatment. Error bars represent the SEM.

number of beetles boring through the treated bark was higher than the number of beetles that died because of the treatments. In all, 60.9 mm of rain fell between days 4 and 8 after application.

Little beetle mortality occurred 15 d after application in all treatments, and only malathion and z-cypermethrin + bifenthrin caused significantly higher beetle mortality than the control treatments ($F = 3.90$; df = 7, 34; $P = 0.006$; Fig. 3). The number of beetles boring through the bark and constructing galleries was not affected by the insecticide treatment ($F = 0.78$; df = 6, 34; $P = 0.59$; Fig. 3). In all, 86.4 mm of rain was recorded between days 8 and 15 after application.

None of the treatments had any effect on *X. glabratus* mortality or in the number of beetles boring through the treated bark at 22 d after treatment ($F = 0.73$; df = 6, 34; $P = 0.63$ and $F = 0.78$; df = 7, 34; $P = 0.59$, respectively; Fig. 3). In all, 58.4 mm of rain was registered between days 15 and 22 after application.

Discussion

Four pyrethroid insecticides with different active ingredients were tested in this study. Bifenthrin showed a high acute toxicity on *X. glabratus*, but under field conditions, effective suppression of *X. glabratus* lasted only 4 d. The effect of bifenthrin was com-

pletely lost 2 wk after application under typical summer rainy conditions in south Florida. These results are strikingly different from those reported when bifenthrin is used against bark beetles. According to DeGomez et al. (2006) and Fettig et al. (2006), bifenthrin confers protection to conifers against bark beetles for one or two seasons applied as trunk-directed sprays at similar rates as in our experiments. Similarly, Oghiakhe and Holliday (2011) reported that bifenthrin provides long-term suppression of the native elm bark beetle *H. rufipes.* It is unclear whether the subtropical conditions of south Florida or the avocado bark characteristics affect the persistence of bifenthrin, or whether some ambrosia beetles are more tolerant to bifenthrin than bark beetles. Reding et al. (2013) reported that bifenthrin did not effectively prevent attacks by ambrosia beetles in nursery trees. Our results suggest that contact with fresh residues of bifenthrin applied at the highest label rate can kill *X. glabratus,* but its suppression will last only few days.

Permethrin is another pyrethroid insecticide regarded as effective for elm bark beetle control (Phillipsen et al. 1986, Pajares and Lanier 1989). Reding et al. (2013) reported that permethrin products were the most effective among a range of insecticides tested to protect nursery plants from ambrosia beetles (i.e., *X. germanus*). By contrast, other researchers reported a
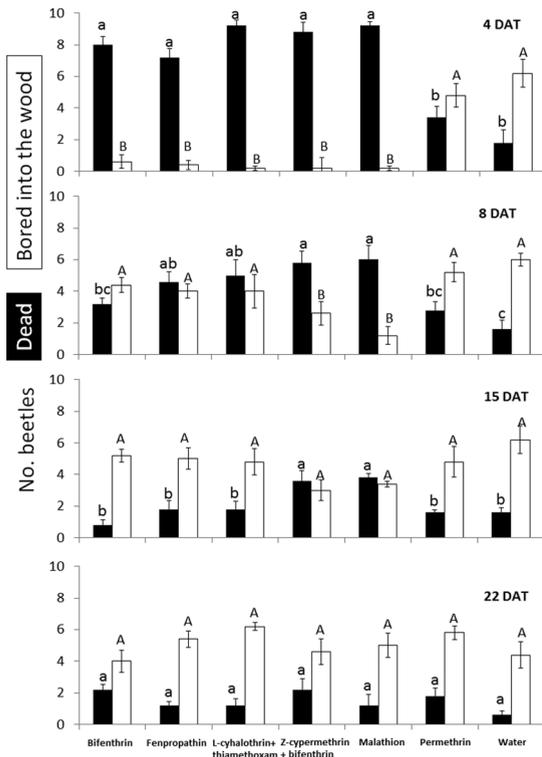
Fig. 3. Persistence of contact insecticides against *X. glabratus*. Avocado trees were treated with insecticides at the highest label rate and limbs cut periodically and exposed to groups of 10 *X. glabratus* under controlled conditions. The black bar represents the number of beetles that were found dead 48 h after exposure to the treated bolts. The white bars represent the number of beetles that bored through the bark and were found alive in galleries inside the bolts 15 d after. DAT, days after treatment. Error bars represent the SEM.

lack of persistence of permethrin; when tested under field conditions, its efficacy diminished within few days of application (Oghiakhe and Holliday 2011). Our results agree with the latter authors; permethrin showed high acute toxicity on *X. glabratus* in laboratory bioassays, but caused low beetle mortality only 4 d after application in the field. However, the rate of permethrin registered for use in avocado is significantly lower than the one used against bark beetles. Prelude (AMVAC) is a formulation of permethrin registered for control of termites and bark beetles (i.e., vectors of Dutch elm disease) as a bark spray at a concentrated rate of ≈5.1 ml a.i./liter H_2O. Permethrin 3.2 AG is registered for use in avocado at 0.22 ml a.i./liter H_2O. At this rate, suppression of *X. glabratus* lasted <8 d.

Fenpropathrin is another pyrethroid insecticide that is registered for use in avocado. Contact with fresh residues of this pesticide under controlled conditions showed a high acute toxicity on *X. glabratus*, but when applied under normal grove conditions, the effect of fenpropathrin was intermediate relative to all

other insecticides. Fenpropathrin is registered for mite and thrips control at a rate of 1.56 liters/ha. However, used at label recommended rates, its efficacy diminished a few days after application. These results coincide with those reported by Peña et al. (2011) using potted avocado plants infested with known numbers of *X. glabratus* in a controlled fashion. They found that fenpropathrin-treated plants had significantly lower numbers of entry holes when checked at 1 d after treatment. However, there were no differences in entry holes between the treated trees and the untreated controls 1 wk later. The pyrethroid mixture of z-cypermethrin + bifenthrin had a high acute toxicity on *X. glabratus* and was one of the two treatments that provided longer beetle suppression in the field experiment. These results coincide with those reported by Peña et al. (2011), who found that z-cypermethrin + bifenthrin was one of the insecticides that provided the most consistent suppression of Scolytinae as a contact insecticide. This insecticide is not currently registered for use in avocado but it could be useful in managing *X. glabratus* infestations. Additional studies toward registration of z-cypermethrin + bifenthrin are underway.

l-cyhalothrin + thiamethoxam caused a high mortality of *X. glabratus*, but its persistence under field conditions was inferior to z-cypermethrin + bifenthrin. The pyrethroid part of the formulation is recommended for management of the long horned beetle, *Anoplophora glabripennis* (Coleoptera: Cerambycidae), an invasive species in the United States (Smith et al. 2007). Peña et al. (2011) reported that l-cyhalothrin + thiamethoxam was one of the mixtures that provided the most consistent suppression of Scolytinae. This mixture is not registered for use on avocado. However, if the persistence of this pesticide could be improved by the addition of adjuvants, it might be useful for managing or preventing *X. glabratus* infestations.

Organophosphate insecticides were highly toxic to *X. glabratus.* Chlorpyrifos and malathion caused high *X. glabratus* mortality in the laboratory bioassays. Malathion was among the two insecticides that provided longer persistence under field conditions. Malathion is registered for use in avocado, whereas chlorpyrifos is not, and there is no interest by the manufacturer to pursue registration (IR4 http://ir4.rutgers.edu/FoodUse/Food_Use1.cfm).

In a previous assessment, malathion caused a significant reduction in the number of scolytines entry holes and beetle emergence from treated logs in several experiments but also provided erratic suppression in one experiment (Peña et al. 2011). Smith (1982) reported that malathion was ineffective on western pine beetle, *Dendroctonus brevicomis* LeConte, 5 mo after application.

Carbaryl and methomyl were ineffective at controlling *X. glabratus.* Carbaryl has been widely used to manage several pine bark beetles (Hastings et al. 2001). However, carbaryl also lacks toxicity toward the southern pine beetle, *Dendroctonus frontalis* Zimmermann, which has a high degree of tolerance for this

insecticide (Hastings et al. 2001). Our experiments showed that *X. glabratus* tolerated carbaryl in the laboratory bioassays. Similarly, *X. glabratus* bored through the bark of avocado bolts treated with methomyl showing tolerance toward this insecticide, which is one of the pesticides currently registered for avocado. Our results agree with those of Peña et al. (2011), who reported higher number of entrance holes and higher beetle emergence in methomyl-treated bolts relative to the nontreated control.

X. glabratus is the main vector of a fungal pathogen that can kill a tree with an inoculation of relatively few spores. This increases the challenge of achieving an integrated approach and also the likelihood that conventional insecticides will be used by avocado growers. None of the tested insecticides could completely prevent *X. glabratus* attack, and their persistence was low during the rainy summer season in south Florida. Organophosphate and pyrethroid insecticides appear to be the most effective groups for suppressing *X. glabratus*. Among the pesticides registered for use in avocado, malathion and fenpropathrin represent the best chemical tools currently available; however, the persistence of all tested insecticides is low, requiring frequent repeated applications. z-cypermethrin + bifenthrin and l-cyhalothrin + thiamethoxam at possibly higher rates and other pesticides may be required to manage *X. glabratus* outbreaks. Moreover, it is imperative to identify effective adjuvants to prolong the efficacy of these contact insecticides to manage *X. glabratus*.

Pest resurgence is a major concern of avocado growers regarding insecticide applications against *X. glabratus*. The choice of an insecticide to be applied against *X. glabratus* should be defined not only by its effectiveness against the vector but also by its effect on direct and indirect pest resurgence. The complex of spider mites and insects that affect avocado in south Florida has been under a 20-yr integrated pest management program (Peña et al. 2013). The most common pests are mirids, thrips infesting flowers, mites, lace bugs, and loopers affecting leaves (Peña et al. 2013), whereas soft, armored scales, mealybugs, and whiteflies are seldom observed. Spray interventions are kept to a minimum because of the effective natural enemy complex keeping these pests under low density levels. Pest resurgence represents a major challenge to design sound chemical management strategies against this invasive vector. The indirect effect on nontarget pests of several contact insecticides recommended against *X. glabratus* is currently being tested by the authors in south Florida avocado groves.

More management tools including more registered pesticides are needed to protect avocados from this beetle–disease complex. In this study, no data were collected about inoculation of *R. lauricola* by *X. glabratus* in the limbs; however, previous experiments infesting small potted avocado trees suggest that a few beetle attacks can be enough to transmit the laurel wilt pathogen. In our experiments we seldom observed 100% beetle mortality, which suggests that the use of contact insecticides might reduce the number of successful attacks, but is not sufficient to completely eliminate the risk of disease transmission. The authors are currently investigating systemic insecticides as an alternative management tactic against *X. glabratus*. Moreover, the potential of fungicides used as preventive and curative treatments against *R. lauricola* is currently under investigation (Ploetz et al. 2011). The current strategy is based in early detection and removal of diseased trees to eliminate beetle breeding sites and fungal inoculum sources. The diseased trees are uprooted, the stump and roots burned, the trunk and limbs are chipped, and the chips and adjacent trees are sprayed with insecticides. Our results suggest that pesticide applications under these conditions can cause a short-term suppression of beetle populations, but other practices are needed to mitigate the adverse effects of this beetle–disease complex.

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