Effect of Trap Type, Trap Position, Time of Year, and Beetle Density on Captures of the Redbay Ambrosia Beetle (Coleoptera: Curculionidae: Scolytinae)

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ABSTRACT The exotic redbay ambrosia beetle, *Xyleborus glabratus* Eichhoff (Coleoptera: Curculionidae: Scolytinae), and its fungal symbiont *Raffaellea lauricola* Harrington, Fraedrich, and Aghayeva are responsible for widespread redbay, *Persea borbonia* (L.) Spreng., mortality in the southern United States. Effective traps and lures are needed to monitor spread of the beetle and for early detection at ports-of-entry, so we conducted a series of experiments to find the best trap design, color, lure, and trap position for detection of *X. glabratus*. The best trap and lure combination was then tested at seven sites varying in beetle abundance and at one site throughout the year to see how season and beetle population affected performance. Manuka oil proved to be the most effective lure tested, particularly when considering cost and availability. Traps baited with manuka oil lures releasing 5 mg/d caught as many beetles as those baited with lures releasing 200 mg/d. Distributing manuka oil lures from the top to the bottom of eight-unit funnel traps resulted in similar numbers of *X. glabratus* as a single lure in the middle. Trap color had little effect on captures in sticky traps or cross-vane traps. Funnel traps caught twice as many beetles as cross-vane traps and three times as many as sticky traps but mean catch per trap was not significantly different. When comparing height, traps 1.5 m above the ground captured 85% of the beetles collected but a few were caught at each height up to 15 m. Funnel trap captures exhibited a strong linear relationship ($r^2 = 0.79$) with *X. glabratus* attack density and they performed well throughout the year. Catching beetles at low densities is important to port of entry monitoring programs where early detection of infestations is essential. Our trials show that multiple funnel traps baited with a single manuka oil lure were effective for capturing *X. glabratus* even when no infested trees were visible in the area.

KEY WORDS exotic, invasive, sassafras, laurel wilt, Lauraceae

The redbay ambrosia beetle, *Xyleborus glabratus* Eichhoff (Coleoptera: Curculionidae: Scolytinae), is an exotic species threatening redbay, *Persea borbonia* (L.) Spreng.; swampbay, *Persea palustris* (Raf.) Sarg.; and possibly sassafras, *Sassafras albidum* (Nutt.) Nees, trees in North America. It was first discovered in the Savannah, GA, area in 2002, but it was already well established at that time and had probably arrived years earlier. Unlike most ambrosia beetles accidentally introduced to North America that cause little damage to live trees in forests, *X. glabratus* carries *Raffaellea lauricola* Harrington, Fraedrich and Aghayeva that causes a wilt disease in redbay; swampbay; avocado, *Persea americana* Mill.; and sassafras trees (Fraedrich et al. 2008, Harrington et al. 2008). Since its arrival, it has spread rapidly and now occurs as far north as

Myrtle Beach, SC; south as far as Dade County, FL, where it poses a threat to the avocado industry (http://www.doacs.state.fl.us/press/2010/03092010.html); and west to Mississippi (http://www.fs.fed.us/r8/foresthealth/laurelwilt/dist_map.shtml). Myrtle Beach and Mississippi are isolated infestations that represent large jumps from the closest areas of continuous infestation, suggesting human movement of infested wood is aiding beetle spread. In Georgia, *X. glabratus*' northern spread has reached the edge of the range of redbay, and questions are now being raised about how or if it will spread northward in the sassafras population. Detection of infested redbay trees is easy because the leaves turn reddish brown and remain on the tree for over a year. Sassafras, however, drops its leaves quickly once the wilt fungus has infected the tree.

An effective monitoring system is needed to help detect *X. glabratus* when it is still at low populations in isolated locations away from the main area of spread, or in northern areas where it will be dependent on sassafras and difficult to detect. In addition to detecting spread in the current area of infestation, effective monitoring traps also are needed at ports in

southern California and other avocado-growing regions. Hanula et al. (2008) showed that redbay and avocado wood were attractive to *X. glabratus*, and Hanula and Sullivan (2008) examined the volatile emissions from redbay wood. Because several compounds present in redbay volatiles were not readily available, they tested manuka oil extracted from *Leptospermum scoparium* Forst. and Forst. and found it to be as attractive to *X. glabratus* as redbay wood. Tests of release rates up to 50 mg/d suggested that release rate of manuka oil had no effect on trap captures of *X. glabratus*, although higher release rates may be more attractive.

Here, we report a series of experiments on the effects of trap color, trap type, trap height, and release rates of manuka oil on trap captures of *X. glabratus*. We also tested the most effective trap and lure combination at seven locations with varying beetle densities and trapped at different times of the year to determine the effectiveness of the traps for capturing beetles at low densities and in different climatic conditions.

Materials and Methods

Manuka Oil Versus Phoebe Oil. Because initial trials comparing manuka oil with phoebe oil were inconclusive (Hanula and Sullivan 2008), we tested them again and compared them to two manuka oil fractions (Coast Biologicals, Bombay, South Aukland, New Zealand) and an unbaited control. The test was conducted in summer 2008 in a heavily infested forest near Claxton, GA. Traps and lures were similar to those described by Hanula and Sullivan (2008). Lures were constructed from 4-ml vials containing 6–7 g of manuka or phoebe oil. Attractants were eluted through a 5-mm-diameter cotton rope wick extending 2 cm above the cap that eluted ≈15 mg/d. Each lure was suspended from a wire between two white sticky traps hung on wooden stakes ≈1.5 m above ground. Each sticky trap was a solitary, white, wing-style trap bottom (23 by 28 cm; Scentry Biologicals, Billings, MT) secured flat with binder clips to a Plexiglas panel (20 by 20 cm). Six lines, each containing five traps assigned randomly to the five bait treatments, were established in the forest. The lines were spaced ≈30 m apart and traps within each line were ≈40 m apart. The test was run from 1 to 15 July 2008, and traps were checked at 7-d intervals.

Manuka Oil Release Rate. We tested manuka oil release rates of 0, 5, 50, 100, and 200 mg/d at two locations. The first trial was conducted at the Claxton site mentioned above that had a very high *X. glabratus* population and the second was at Lake Warren State Park in Hampton, SC, where populations were moderate to low. The 5-mg/d releasers were constructed from vials as described above but with only 0.5 cm of wick extending above the cap (Hanula and Sullivan 2008). The 50-, 100-, and 200-mg/d releasers consisted of one, two, or four of the 50-mg/d manuka oil releasers manufactured by Synergy Semiochemicals Corp. (Burnaby, BC, Canada). Lures were hung between two white sticky traps as described above. At the

Claxton site, traps were placed along the same lines used in the previous trial. Traps were operated for 2 wk from 15 to 29 July 2008 and checked weekly. At the Lake Warren site, traps were arranged in six lines with 100 m between lines of traps and 50 m between traps within lines. Traps were operated from 7 August to 4 September 2008, and samples were collected once at the end of the experiment.

Lindgren (1983) showed that a single smoke source in the middle of a multiple-funnel trap produced a narrow smoke plume, whereas two or more sources distributed from the bottom to the top of the trap resulted in wide plumes over the entire trap length. Therefore, we conducted a third trial from February to June 2009 at Jekyll Island, GA, by using multiple-funnel traps (eight-funnels) to see whether more beetles were caught by dispersing multiple baits along the length of the trap. Traps were baited with zero, one, two, or three of the 50-mg/d releasers. Traps with single releasers had the releaser in the center of the trap; those with two had releasers in the center and at the bottom of the trap; and those with three had them at the top, middle, and bottom. Traps were placed in groups with at least 25 m between treatments within groups and 100–300 m between groups. Traps were checked monthly and rotated between positions within locations at each check. Baits were replaced bimonthly.

Manuka Oil Plus Ethanol. *X. glabratus* breeds in decaying trees that probably produce ethanol (Byers 1992, and references therein), so we examined its response to ethanol alone and in combination with manuka oil. Traps were deployed on Jekyll Island at five locations at least 100 m apart and traps were spaced at least 25 m apart at each location. Multiple funnel traps were hung from ropes tied between two nonhost trees at each trap position and baited with either Contech (Burnaby, BC, Canada) gelled, ultra-high release rate ethanol lures, 50 mg/d manuka oil lures or the two combined. Traps were operated from 5 November 2009 to 5 April 2010 and checked monthly. Baits were replaced bimonthly.

Trap Color. We tested trap color at the Claxton and Lake Warren sites by using two different types of traps. At the Claxton site, we used sticky traps consisting of a clear acetate sheet (3.3 by 4.3 cm) sprayed with Tangle-Trap (Grand Rapids, MI). These clear sticky traps were then placed over a similar sized piece of colored 3-mm-thick foam (Funky Foam, Crafts, etc.!, Oklahoma City, OK) in either white, red, black, blue, or yellow. Both the clear sticky trap and foam were attached to Plexiglas panels as described above. Traps were placed along the same lines used in the previous trials with two traps of the same color hung on opposite sides of the wooden poles and a 50-mg/d manuka oil lure in between. Traps were operated from 5 to 19 August 2008 and checked weekly.

At Lake Warren, we tested Plexiglas cross-vane traps identical to those used by Ulyshen and Hanula (2007) but instead of white buckets we used gray and the Plexiglas panels were painted white, black, red, yellow or purple. We compared the colored cross-

vane traps to white sticky traps that were the standard trap used in previous attractant studies (Hanula and Sullivan 2008) and were identical to those described above. Cross-vane traps were hung from metal poles ≈1 m above the ground in four lines. Traps within lines were ≈20 m apart and lines were ≈100 m apart. Traps were operated from 11 September to 12 October 2008, and samples were collected once.

Trap Height. The effect of trap height was tested twice at the Lake Warren site. In 2008, sticky traps were hung at ≈3-m intervals starting at 1.5 m above ground and going up to 13.7 m. Each trap consisted of a single, white, wing-style trap bottom folded in half with the sticky side out. These were attached to a rope with binder clips at the top and bottom of the trap. The rope was looped over a branch in the canopy of a pine tree by using the technique described by Ulyshen and Hanula (2007). A single 50-mg/d manuka oil lure was placed inside the folded trap. The six pine trees with traps were spaced at least 100 m apart. Traps were checked monthly from 4 September to 3 November 2008.

The same trees were used in 2009 but instead of sticky traps we tested eight-funnel multiple funnel traps at 1, 7, and 15 m above ground. Each trap was tied to the rope at the appropriate height and baited with a single 50-mg/d manuka oil lure placed so it was inside the middle funnel. Traps were deployed from 3 September to 1 October 2009, and samples were collected once.

Trap Type. We compared white sticky traps, red cross-vane traps, and eight-funnel multiple funnel traps for effectiveness in catching *X. glabratus* at Jekyll Island, GA, from 21 October 2008 to 10 February 2009. Six trapping locations were selected at least 100 m apart, and one trap of each type was placed ≈20 m apart at each location. Two sticky traps attached to Plexiglas panels were hung from a wooden pole ≈1.5 m above ground as described above, and the red cross-vane traps and funnel traps were deployed in the same manner as described above. All traps were baited with a single 50-mg/d manuka oil lure. Samples were collected monthly, and sticky traps were replaced each month.

Redbay Wood Plus Manuka Oil. We were interested in determining whether redbay wood plus manuka oil would catch more beetles than either lure alone so we tested these lures on funnel traps at Hunting Island State Park, SC, from 18 August to 22 September 2009. Hunting Island State Park was in the later stages of infestation (few live host trees left), so populations of *X. glabratus* were moderate to low. We selected six locations spaced at least 100 m apart and deployed three traps at each location ≈25 m apart. Traps were hung on a rope tied between two nonhost trees ≈1.5 m above the ground and baited with either a 0.5-m-long section of freshly cut redbay, a single 50-mg/d manuka oil lure or both. Redbay bolts, with 3-cm-wide strips of bark removed along their length on either side to increase volatile emissions, were hung outside of the funnels as close to the trap as possible. Manuka oil lures were placed inside the cen-

ter funnel so they were not blocking the hole. Traps were operated for 35 d from 18 August to 22 September 2009, and samples were collected once.

Trap Performance at Different Beetle Densities. Hanula et al. (2008) attached a sticky trap to redbay bolts and deployed them at seven locations ranging from low to high *X. glabratus* populations. They found that trap captures were correlated with the number of beetle attacks on the bolts, and the number of dead redbay trees nearby. We were interested in determining the effectiveness of multiple funnel traps over a range of population densities and whether they too would be predictive of beetle attack densities on freshly cut bolts, so we tested them at the same sites as Hanula et al. (2008). *X. glabratus* densities were low at Hilton Head Island, SC (two sites), and Colonels Island, GA; moderate at Edisto Beach State Park and Hunting Island State Park, SC, and Richmond Hill Wildlife Management Area, GA; and high at Jekyll Island, GA. At each location, we had three trapping sites spaced at least 50 m apart. At each trapping site, we hung a fresh redbay bolt with a single sticky trap attached and a 50-mg/d manuka oil lure to monitor attack densities. A multiple funnel trap baited with a 50-mg/d manuka oil lure was hung 10 m from each sticky trap. The traps were operated 20 August to 21 September 2009, and samples were collected once.

In addition, six multiple funnel traps were deployed on Jekyll Island from December 2009 to June 2010 and checked monthly to determine whether funnel traps were effective for monitoring beetle flight activity year round.

Statistical Analyses. Each trapping trial was analyzed as a two-way analysis of variance (ANOVA) with treatment and replicates (lines or groups) as the independent variables and beetle catch as the dependent variable by using Proc GLM (SAS Institute 2000). Data in each trial were pooled for analysis except for the release rate trial at Jekyll Island. In that trial data were analyzed for each month separately because most months at least one trap was disturbed by animals or fell down. Data were transformed using a log transformation when the Shapiro–Wilk test for normality of ANOVA residuals (Proc Univariate; SAS Institute 2000) indicated they were not normally distributed. Residuals of log transformed data also were tested to ensure normality. Bartlett's test (Proc GLM) was used to determine whether variances were homogeneous. Means were separated using the Ryan–Einot–Gabriel–Welsch multiple comparison test (Day and Quinn 1989). Relationships between X. *glabratus* entrance hole densities and trap catches, and between beetle catches on sticky traps and in funnel traps, were analyzed by simple linear regression using Proc GLM.

Results

Manuka Oil Versus Phoebe Oil. Mean numbers of *X. glabratus* captured in traps baited with whole manuka oil, two fractions of manuka oil, or phoebe oil were not significantly different, but all caught more *X. glabratus* than unbaited control traps (Table 1). Al-

Table 1. Mean numbers of *X. glabratus* captured per day on white sticky traps baited with manuka oil, two fractions of manuka oil, or phoebe oil near Claxton, GA, from 1 to 15 July 2008

Treatment	N	Mean *X. glabratus*/ trap/d $\pm$ SE[a]
Control	6	1.6 $\pm$ 0.62a
Phoebe oil	6	23.1 $\pm$ 7.63b
Low odor manuka oil	6	13.3 $\pm$ 4.06b
Fraction 7 manuka oil	6	8.0 $\pm$ 1.60b
Manuka oil (whole)	6	8.1 $\pm$ 1.91b

[a] Analyses were conducted on log-transformed data. Means followed by the same letter are not significantly different according to the Ryan–Einot–Gabriel–Welch multiple range test ($P < 0.05$).

though not significantly different, phoebe oil caught almost twice as many beetles as low-odor manuka oil, the second most attractive bait. Whole manuka oil and fraction 7 that contained most of the highly volatile compounds in manuka oil caught similar numbers of beetles but only approximately a third of the number caught in phoebe oil baited traps.

Manuka Oil Release Rate. Increasing release rates of manuka oil up to 200 mg/d did not increase captures of *X. glabratus* at either a high or low population site (Table 2). The Claxton, GA, site had much higher populations than Lake Warren State Park at the time of the study as indicated by mean catches in unbaited control traps of more than six beetles per trap per d compared with 0.5 beetle per trap per d. Despite differences in populations, traps baited with 5 mg/d caught similar numbers of beetles as those baited with 200 mg/d at both locations. In addition, distributing lures over a greater surface area on multifunnel traps did not improve trap catch (Table 3). During each month, single 50-mg/d baits in the center of the traps caught as many or more beetles as two (100 mg/d) and three baits (150 mg/d) distributed over the length of the trap.

Manuka Oil Plus Ethanol. Multiple funnel traps baited with ethanol alone caught only 0.1 (SE = 0.07) *X. glabratus* per trap per d compared with 8.7 beetles per trap per d (SE = 1.70) with manuka oil alone and 8.0 beetles per trap per d (SE = 1.67) when traps were

Table 2. Mean number of *X. glabratus* captured per day on white sticky traps at two sites with either high (Claxton) or low (Lake Warren) populations of beetles

Release rate (mg/d)		Mean *X. glabratus*/trap/d $\pm$ SE[a]		
	N	Claxton GA	N	Lake Warren State Park
0	6	6.2 $\pm$ 2.0a	6	0.5 $\pm$ 0.2a
5	6	21.6 $\pm$ 4.5b	6	3.1 $\pm$ 0.4b
50	6	12.5 $\pm$ 1.9b	6	4.0 $\pm$ 0.4b
100	6	15.0 $\pm$ 2.7b	6	3.4 $\pm$ 0.1b
200	6	18.6 $\pm$ 4.2b	6	3.9 $\pm$ 0.4b

Traps at the Claxton site were deployed from 15 to 29 July 2008 and those at Lake Warren from 7 August to 4 September 2008.

[a] Analyses were conducted on log-transformed data. Means within columns followed by the same letter are not significantly different according to the Ryan–Einot–Gabriel–Welch multiple range test ($P < 0.05$).

baited with manuka oil and ethanol. Both treatments with manuka oil caught significantly ($F_{2,8} = 57.4$; $P < 0.001$) more *X. glabratus* than ethanol alone but ethanol plus manuka oil had no effect on trap catch.

Trap Color. None of the trap colors tested was consistently better than the others (Table 4). In the Claxton trial, where beetle populations were high, red sticky traps caught significantly more beetles than white or yellow but not black or blue. Black and blue traps caught similar numbers of beetles but significantly more than yellow. At Lake Warren State Park, all colored cross-vane traps except black caught more than white sticky traps. Black cross-vane traps caught fewer beetles than white but otherwise the traps were approximately equal in their effectiveness.

Trap Height. We conducted two tests with two different traps to determine the vertical distribution of *X. glabratus* in a forest (Fig. 1). In 2008, using sticky traps, 202 beetles in total were captured of which 171 (85%) were caught at 1.5–2 m above ground. Traps at 5 and 8 m caught 14 and 10 beetles, respectively, whereas traps at 11 and 14 m caught three and four beetles during the experiment. Traps at the lowest position caught significantly more than higher traps ($F_{4,19} = 12.58$; $P = 0.0001$).

In 2009, multiple funnel traps produced similar results ($F_{2,7} = 15.02$, $P = 0.003$) (Fig. 1). We caught 87 beetles in total, with 86% of those caught at the lowest position ≈1 m above ground. Traps at 7.2 and 15 m caught seven and five *X. glabratus*, respectively.

Trap Type. Although multiple funnel traps ($\bar{x} = 10.4$ beetles per trap per d, SE = 4.4) caught twice as many beetles as red cross-vane traps ($\bar{x} = 5.0$ beetles per trap per d, SE = 1.4) and 3 times as many as white sticky traps ($\bar{x} = 2.8$ beetles per trap per d, SE = 0.8) the differences were not significant ($F_{2,10} = 1.69$; $P = 0.12$).

Redbay Wood Plus Manuka Oil. Redbay wood alone ($\bar{x} = 0.06$ beetle per trap per d, SE = 0.02) was significantly ($F_{2,10} = 7.43$; $P < 0.01$) less attractive to *X. glabratus* than manuka oil alone ($\bar{x} = 0.98$ beetle per trap per d, SE = 0.37) and did not increase attraction when combined with manuka oil ($\bar{x} = 0.76$ beetle per trap per d, SE = 0.11).

Trap Performance at Different Beetle Densities. Funnel traps 10 m from hanging bolts and sticky traps attached to the bolts exhibited significant linear relationships with the number of beetle entrance holes (attacks) in the hanging bolts (Fig. 2). Funnel trap captures also exhibited a linear relationship with sticky trap captures (Fig. 3).

The seasonal pattern of adult activity in 2009, based on funnel trap captures using manuka oil, showed that peak catch occurred in early September (Fig. 4), which was very similar to that reported by Hanula et al. (2008).

Discussion

In a previous trial, traps baited with phoebe oil caught more *X. glabratus* than traps baited with low odor manuka oil but not more than those baited with

Table 3. Mean number of *X. glabratus* captured per day in eight-unit multiple funnel traps with manuka oil lures (50 mg/d release rate) in the middle funnel (1 bait); middle and bottom funnel (2 baits); or middle, bottom and top funnels (3 baits) at Jekyll Island, GA, 2009

No. baits	Mean *X. glabratus*/trap/d ± SE[a]							
	N	Feb	N	Mar	N	April	N	May
0	5	0.2 ± 0.1a	5	0.2 ± 0.1a	6	0.3 ± 0.1a	6	0.1 ± 0.03a
1	6	3.3 ± 1.3c	6	4.0 ± 1.6b	5	2.1 ± 0.4b	6	2.2 ± 0.7b
2	6	1.3 ± 0.1b	5	4.1 ± 0.8b	6	2.9 ± 0.7b	6	2.3 ± 0.4b
3	6	1.2 ± 0.2b	6	3.5 ± 0.6b	6	2.5 ± 1.2b	6	2.7 ± 0.5b

[a] Analyses were conducted on log-transformed data. Means within columns followed by the same letter are not significantly different according to the Ryan–Einot–Gabriel–Welch multiple range test ($P < 0.05$).

whole manuka oil or fraction 7 (Hanula and Sullivan 2008). In that study, phoebe oil caught twice as many beetles as manuka oil, but the differences were not significant and neither caught more than logs from redbay trees. In contrast, Crook et al. (2008) found phoebe oil was almost twice as attractive as manuka oil to emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae). It is unclear why captures of *X. glabratus* tend to be higher on phoebe oil baited traps, but it may be that phoebe oil contains an effective short-range attractant that increases beetle landing rate, similar to the response of *Trypodendron lineatum* (Olivier) entering traps emitting low rates of ethanol (Salom and McLean 1990). It is also possible that six replicates were insufficient to detect the difference. Regardless, phoebe oil is difficult to acquire so manuka oil lures are probably the best for future work on *X. glabratus.*

Hanula and Sullivan (2008) found no positive relationship between release rates of manuka oil up to 50 mg/d and catches of *X. glabratus.* In this study, release rates up to 200 mg/d did not increase trap catch either. Likewise, increasing release rates of manuka oil up to 500 mg/d did not affect captures of emerald ash borer (Crook et al. 2008). In addition, distributing three lures over the length of eight-unit funnel traps did not increase trap catches of *X. glabratus.* Lindgren et al. (1983) found that lures placed near the bottom of

Scandinavian drainpipe traps were more effective for capturing *T. lineatum* than lures in the middle or at the top. In our trial, a single lure in the middle was as effective as lures at the middle and bottom, or middle, top and bottom, even though the smoke trials of Lindgren (1983) suggested middle placement results in a very narrow odor plume.

Most studies of the effects of release rates on ambrosia beetles compared release rates of ethanol. For example, Montgomery and Wargo (1983) found that their low rate of ethanol caught more Scolytidae, which were primarily ambrosia beetles, than the medium rate but not the high rate. Klimetzek et al. (1986) and Schroeder (1988) examined individual species responses to increasing release rates of ethanol and found that ambrosia beetle catches tended to increase with increased release rates. However, for many bee-

Table 4. Effect of trap color on mean numbers of *X. glabratus* captured per day at two sites in 2008

Site, trap color and type	N	Mean *X. glabratus*/trap/d ± SE[a]
Claxton		
Red sticky	6	2.4 ± 0.4a
Black sticky	6	1.6 ± 0.2ab
Blue sticky	6	1.6 ± 0.4ab
White sticky	6	1.0 ± 0.3bc
Yellow sticky	6	0.4 ± 0.2c
Lake Warren State Park		
Red cross-vane	4	2.7 ± 0.1bc
Black cross-vane	4	1.1 ± 0.2ac
Purple cross-vane	4	2.5 ± 0.4bc
White cross-vane	4	3.2 ± 0.7b
Yellow cross-vane	4	3.3 ± 1.1bc
White sticky	4	0.5 ± 0.1a

[a] Analyses were conducted on log-transformed data. Means for the Claxton or Lake Warren sites followed by the same letter are not significantly different according to the Ryan–Einot–Gabriel–Welch multiple range test ($P < 0.05$).
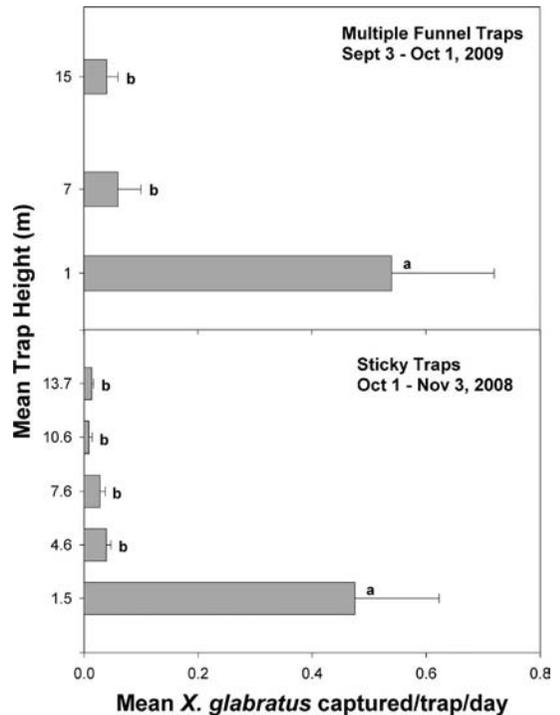
Fig. 1. Mean ± SE daily catch of redbay ambrosia beetles at different heights above the ground at Lake Warren State Park, SC, on sticky traps in 2008 and in funnel traps in 2009.
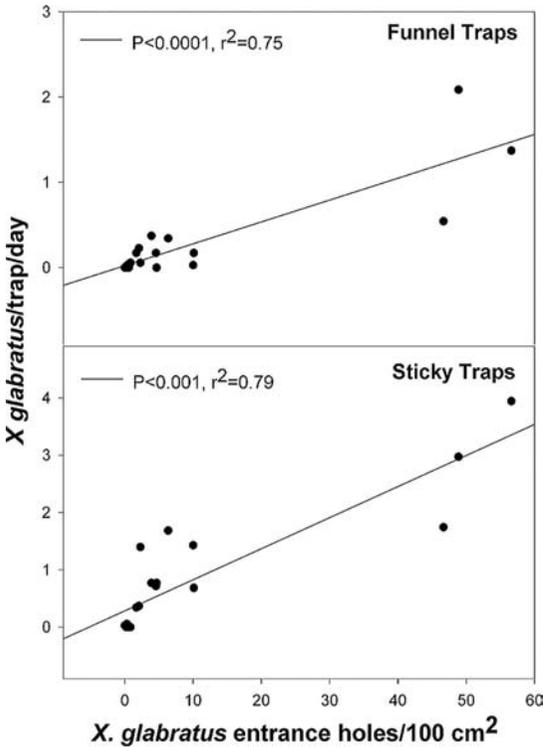
Fig. 2. Linear regression of the mean number of redbay ambrosia beetles captured per day in eight-unit multiple funnel traps or sticky traps and the number of beetle entrance holes in bolts of redbay wood left exposed to attack for 1 mo at 21 trapping locations (three locations each at seven sites). Sticky traps were attached directly to the bolts, whereas multiple funnel traps were ≈10 m away.

tles, ethanol is not the sole attractant, and the combination of ethanol with other host or insect produced attractants results in a myriad of responses from synergy to inhibition (e.g., Schroeder 1988, Byers 1992, Shore and Lindgren 1996, Miller and Rabaglia 2009).
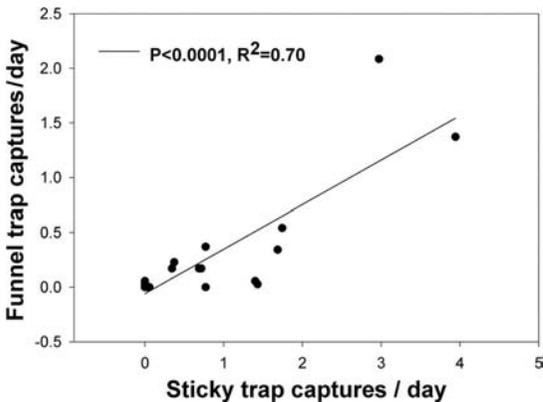

Fig. 3. Linear regression of the number of redbay ambrosia beetles captured per day in eight-unit multiple funnel traps baited with manuka oil and the number captured on white sticky traps attached to a bolt of redbay wood. Traps were 10 m apart.
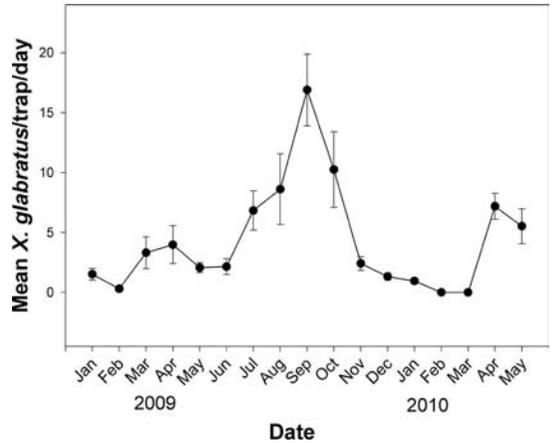

Fig. 4. Mean ± SE daily catch of redbay ambrosia beetles in six eight-unit multiple funnel traps baited with a single 50-mg/d manuka oil lure and deployed on Jekyll Island, GA, from January 2008 to May 2009. Traps were checked monthly and lures were replaced bimonthly.

In contrast to many other ambrosia beetles *X. glabratus* was not attracted to ethanol, which may explain why the infestation was so widespread before beetles were detected in alcohol baited monitoring traps at Port Wentworth near Savannah, GA. Ethanol and α-pinene are widely used as general attractants in detection traps for a wide variety of beetle species (Brockerhoff et al. 2006, Haack 2006, Lee et al. 2007, Miller and Rabaglia 2009). Currently, manuka oil baited traps seem to be fairly specific to *X. glabratus* in the southeastern United States because we rarely catch more than a few other scolytid beetle species and none in large numbers that would suggest attraction (J.L.H., unpublished data). However, because *X. glabratus* and laurel wilt may be a serious threat to avocado-growing regions and their potential to kill other trees in the Lauraceae is unknown, separate flight intercept traps baited with manuka oil may be warranted at ports of entry. In addition, tests of manuka oil and other lures in Asia and elsewhere would help determine how widely attractive it is to other potential forest pests and its potential utility in a broader trapping scheme.

X. glabratus showed no strong preference for trap color in our two trials and, in general, bark beetle responses to color vary widely. For example, Strom and Goyer (2001) found that white and yellow traps were less effective for capturing southern pine beetles, *Dendroctonus frontalis* Zimmermann, than black, blue, brown, gray, green, or red traps. Dubbel et al. (1985) tested colored flight intercept traps for the bark beetle *Ips typographus* (L.) and *T. lineatum* and found no difference in catch among clear, black, green, gray or redbrown traps, but white caught significantly fewer beetles. Abbasi et al. (2007) tested different color sticky traps for monitoring an ambrosia beetle in mango, *Mangifera indica* L., trees. They found green traps caught the most beetles, whereas yellow, blue, and red were the least effective. Black

and white traps performed equally well but did not catch as many as green traps. Cloclet da Silva et al. (2006) found green traps caught more coffee berry borers, *Hypothenenus hampei* (Ferrari), than transparent or red traps at their mid-level ethanol release rate but not at the high or low levels. Bark beetle response to color probably varies with species and may vary with trap location. For example, Niemeyer (1985) found that black traps in open areas with no trees nearby were more effective than white, possibly because in open areas black provided an optical aid for orientation.

A variety of studies have looked at the vertical distribution of bark and ambrosia beetles, and most are consistent with the results of the current study in suggesting scolytines are generally concentrated near the ground. In a recent comparison of beetles collected in unbaited flight intercept traps, for example, Ulyshen and Hanula (2007) found Scolytinae to be significantly more abundant and species rich at 0.5 m than at ≥15 m. Only genera known to attack small twigs and branches, such as *Pityophthorus*, were more common high in the canopy. Similarly, Chapman and Kinghorn (1958) captured much higher numbers of *T. lineatum* at 5 feet (1.5 m) than at 15 (4.6) or 25 feet (7.6 m) above ground, and Roling and Kearby (1975) reported that the majority of ambrosia beetles from several different species were capture in traps <3 m. Captures of *Xylosandrus germanus* (Blandford) were also highest in traps 0.5 m above ground compared with 1.7 or 5 m regardless of trapping location or year (Reding et al. 2010). However, *Xylosandrus crassiusculus* (Motschulsky) were not always captured in the low traps. This may be due to conditions in the trapping area. For example, Ulyshen et al. (2010) found that the presence of a heavy shrub layer resulted in more *X. crassiusculus* captures in unbaited traps above the shrub canopy at 5 m compared with those below the canopy at 0.5-m height. Clearly, most *X. glabratus* fly near the ground which makes monitoring or control efforts by using traps or lures easier. However, at least a few beetles flew at heights up to 15 m and those beetles also pose a threat to trees because only a single beetle is needed to inoculate a tree with the laurel wilt fungus. Whether those beetles were flying at those heights naturally or attracted to them by the manuka oil lures is unclear, but either way their presence in the canopy complicates control strategies such as trap out or attract and kill.

Funnel traps caught as many or more *X. glabratus* as sticky traps or cross-vane traps but not significantly more. Several studies have examined the effect of trap type on captures of ambrosia beetles (Lindgren et al. 1983, Flechtmann et al. 2000, Oliver et al. 2004), and in most cases, multiple funnel traps work as well or better than other trap types. Funnel traps are widely used in monitoring programs (Brockerhoff et al. 2006), commercially available, and easy to use. Although initially expensive, they are durable and are probably more cost effective than sticky traps in the long run.

Hanula and Sullivan (2008) demonstrated that manuka oil was as attractive as redbay wood alone. Although our tests of redbay wood with manuka oil cannot rule out additional attractants in redbay that do not also exist in manuka oil, they do demonstrate the importance of having the lure inside the funnels of multiple funnel traps. Redbay wood alone caught few beetles, even though we scraped bark from opposite sides of each redbay bolt so volatiles from the wood were eluted over their entire length and the wood was in direct contact with the edge of the funnels. This was probably due to the placement of the bolts outside of the trap rather than inside, like the manuka oil lure, because beetles attracted by the redbay wood could land on it without entering the trap.

The seasonal pattern of adult activity in this experiment (Fig. 4) was very similar to 2006 at Hunting Island State Park, SC (Hanula et al. 2008). In that study, *X. glabratus* also exhibited a single peak of activity in early September when traps were attached to dead or dying redbay trees. Traps baited with manuka oil caught beetles throughout the year, even in the coldest months when we caught at least one beetle each month.

Our results suggest a standard multiple funnel trap placed near the ground with a single commercially available manuka oil lure (50-mg/d release rate) attached near the middle of the trap should be highly effective at detecting redbay ambrosia beetles throughout the year, even when no infested trees are visible in the area. Multiple funnel traps baited with ethanol and α-pinene are already widely used in monitoring programs. Adding separate traps baited with manuka oil should improve detection of the redbay ambrosia beetle at ports-of-entry and decrease the likelihood of them becoming established before detection.

Acknowledgments

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