

Influence of Trap Distance From a Source Population and Multiple Traps on Captures and Attack Densities of the Redbay Ambrosia Beetle (Coleoptera: Curculionidae: Scolytinae)

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Abstract

The redbay ambrosia beetle, *Xyleborus glabratus* Eichhoff, is the principal vector of laurel wilt disease in North America. Lures incorporating essential oils of manuka plants (*Leptospermum scoparium* J. R. Forster & G. Forster) or cubeb seeds (*Piper cubeba* L.f.) are the most effective in-flight attractants to date. Using grids of traps baited with these essential oil lures, we evaluated 1) the effect of trap distance from a source beetle population on beetle captures, 2) the feasibility of trapping out low-density beetle populations, and 3) the effect of trap spacing on beetle captures. In the first experiment, increasing trap distance up to 300 m from a source *X. glabratus* population had little effect on beetle captures. In a second experiment conducted in a study area with very low beetle densities, trapping for 5 mo prior to deploying freshly cut, uninfested redbay bolts had no effect on subsequent attack densities. In a third experiment, numbers of *X. glabratus* captured in traps in the center of a grid of nine traps spaced 1 or 5 m apart were compared with lone baited or unbaited traps 30 m away. Relative to the more distant traps, the grid of baited traps neither increased captures in the unbaited center trap nor decreased captures in the baited center trap, regardless of spacing. The results suggest that the effective trapping distance of essential oil lures for *X. glabratus* is <1 m, and that newer, more attractive lures will be needed to be useful in managing *X. glabratus* populations.

Key words: laurel wilt, *Xyleborus glabratus*, trap efficiency, effective trapping distance, cubeb oil

Millions of redbay trees, *Persea borbonia* (L.) Sprengel, have been killed by the Asian redbay ambrosia beetle, *Xyleborus glabratus* Eichhoff, and its mycangial fungus, *Raffaelea lauricola* Harrington, Fraedrich, and Aghayeva, which causes laurel wilt disease in North America (Fraedrich et al. 2008, Harrington et al. 2008). Currently, laurel wilt and its insect vector are found from North Carolina to the southern tip of Florida and westward to Texas. In addition to redbay and other *Persea* species, *X. glabratus* and laurel wilt have been recovered from dying sassafras, *Sassafras albidum* (Nuttall) Nees (Riggins et al. 2011, Bates et al. 2013), and camphortrees, *Cinnamomum camphora* (L.) Presl (Smith et al. 2009a,b; Fraedrich et al. 2015), in forests. California bay laurel, *Umbellularia californica* (Hook. and Arn.), is also a suitable host for the beetle (Mayfield et al. 2013, Kendra et al. 2014b), and a variety of other Lauraceae are potential hosts based on laboratory trials (Fraedrich et al. 2011, Peña et al. 2012, Ploetz and Konkol 2013, Kendra et al. 2014b). Thus far, no viable control strategies have been developed.

Insecticides are ineffective and have short residual presence (Peña et al. 2011, Carrillo et al. 2013), and the fungicide propiconazole is effective for one year, but requires stem injections that are too expensive for use in forests (Mayfield et al. 2008a). Redbay ambrosia beetle can transmit laurel wilt to a healthy tree with as few as two attacks, and excluding beetles from the lower 3 m of the bole is inadequate to protect trees (Maner et al. 2013a), so highly effective whole tree treatments will be required. Even if effective insecticides can be found, frequent whole tree applications are not viable options for controlling this pest in forests where host tree densities can be >400 trees per hectare (Hanula et al. 2008, Evans et al. 2014, Cameron et al. 2015).

One option mentioned as a possible control strategy is use of attractants to remove the vector in “trap out” or “attract-and-kill” treatments, which have proven effective for some insects (Reddy and Guerrero 2010) including bark beetles. For example, Schlyter et al. (2001) reported successful reduction of tree mortality caused by *Ips*

duplicatus (Sahlberg) during 3 yr of mass trapping in a 2,000-ha spruce forest that was isolated from surrounding forest habitat. Likewise, Lindgren and Fraser (1994) reported successful mass trapping of two ambrosia beetles, *Trypodendron lineatum* (Olivier) and *Gnathotrichus sulcatus* (LeConte) over a 12-yr period at a log storage area. Both examples included pheromone-based lures, and reducing insect damage was possible with moderate population reductions. In contrast, extensive testing of mass trapping using pheromones combined with host attractants for elm bark beetles (*Scolytus multistriatus* (Marsham)), which like redbay ambrosia beetles vector a pathogen that kills trees, did not prove to be effective (Yonker 1990) even in isolated populations of host trees (Birch et al. 1981).

Redbay ambrosia beetles are atypical among *Xyleborini ambrosia* beetles in that they have a host range restricted to a few species and do not respond to ethanol as an attractant (Hanula et al. 2011, Kendra et al. 2014a, and Johnson et al. 2014). Hanula and Sullivan (2008) demonstrated that redbay trees contain volatile attractants and that essential oils extracted from manuka plants (*Leptospermum scoparium* J. R. Forster & G. Forster) and Brazilian walnut (*Ocotea porosa* (Nees & Martius) Barroso) were as attractive to beetles as small logs cut from healthy redbay trees.

More recently, bubble lures containing cubeb oil (from *Piper cubeba* L.f.) have also proven to be as attractive to redbay ambrosia beetle as manuka oil lures but longer lasting (Hanula et al. 2013, Kendra et al. 2014a). Hanula and Sullivan (2008) suggested that α -copaene was the primary attractant, and Kendra et al. (2014b) demonstrated that beetle antennae responded to it and eucalyptol, α -cubebene, α -humulene, and calamenene. Kuhns et al. (2014a) found eucalyptol was also attractive and elicited boring behavior in laboratory bioassays. In addition, Kuhns et al. (2014b) found that volatiles of the fungus, *R. lauricola*, were attractive and that they synergized attraction of manuka oil lures. Despite considerable work on host and fungal symbiont attractants, no one has demonstrated that lures based on essential oils are more attractive than redbay or swamp bay (*P. palustris* (Rafinesque) Sargent) wood, the most common, naturally occurring sources of olfactory attractants in coastal plain forests. Lures that are more attractive than host trees would be more likely to capture beetles before they attack host trees.

To implement control strategies based on use of essential oil lures like manuka oil or cubeb oil, it is important to understand the behavior of *X. glabratus* in response to these host odor cues. In addition, it is necessary to know if traps deployed in a forest can protect host material. Recently, Kendra et al. (2015a) demonstrated that sticky traps baited with fresh lures of either essential oil only caught 20–28 percent of the beetles released in an outdoor cage, and Cameron et al. (2015) caught no beetles in areas beyond the advancing front of laurel wilt (determined by the presence of dying trees) suggesting that these lures may be relatively short range attractants. To explore how redbay ambrosia beetles respond to lures in the field we: 1) deployed manuka oil-baited traps at varying distances from the edge of a source population to examine catch rates of *X. glabratus* in the absence of competing attractants from host trees; 2) placed traps in 2-ha forest plots with very low populations of *X. glabratus* to test whether they could capture enough beetles to reduce attacks on freshly cut, uninfested host logs; and 3) examined how trap spacing affected trap catches.

Materials and Methods

Trap Distance From a Source Population

The study area was near Oak Park, GA, ~128 km west of Savannah, GA, and contained a small creek with thousands of redbay trees

growing along it. At the time of the study, (August–November 2011) the redbay population was heavily infected with *R. lauricola*, and the trees were producing large numbers of beetles (Maner et al. 2013b). The experiment was conducted in a loblolly pine (*Pinus taeda* L.) plantation and an adjoining turkey oak (*Quercus laevis* Walter) forest adjacent to the infested drainage but with almost no redbay trees (Fig. 1). Prior to initiation of trapping, we surveyed the entire pine plantation and turkey oak forest and removed three infested trees (all <8 cm diameter at breast height [DBH]) so that at the time of the study there were no sources of redbay ambrosia beetles within ~200 m of the plot boundaries, except the source population along the drainage to the north of the plot (Fig. 1), and no live redbay trees >8 cm DBH. Within the uninfested forest, we laid out a grid of trapping positions in 5 rows spaced 30 m apart perpendicular to the edge of the infested drainage. Within each row, we established 10 trapping positions starting at 30 m from the edge of the infested area and then every 30 m to 300 m from the edge. At each trap position, a rope was tied between two trees so that the center of the traps were ~1.5 m above ground, the height at which most *X. glabratus* fly (Hanula et al. 2011, Brar et al. 2012).

Traps consisted of 8-unit Lindgren funnel traps with wet collection cups filled with 50% propylene glycol solution containing a drop of unscented liquid dish detergent to reduce surface tension. These traps are considered as good as or better than other trap types for capturing *X. glabratus* (Hanula et al. 2011, Brar et al. 2012), are commercially available, and easy to use. Traps were baited with full-size manuka oil lures (Synergy Semiochemicals Corporation, Burnaby, BC Canada) placed inside the center funnel of each trap. Lures were replaced every 2 wk when samples were collected. Trap distances from the infested area were varied every 2 wk in a series of four trials. In trial 1, traps were placed at 30, 150, and 300 m from the infested area. In trial 2, traps were positioned 30, 120, and 270 m from the edge. In trial 3, traps were placed at 30, 90, and 240 m. In trial 4, traps were placed at 30, 60, and 210 m from the infested area. In a fifth and final trial, traps were placed at every location within the grid (50 traps) and left for 28 d. After each trial, samples were sieved in the laboratory to remove insects, which were then air-dried prior to sorting and identification.

Trap Effects on Beetle Density

In 2012, we used grids of multiple funnel traps at Hunting Island State Park, SC, to determine if trapping *X. glabratus* in a forest could remove enough beetles to reduce the number of attacks on sections of redbay wood hung in the same plots. We selected Hunting Island because beetle populations had been monitored there since 2007, and population densities had declined from 32.8 ± 8.9 attacks/100 cm² of bark surface area during the peak of the infestation (Hanula et al. 2008) to <1 in 2011 (0.6 ± 0.24 attacks/100 cm²; Maner et al. 2014). In addition, suitable host trees had been virtually eliminated by laurel wilt by 2012, so natural host attraction sources were limited to seedlings and small saplings in the forest.

The study site was located on the southwestern portion of the island in maritime forest consisting of an overstory of mature slash (*Pinus elliotii* Engelman) and loblolly pine, a midstory of live oaks (*Quercus* spp.), and an understory of palmetto (*Sabal palmetto* (Walter) Loddiges). The site was bordered by a two lane road and salt marsh to the west, and salt marsh and tidal river to the south (Fig. 2). We established eight 2-ha plots in the forest along the road with ~50 m spacing between plots. At the time of plot establishment on 1 May 2012, we sampled five 0.04-ha subplots in each plot to determine the size and density of live redbay trees in the forest.

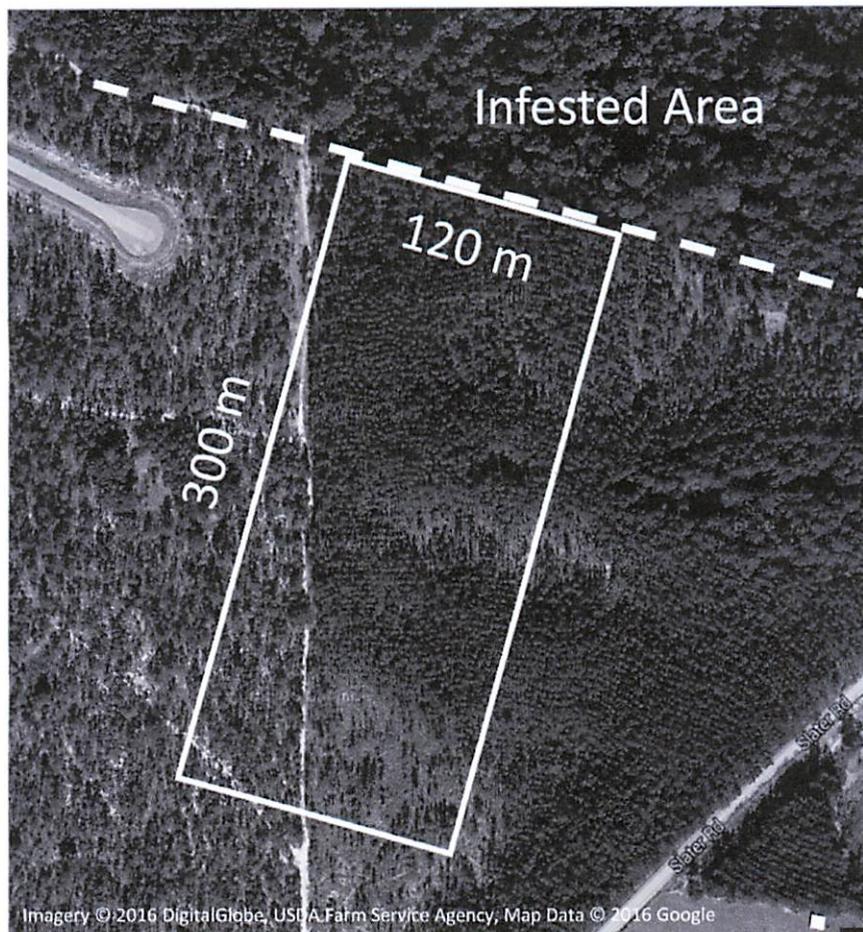


Fig. 1. Aerial view of a study location near Oak Park, GA, showing the location where a grid of traps (rectangle) was placed in a forested area without infested redbay trees adjacent to a heavily infested forest.

Subplots were located at plot centers and half the distance from the center and each corner. Within each subplot, we counted and measured the diameter (30 cm above ground) of all redbay trees or saplings that were at least 60 cm tall. Then, 9 funnel traps, suspended between two trees as before and baited with full-size manuka oil lures, were deployed in half of the plots and the other half had no traps (Fig. 2). Traps were hung in 3 rows of 3 traps (Fig. 2), were operated continuously from May to September, and samples were collected and lures replaced monthly during that time. Samples were sorted and all redbay ambrosia beetles were identified and counted. On 13 August, 5 bolts (small logs 8–12 cm diameter and 40–45 cm long) of freshly cut, uninfested redbay wood were hung in each plot with one near the plot center and the other four half the distance from plot center and the traps diagonal to it (Fig. 2). This insured that the redbay bolts were within the trap array. The bolts were hung from ropes between two trees, so they were 1.5–2 m above ground and above the level of the dense palmetto understory. Bolts were left in the plots until 11 September to allow ambrosia beetles to attack them. Timing of bolt exposure to attack coincided with peak seasonal emergence and flight activity of the beetle on Hunting Island (Hanula et al. 2008). Bolts were collected in September and returned to the laboratory where the bark was scraped from them and all *X. glabratus*-sized gallery entrance holes were counted (Hanula et al. 2008).

Trap Spacing

In 2015, an experiment was set up at Ochopee Dunes Natural Area near Swainsboro, GA, to test whether traps within close proximity to each other affected trap catches. The study area consisted of relict river dunes from the Ogeechee River that were covered by a sparse turkey oak and longleaf pine forest with no redbay or swampbay trees mixed in. The redbay occurred in the ecotone between the study area and the river floodplain forest so that the closest redbay tree to the study area was ~30–40 m. The forest was in the later stages of a laurel wilt epidemic, so redbay ambrosia beetle populations were low.

The experiment was a randomized complete block design consisting of five blocks spaced 100–200 m apart in a line paralleling the river in the turkey oak forest. Each block contained a grid of nine traps arranged in three rows of three traps each equally spaced within and between rows (Fig. 3). Two additional traps were located 30 m from the trap grid in opposite directions parallel to the river. One of these was baited and the other unbaited. In the first trial, traps within the grid were baited with one cubeb oil double bubble lure (product number 3087, Synergy Semiochemicals) hung inside the middle funnel, and the traps were spaced 1 m apart. The traps were deployed on 17 August 2015, and samples were collected 3 wk later on 8 September. At that time, a second trial was set up by moving the traps within the grid, so they were 5 m apart. Samples were collected at the end of the second trial (28 September), and a third



Fig. 2. Aerial view (left) of an *X. glabratus* trap out study on the south end of Hunting Island State Park, SC showing the location of 2-ha plots, and the arrangement (right) of traps and freshly cut redbay bolts within plots. Control plots had no traps.

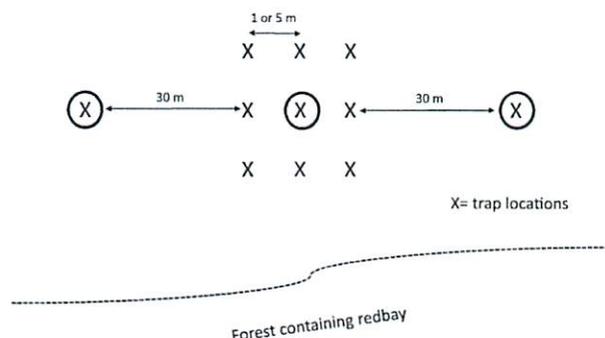
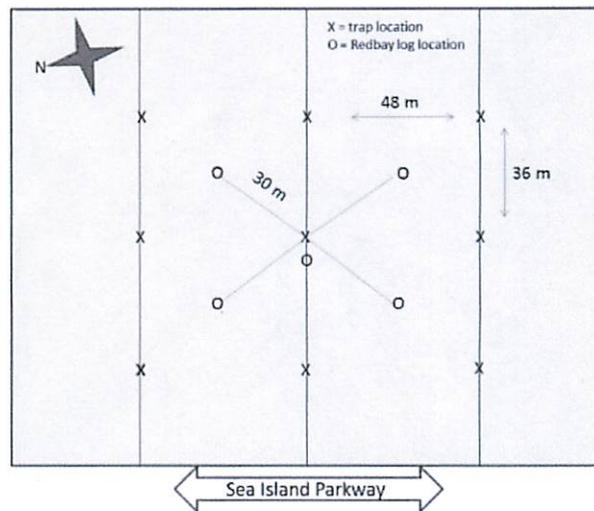


Fig. 3. Diagram of the trap arrangement in a trap-spacing study conducted on Ochoopee Dunes Natural Area near Kite, GA. One of the two traps away from the grid was baited with cubeb oil, and the other was unbaited. The center trap within the grid was either baited or unbaited, and the surrounding traps of the grid were always baited.

trial was set up, in which traps within the grid were returned to the same positions as the first trial (1 m spacing), but the center trap was removed and replaced with a new, unbaited trap. This was done to insure that no residual cubeb oil would be on the center trap. Baits in the remaining traps were replaced with new cubeb oil lures. Traps were left for 3 wk and collected on 19 October. In a final trial, the center trap was left unbaited, and the surrounding grid traps were moved to the 5 m spacing locations.

Statistical Analyses

Trap distance from a source population data was analyzed using two-way analysis of variance (ANOVA) with distance and replicates (rows) as the independent variables and beetle catch as the dependent variable using the general linear models procedure of SAS (Proc GLM; SAS Institute 2000). Data were log transformed when the Shapiro–Wilk test for normality (Proc Univariate; SAS 2000)

indicated they were not normally distributed. Means were separated using the Ryan–Einor–Gabriel–Welsch (REGWQ) multiple comparison test (Day and Quinn 1989) if the ANOVA indicated a significant difference.

Numbers of attacks on bolts of redbay wood were not normally distributed and data transformation did not correct the problem, so we used the nonparametric Wilcoxon two-sample test in the NPAR1WAY procedure of SAS to test for a treatment effect.

Each trial within the trap spacing experiment had four treatments consisting of the center trap of the grid, the average catch of the 8 traps surrounding the center trap, and the baited and unbaited traps 30 m from the grid. Data for trial 1 were normally distributed and were analyzed as a two-way ANOVA using the general linear models procedure of SAS (Proc GLM; SAS Institute 2000) with treatments and replicates as the independent variables and beetle catch as the dependent variable. In trials 2 and 3, data were square-root transformed to achieve normality and reduce heteroscedasticity prior to two-way analysis.

In trial 4, data were not normally distributed and transformation did not correct the problem, so trap catch data were nonparametrically ranked for analysis using the rank procedure of SAS. Mean separation was achieved with the REGWQ multiple comparison test.

Results

Trap Distance From a Source Population

Trap captures of *X. glabratus* were high throughout the study ranging from ca. 50–300 beetles/trap or 4–21 beetles/trap/d despite being located up to 300 m from infested trees. Trap distance from a source population of *X. glabratus* had little effect on the numbers of beetles captured. In trial 1, traps 300 m from the source caught fewer beetles than those at 30 and 150 m, but in trial 2, traps at 270 m caught the same number as those at 30 and 120 m (Fig. 4). In trial 3, traps at 240 m caught more beetles than those at 30 m, while in trial 4,

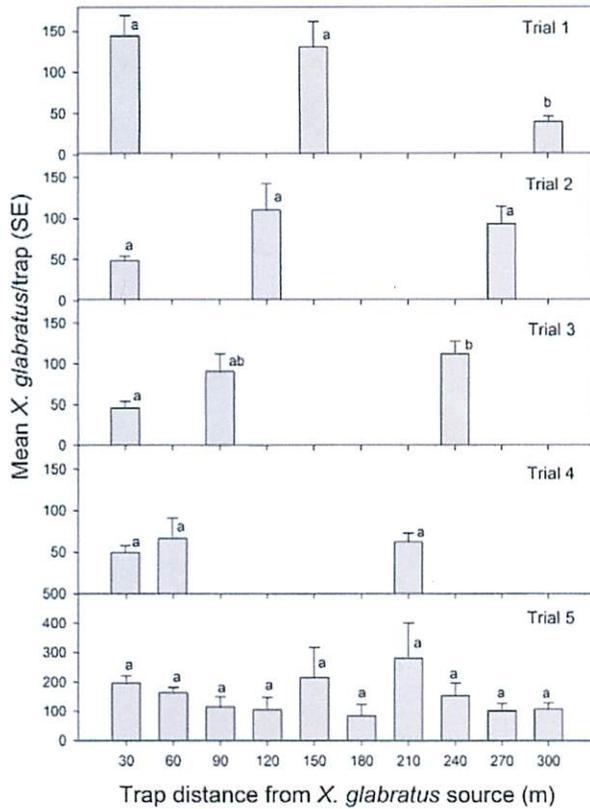


Fig. 4. The mean numbers of *X. glabratus* captured in 8-unit multiple funnel traps baited with manuka oil. Trials varied in the distance of traps from the edge of a high density source of *X. glabratus*. Within graphs, bars with the same letter are not significantly different ($\alpha = 0.05$).

traps at 30, 60, and 210 m caught similar numbers of *X. glabratus*. When traps were placed at all positions (trial 5) there were no significant differences in beetle captures regardless of distance from the source. Even traps at 300 m from the source population captured high numbers of beetles despite having 45 traps between them and the source of beetles. Likewise, captures in the middle of the grid (at 150 and 180 m) were not affected by being surrounded by similar traps. In addition, there were no significant row effects in any of the trials, suggesting that beetles were not approaching the trap grid from the east or west or, if they were, the traps did not affect their movement through the grid. When we plotted individual trap captures for the entire grid there was no apparent pattern (Fig. 5). Trap captures near the edge (30 and 60 m) of the infested area tended to be more consistent, with greater variability with increasing distance. The trap with the highest capture was 240 m from the edge, and the trap with the second highest capture was near the center of the grid (row 2, 150 m). There was no evidence that the center of the grid had lower captures or that captures declined with distance from the edge.

Trap Effects on Beetle Density

The numbers of redbay seedlings and saplings in the study area were high, averaging 546 per hectare (± 84.6 SE), but the average diameter was only 1.6 cm (± 0.14 SE), and the largest tree was 8.2 cm in diameter. The plots had an estimated 124 trees per hectare greater than 2.5 cm in diameter. During the survey, one tree (5.6 cm diameter) had signs of laurel wilt but no signs of active *X. glabratus* beetle boring. No active infested trees were observed in the general

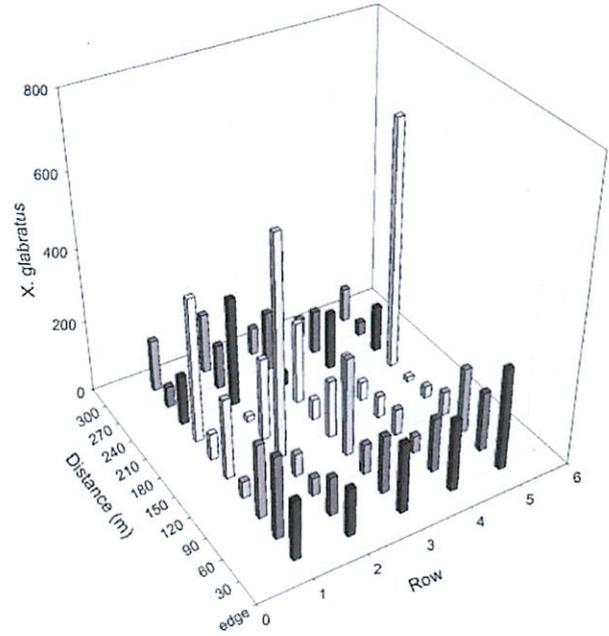


Fig. 5. Graph showing the number of *X. glabratus* captured in individual traps within a grid of traps, baited with fresh manuka oil lures, spaced 30 m apart, and varying in their distance from the edge of a high-density population of beetles.

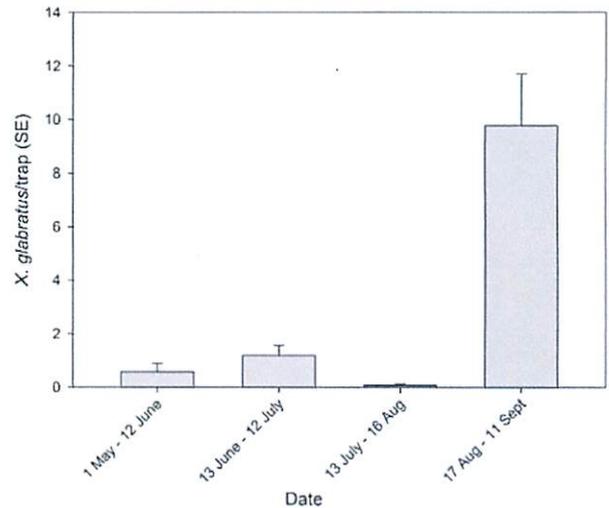


Fig. 6. Mean numbers of *X. glabratus* captured in 8-unit funnel traps baited with fresh manuka oil lures at the beginning of each trapping period in treated plots on Hunting Island State Park, SC, where traps were being used to remove beetles to reduce attack densities on host logs.

vicinity of the plots. Captures of *X. glabratus* were low throughout the study (Fig. 6) as expected based on the tree surveys and the infestation history of the study area (post laurel wilt epidemic). Traps captured < 1.2 beetles/trap/mo from May through mid-August but from 17 August to 11 September trap catch increased to nearly 10 beetles/trap or 0.39 beetles/trap/d (Fig. 6). Traps in the vicinity of redbay bolts had no effect ($Z = 0.433$; $P = 0.33$) on the numbers of *X. glabratus*-sized entrance holes in the bolts. There were an average of 10 ± 3.0 holes/plot (all bolts combined) on plots with traps and 11.8 ± 7.8 holes/plot on untreated control plots, resulting in densities of 0.15 ± 0.04 attacks/100 cm² of bark surface ($n = 20$) on

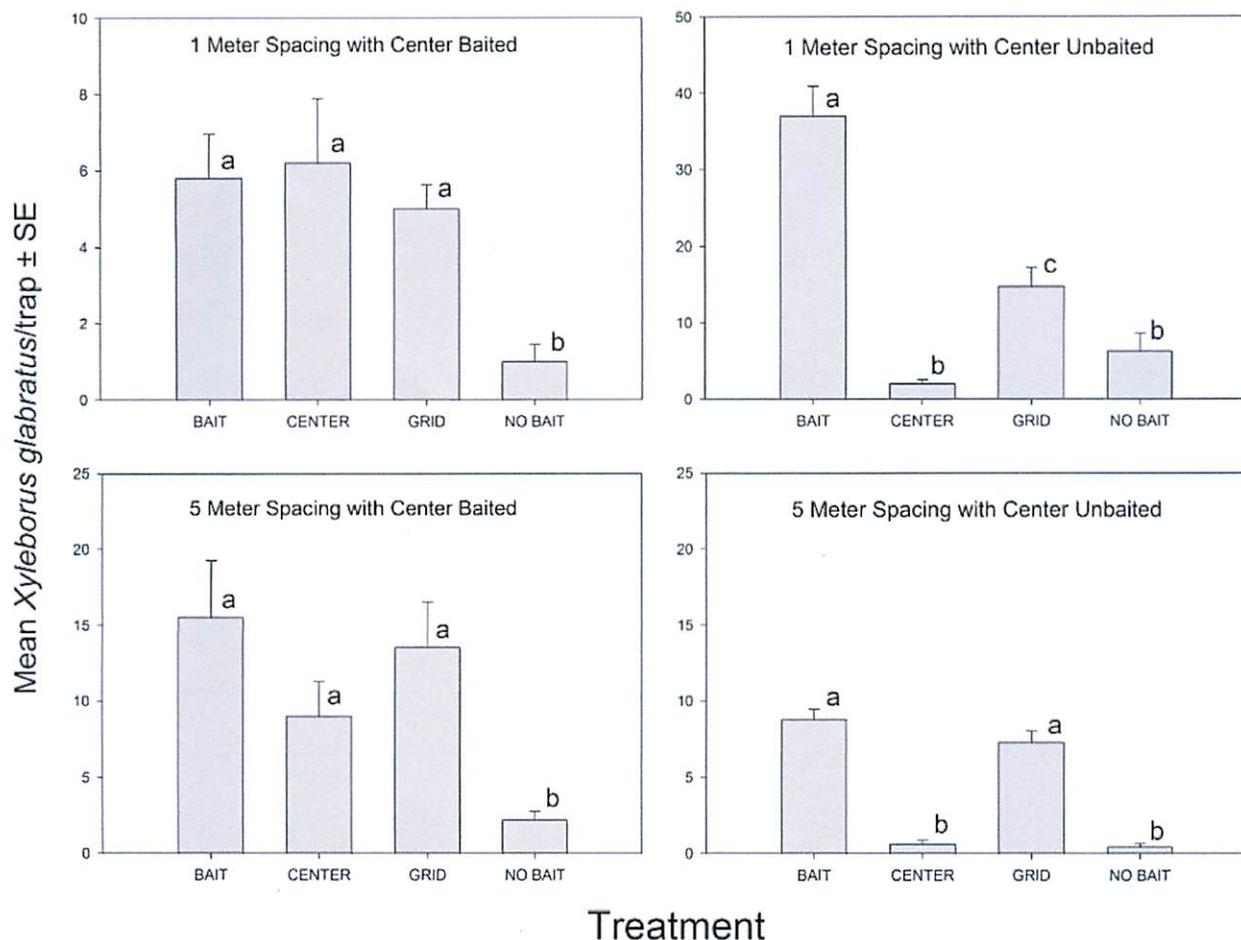


Fig. 7. Mean numbers of *X. glabratus* captured in 8-unit funnel traps baited with cubeb oil lures. Treatments were isolated traps with bait or without (no bait) 30 m from a grid of traps; center trap within a grid of 9 traps (center); and the average of the traps in the grid surrounding the center trap (grid). Trials varied in the spacing of traps within the grid, and whether the center trap of the grid was baited or not. Bars within graphs with the same letter are not significantly different ($\alpha = 0.5$).

treated plots and 0.16 ± 0.05 attacks/100 cm² ($n = 20$) on control plots. The center bolt was surrounded by traps and four other red-bay odor sources (bolts), so they should have received the maximum protection. When we compared attacks on center bolts only, bolts on plots with traps had 0.28 ± 0.07 attacks/100 cm², while only one center bolt on the control plots had attacks and the plot mean was 0.12 ± 0.12 attacks/100 cm².

Trap Spacing

In the first trial, the number of beetles captured in unbaited traps 30 m from the grid was significantly lower ($F_{3,12} = 4.72$, $P < 0.02$) than in the other treatments, and there was no difference in captures among baited traps (Fig. 7). Traps in the center of the grid surrounded by eight baited traps 1 m away caught approximately six beetles per trap, which was similar to the other baited traps in the grid and the isolated baited trap 30 m away.

During the second trial, when traps were spaced 5 m apart within the grid the traps captured more beetles overall but the results were similar. The baited traps in the center of the grid captured similar numbers of beetles as the average of traps surrounding it in the grid and the single baited trap 30 m away, but more than the unbaited trap 30 m away (Fig. 7).

In trial 3, the center unbaited traps caught fewer *X. glabratus* than the baited traps surrounding them even though those traps were only 1 m away. Unbaited traps away from the grid caught similar numbers of beetles as unbaited traps in the middle of the grid of baited traps and fewer beetles than baited traps in the grid or away from it. More beetles were captured in baited traps located away from the grid than in baited traps in the grid in trial 3.

Trial 4 was similar to trial 3 in that unbaited traps in the center of a grid of baited traps spaced 5 m apart caught the same number of beetles as unbaited traps 30 m away from the grid. Baited traps within the grid caught more than the unbaited center traps and the unbaited traps away from the grid, and the same numbers of beetles as baited traps 30 m from the trap grids.

Discussion

Large numbers of *X. glabratus* moved away from an area of high host tree availability and beetle activity into an area with almost no suitable host material consistently over a 2-mo period. Beetles were captured at least 300 m from the source without any decline in abundance from the edge of the infested area. We expected greater numbers of beetles captured closer to the infested area, with a gradient of beetle abundance declining as distance from the source increased.

For example, decreasing numbers of *Ips typographus* (L.) were captured in traps 50 to 500 m from releases of relatively small numbers of beetles (Zumr 1992, Zolubas and Byer 1995, Duelli et al. 1997), while Birch et al. (1981) found elm bark beetle captures declined as distance from the source (towns with numerous infested trees) increased up to 8 km from the nearest infested elm tree. Unlike most studies where relatively small numbers of beetles are released, our study was similar to Birch et al. (1981) in that we trapped near a heavily infested forest that was likely producing tens of thousands of beetles per day based on the number of infested trees, attack densities on them (Maner et al. 2013a), and numbers of beetles emerging per beetle gallery (Maner et al. 2013b). Thus, the 300 m distance we tested may have been too short for a gradient to be detectable in the presence of such high beetle numbers.

Manuka oil or similar essential oils are attractants comparable with wounded or fresh cut host trees (Hanula and Sullivan 2008, Hanula et al. 2011). In addition, black silhouettes of cylinders influence captures of beetles when essential oil lures are included (Mayfield and Brownie 2013) but unbaited multiple funnel traps, which also present a black silhouette to beetles, catch very few or no *X. glabratus* (e.g., Hanula and Sullivan 2008, Hanula et al. 2011). If unbaited traps or silhouettes are perceived by the beetles similar to nonhost trees, these previous studies indicate that *X. glabratus* do not readily land on a tree-like surface if there is no attractant eluting from it. If that is the case, then our results suggest *X. glabratus* flight through a forest is not guided by directed orientation to a host odor source and that they must be in close (<30 m, the distance between traps in our first experiment) proximity to a source of attraction before they respond with oriented flight to it.

Likewise, our second experiment resulted in no reduction in the numbers of *X. glabratus* attacks on freshly cut redbay bolts despite trapping in the area for almost 5 mo, which is consistent with the finding that traps within 30 m of each other do not affect trap captures. As no dead or dying redbay were evident in the study area, beetles captured in the traps were most likely flying through from other areas. Attack densities were 75% lower in 2012 than in 2011 (Maner et al. 2014). Despite the very low numbers of beetles in the area, small size of living host trees, and lack of dead or dying trees that might be producing competing host attractants, trap densities of nine traps per hectare were insufficient to reduce beetle attacks on host logs. Because *X. glabratus* densities were extremely low and there were no competing natural odor sources, essential oil-baited traps should have been at their maximum efficiency. Trapping at higher trap densities, and over longer periods and larger areas may be effective but most likely cost prohibitive.

Schlyter (1992) divided the movement of an insect before it reaches an attractant source into two parts, the first being undirected movement that is either completely random within a preferred habitat or by wind drift. The second is directed flight toward an odor source. Likewise, Kendra et al. (2014b) suggested that *X. glabratus* oriented to long-range attractant cues while in flight and then followed a series of cascading events resulting in host acceptance and boring behavior. Byers (2004) considered long-range to be attraction over 1 m or more and considered bark beetle attraction to a pheromone to be long-range. Vité and Gara (1962) found *Ips paraconfusus* Lanier were attracted from 15–30 m away from an infested log. Examples of pheromone response distances provided by Byers (2004) included 17 m for *I. paraconfusus* (Byers 1983) and 12 m for *Scolytus quadrispinosus* Say (Goeden and Norris 1964). Similarly, Byers (2004) reported observing *I. typographus* responding to an infested log as far as 50 m away and cited Jactel's (1991) work showing an estimated maximum attraction distance for *Ips sexdentatus*

(Boerner) of 80 m, the latter two examples presumably representing the outer limits of pheromone perception and response.

In our third experiment, we were interested in determining what constituted long-range attraction of *X. glabratus* to a host odor source. Essential oil lures for *X. glabratus* likely contain all the components necessary to illicit a landing response as sticky traps baited with them catch the same numbers of beetles as similar traps baited with fresh cut host wood, while unbaited traps or traps baited with nonhost wood perform poorly (Hanula and Sullivan 2008, Hanula et al. 2011, Kendra et al. 2014b). In our third experiment, baited and unbaited traps in the center of a grid of traps spaced 1 m apart were not affected by the surrounding traps showing that no interference among traps occurs even at this short distance and that oriented flight to an odor source was occurring at <0.5 m distance from it. It is possible that the grid of traps acted like a single large lure attracting beetles from the infested forest nearby but that seems unlikely, as surrounding traps failed to reduce the catch of baited center traps or increase the catch of unbaited center traps.

These results were not unexpected. For example, McMahan et al. (2010) studied trap-spacing effects using the bark beetle, *Ips pini* (Say). They found that traps containing "high activity" lures (pheromone at high release rates) had no effect on captures of traps containing "low activity" lures (low release rates) when spaced 15 m apart, but at 3 m, the high activity traps increased captures in the nearby low activity traps, indicating that response distance was between 3 and 15 m. In our third experiment, unbaited control traps were "low activity," presenting only silhouettes for attraction, but even when surrounded by "high activity" cubeb oil-baited traps they failed to catch more beetles than similar, isolated traps, 30 m away. These data indicate that "long-range" attraction to these essential oil lures was <1 m for *X. glabratus*.

Byers et al. (1989) presented the concept of effective attraction radius (EAR), which is the radius a passive sticky trap would need to be to intercept the same number of beetles as a smaller baited trap. The low numbers of beetles in the study area resulted in zero captures in unbaited traps in some replicates, so we used data from Hanula et al. (2013) where captures were higher, but the same lure and traps were used, to calculate the EAR of 8-unit funnel traps baited with cubeb oil for *X. glabratus*. The mean EAR was 0.84 m ($n=6$, SE=0.11). This low EAR is not unusual for bark beetles (Byers et al. 1989, Byers 1999, Schlyter 1992). Effective attraction radius is lure and trap dependent, so more attractive lures or more efficient traps would increase the value.

Studies thus far suggest more attractive lures are needed for them to be useful for management of *X. glabratus* populations. Improving lure quality likely means finding new attractants as increasing release rates of essential oils from 5 to 200 mg/day did not increase beetle captures in the field (Hanula and Sullivan 2008, Hanula et al. 2011). Cubeb oil is as effective as other essential oils tested (Hanula et al. 2013, Kendra et al. 2015a,b), but in field cage bioassays, traps baited with it only captured ~28% of the beetles released in small cages <2 m per side (Kendra et al. 2015a). Recently, Kendra et al. (2015b) reported capturing twice the number of beetles with lures containing 50% α -copaene compared with cubeb oil lures containing lower quantities of the same compound. Doubling the attractiveness of lures for *X. glabratus* is a big improvement but if that equates to a doubling of their attractive distance then our results suggest the lures still have a relatively short range. It is possible that other attractants might increase captures or influence response distances. For example, volatiles produced by *R. lauricola* increased trap captures when combined with manuka oil (Kuhns et al. 2014b). In other trials, eucalyptol elicited the highest response from

X. glabratus female antennae (Kendra et al. 2014b), and Kuhns et al. (2014a) reported it was as attractive as manuka oil in traps and elicited a beetle boring response in laboratory bioassays.

Byers (2004) considered long-range attraction of a bark beetle to host odors to be 1 m or more and summarized efforts to use bark beetle pheromones (longer-range attractants) in control strategies, showing that very few examples of successfully control have been reported. For attractants to be effective for control of *X. glabratus* in forests, longer-range attractants that catch a higher proportion of the population will be needed.

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