A Comparison of Trap Type and Height for Capturing Cerambycid Beetles (Coleoptera)

ELIZABETH E. GRAHAM,[1,2] THERESE M. POLAND,[3] DEBORAH G. MCCULLOUGH,[1,4] AND JOCELYN G. MILLAR[5]

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ABSTRACT Wood-boring beetles in the family Cerambycidae (Coleoptera) play important roles in many forest ecosystems. However, increasing numbers of invasive cerambycid species are transported to new countries by global commerce and threaten forest health in the United States and worldwide. Our goal was to identify effective detection tools for a broad array of cerambycid species by testing some known cerambycid attractants and a pheromone in different trap designs placed across a range of habitats. We compared numbers and species richness of cerambycid beetles captured with cross-vane panel traps and 12-unit Lindgren multiple-funnel traps, placed either at ground level (1.5 m high) or canopy level (≈3–10 m high), at eight sites classified as either residential, industrial, deciduous forest, or conifer forest. We captured 3,723 beetles representing 72 cerambycid species from 10 June to 15 July 2010. Species richness was highest for the subfamilies Cerambycinae and Lamiinae, which accounted for 33 and 46% of all species captured, respectively. Overall, the cross-vane panel traps captured ≈1.5 times more beetles than funnel traps. Twenty-one species were captured exclusively in traps at one height, either in the canopy or at ground level. More species were captured in hardwood sites (59 species) where a greater diversity of host material was available than in conifer (34 species), residential (41 species), or industrial (49) sites. Low numbers of beetles ($n < 5$) were recorded for 28 of the beetle species. The number of species captured per week ranged from 49 species on 21 June to 37 species on 12 July. Cross-vane panel traps installed across a vertical gradient should maximize the number of cerambycid species captured.

KEY WORDS Cerambycidae, wood-borer detection, trapping, monitoring, flight-intercept trap

Wood-boring beetles in the family Cerambycidae (Coleoptera) play important roles in many forest ecosystems. However, an increasing number of species are invading new countries via international commerce, and some of these exotic species threaten forest health in North America and globally (Paine et al. 1995, Nowak et al. 2001, Brockerhoff et al. 2006). At high densities, larvae of these beetles can damage and kill trees in natural forests, urban forests, plantations, and orchards, and degrade lumber by infesting saw logs (Solomon 1995, Allison et al. 2004). Nonnative cerambycids represent a substantial threat because they are easily transported as larvae or pupae within dunnage wood and other packing materials, and such materials have been identified as a major pathway for introducing exotic wood-borers (Brockerhoff et al. 2006, Haack 2006). In addition, both larvae and adult beetles can be found in firewood, nursery stock, and a variety of imported commodities (McCullough et al. 2006). Since 1985, at least five exotic cerambycid species have become established in the continental United States (Haack 2006), including a major pest, the Asian longhorned beetle, *Anoplophora glabripennis* (Motschulsky). Asian longhorned beetle and *Tetropium fuscum* (F.), a major pest of spruce trees (*Picea* spp.), have also become established in parts of Canada (Smith and Hurley 2000, Canadian Food Inspection Agency [CFIA] 2012).

Historically, detection and control methods for cerambycid beetles have been limited by our rudimentary knowledge of their host selection and mate finding mechanisms, which in turn has hindered the development of effective attractants and traps (Liebhold and Tobin 2008). This lack of proper monitoring tools for cerambycid beetles has increased the risk that nonnative species will become established or remain undetected until damage becomes obvious. The availability of effective trapping techniques for cerambycid beetles would facilitate an Early Detection Rapid Response (EDRR) program similar to the current program directed at bark and ambrosia beetles (Rabaglia 2008).

Substantial progress has been made in the identification of pheromones and related attractants for ce-

[1] Department of Entomology, Michigan State University, 1407 S. Harrison Road, Rm. 220, East Lansing, MI 48823.
[2] Corresponding author, e-mail: graha139@msu.edu.
[3] USDA Forest Service, East Lansing, MI 48823.
[4] Department of Forestry, Michigan State University, East Lansing, MI 48823.
[5] Department of Entomology, University of California, Riverside, CA 92521.

rambycid beetles over the past decade, with field bioassays of a library of cerambycid pheromones identifying likely attractants for several hundred species (Millar et al. 2009). It has become abundantly clear that the use of attractant pheromones in the family Cerambycidae is far more prevalent than was apparent from even quite recent reviews of cerambycid chemical ecology (Hanks 1999, Allison et al. 2004). The host volatiles, ethanol and α-pinene, have also been used to detect many conifer feeding species (Chénier and Philogène 1989, Sweeney et al. 2004, Miller 2006). Studies have demonstrated that intercept traps with a long vertical silhouette, such as commercially available Lindgren multiple-funnel traps and cross-vane panel traps, consistently capture cerambycids (McIntosh et al. 2001, Morewood et al. 2002, Sweeney et al. 2006, Nehme et al. 2009). Rapid advances in the identification of effective attractants for numerous species, including important invasive species, coupled with effective trap designs (de Groot and Nott 2001, McIntosh et al. 2001, Morewood et al. 2002, Graham et al. 2010), should provide the fundamental knowledge required to develop efficient detection and monitoring methods for a broad range of cerambycid species.

Attractant-baited traps can be used most effectively for surveillance if they are placed in environments that are most likely to harbor target species. In theory, the combination of trap design, lure, and trap placement that yields the greatest diversity of species should be most likely to capture an unknown, nonnative species. Exotic insects are more likely to arrive in cities than rural or natural settings because the cities provide egress to the invaders through commerce and travelers arriving at ports of entry (National Research Council [NRC] 2002, Liebhold et al. 2006, McCullough et al. 2006). Thus, traps placed in the vicinity of warehouses, pallet yards, and residential developments with numerous tree species may be most useful for early detection of newly introduced cerambycid species. Conversely, focusing trapping efforts in forested areas with abundant host material and potentially higher beetle densities may yield a more diverse assemblage of species. Cerambycid abundance and diversity also differs among specific regions of trees (Yanega 1996, Lingafelter 2007), but only a few studies have sampled beetles across a vertical gradient (Su and Woods 2001, Vance et al. 2003, Wermelinger et al. 2007).

The goal of this study was to identify an effective detection protocol for a broad range of cerambycid species by comparing: 1) commercially available trap types for capturing cerambycid species attracted to lures containing a pheromone and/or host volatiles; 2) the species composition captured in traps at the canopy and ground level; 3) whether the number of cerambycid species captured differs between urban, industrial, and forested habitats.

Materials and Methods

We sampled cerambycids using paired flight-intercept traps set at ground level ($\approx$1.5 m off the ground) or canopy level ($\approx$3–10 m off the ground) from 10 June to 16 July 2010, at eight different sites in Oakland, Ingham, and Kalamazoo counties, MI. Sites were classified as residential, industrial, deciduous forest, or conifer forest, with two replications of each site type (see Table 1 for detailed descriptions). Traps were located along a 250 m linear transect running along the edge of a wooded stand at each site. Fifteen variable-radius plots (10 factor prism) spaced 15–20 m apart were used to estimate total basal area (Grosenbaugh 1952). Diameter at breast height (dbh) was measured for the dominant tree species at each site. Weather data were acquired from the closest available weather station through the Michigan State University (MSU) Enviro-weather Automated Weather Station Network (MAWN; http://www.agweather.geo.msu.edu/mawn/mawn.html). The weather information for the two sites located at the W.K. Kellogg Experimental Forest (Kalamazoo County) was accessed through www.wunderground.com because it was not available on MAWN.

Insect Traps and Lures. We compared two types of traps at the two different heights to determine the most effective combination for capturing cerambycid beetles. Cross-vane panel traps (AlphaScents, Portland, OR; hereafter referred to as panel traps) and 12-unit Lindgren multiple-funnel traps (Contech Enterprises, Inc., Delta, British Columbia, Canada; hereafter referred to as funnel traps) were chosen because they are available commercially and widely used for cerambycid trapping (de Groot and Nott 2001, McIntosh et al. 2001, Morewood et al. 2002). Panel traps were modified to capture beetles alive by replacing the supplied collection basin with a plastic funnel that directed beetles into a plastic jar (see Graham et al. 2010). Funnel traps were fitted with dry collection cups with a screen on the bottom to drain precipitation to also capture beetles alive. We chose to capture the beetles alive so that we could return any species captured in large numbers to the site. Because we were comparing trap efficacy and not beetle response to synthetic lures we were not concerned that the live beetles might produce pheromone that could influence attraction to the lures. In a recent study, we found panel traps fitted with wet collection cups captured significantly more beetles than panel traps fitted with dry collection cups and funnel traps fitted with wet collection cups captured a similar number of beetles as funnel traps fitted with dry collection cups (Graham and Poland 2012). Therefore, any effect of pheromone produced by live beetles on trap capture should be negligible. All traps were treated with Fluon PTFE (AGC Chemicals Americas, Inc., Exton, PA), which renders the traps more slippery, thereby increasing beetle capture and retention (Graham et al. 2010). Fluon was applied to the panel traps with a paint roller and applied to funnel traps by dipping them into a bucket of Fluon until the surface was thoroughly coated.

Each site contained eight blocks of traps with each block comprised of four traps: a panel trap in the canopy, panel trap at ground level, funnel trap in the canopy, and funnel trap at ground level. Traps at ground level were positioned 1–2 m from the edge of the stand and sus-

Table 1. Detailed descriptions of the eight sites used in this study and total no. of cerambycid beetles and species captured

Name	Location	Site description and area	Basal area (mean ± SD m^2/ha)	Dominant overstory species	Mean ± SD max daily air temp (°C)	Mean ± SD max wind speed (kph)	Days with rain, amt (d, cm)[a]	Total no. of cerambycid species	Total no. of beetles
W.K. Kellogg Experimental Forest	Augusta, Kalamazoo County, MI	Deciduous Forest (288 ha)	25.4 ± 6.6	*Liriodendron tulipifera* L., *Acer rubrum* L., and *Carya glabra* (Mill.)	27 ± 3.0	24.2 ± 7.7	14, 5.2	39	475
Tollgate Education Center	Novi, Oakwood County, MI	Deciduous Forest (64.75 ha)	25.7 ± 6.8	*A. saccharum* Marsh, *Tilia americana* L. and *Quercus rubra* L.	27.7 ± 3.3	26.8 ± 7.9	12, 7.4	44	893
W.K. Kellogg Experimental Forest	Augusta, Kalamazoo County, MI	Coniferous Forest (1.25 ha)	27.6 ± 4.1	*Pinus resinosa* Aiton	27 ± 3.0	24.2 ± 7.7	14, 5.2	21	240
Lakeshore Park	Novi, Oakwood County, MI	Coniferous Forest (247 ha)	23.7 ± 4.9	*P. strobus* L., *P. resinosa*, and *P. banksiana* Lamb.	27.7 ± 3.3	26.8 ± 7.9	12, 7.4	28	224
Oakland County Industrial Site	Novi, Oakwood County, MI	Industrial Site (3 ha)	26.4 ± 11.7	*C. glabra*, *Q. rubra*, and *A. saccharum*	27.7 ± 3.3	26.8 ± 7.9	12, 7.4	41	400
Ingham County Industrial Site	Lansing, Ingham County, MI	Industrial Site (2.1 ha)	14.9 ± 7.4	*A. negundo* L., *Populus deltoids* Bartram ex Marsh, and *Ulmus americana* L.	27.4 ± 3.0	31.3 ± 9.6	10, 4.5	22	645
Ingham County Residential Site	East Lansing, Ingham County, MI	Residential Site (46.5 ha)	11.7 ± 6.5	*C. glabra*, *Q. rubra*, and *A. saccharum*	27.4 ± 3.0	31.3 ± 9.6	10, 4.5	31	641
Oakland County Residential Site	Novi, Oakland County, MI	Residential Site (3 ha)	26.9.7 ± 7.5	*A. saccharinum* L. and *U. americana*	27.7 ± 3.3	26.8 ± 7.9	12, 7.4	20	205

Deciduous Forest sites were forest stands with deciduous trees as the dominant species. Conifer Forest sites were forest stands with conifer trees as the dominant species. Industrial sites were wooded areas immediately adjacent to warehouses and industrial parks. Residential sites were wooded areas adjacent to newly developed housing or business complexes in residential areas.

[a] Refers to the no. of days with rainfall during the course of the study and the total amt of rainfall at each site.

pended from steel reinforcing bar poles at a height of ≈1.5 m with the bottom of the trap ≈0.5 m above ground. Canopy traps were suspended in the mid canopy of an adjacent tree (≈3–10 m high) using a rope launched over a branch with a Big-Shot line launcher (Sherrill Tree, Greensboro, NC). Traps were hung in a variety of species of trees, selecting the most conveniently located branches in trees along the edge of the stand. The traps were positioned away from the bole of the tree and hanging branches that may interfere with the trap. Traps at ground level and in the canopy were paired using the same trap type such that the canopy trap was suspended above the ground level trap of the same trap type. The type of trap at each paired trap location was randomly assigned within the block. Traps within a block were separated by a minimum of 15–20 m. The blocks were separated by 20 m. The positions of the traps were rotated within the block every 2 wk to control for any location effects.

Traps were baited with commercial lures containing the host volatiles α-pinene and ethanol (Contech Enterprises, Inc.), or the racemate of the known cerambycid pheromone 3-hydroxyhexan-2-one (referred to as 3R* from here on) (Hanks et al. 2007, Millar et al. 2009), synthesized from 1-hexyn-3-ol as described in Millar et al. (2009). Pheromone lures consisted of clear polyethylene sachets (press-seal bags, Cat. No. 01-816-1A, 5.1 × 7.6 cm, 0.05-mm wall thickness, Fisher, Pittsburg, PA) with a cotton wick inside (Richmond Dental, Charlotte, NC) to which 1 ml of a 5% solution of 3R* in ethanol was added. The 3R* lures had a release rate of 4.4 mg ± 1.6/d (mean ± SD) determined gravimetrically in the field during the course of the experiment. The α-pinene was emitted from a 15 ml polyethylene bottle with an estimated release rate of 150 mg/d and ethanol was emitted from ultra-high release plastic sleeves at an estimated release rate of 800 mg/d (release rates reported by the supplier). Pheromone lures were replaced every 2 wk and the host volatiles were replaced only if damaged or nearly empty.

To maximize the number of species captured at each site type, we selected lures likely to be most effective in the specific site. Therefore, the host volatiles ethanol and α-pinene, which are known to attract a number of conifer feeding species (Sweeney et al. 2004, Miller 2006), were used in conifer stands, and 3R* pheromone lures, which are known to attract many hardwood feeding species in the subfamily Cerambycinae, were used in deciduous stands. A combination of the host volatiles and the 3R* pheromone was used at the industrial and residential sites, where both conifer and deciduous trees were present and where the potential for nonnative species to be present seemed relatively high. Traps were emptied weekly, with all cerambycid beetles being removed, counted, and identified to species using keys in Lingafelter (2007) and Yanega (1996).

Statistical Analysis. Effects of trap type and height of the trap on the number of beetles captured per trap and the number of species captured per trap were tested with the generalized linear mixed model (PROC GLIMMIX; SAS Institute 2001) because assumptions of analysis of variance (ANOVA) were violated by heteroscedasticity (PROC UNIVARIATE; SAS Institute 2001, Sokal and Rohlf 1995). Trap type and height of the trap were tested as fixed effects with a total of four treatments: panel ground, panel canopy, funnel ground, and funnel canopy. The lures had a significant effect on the species captured; therefore, we did not pool the data for all trap catches but compared trap catches with the same lures at the different sites. The data were pooled for traps baited with the same lures (i.e., host volatiles, 3R*, or both) with block, date, and site included in the model and degrees of freedom were determined using the ddfm = KR method. The response distribution for comparing the numbers of beetles captured was specified as negative binomial with the link function set as log. The response distribution for comparing the number of species captured was specified as poisson with the link function set as log. Block and site were included as random effects. Differences in the numbers of beetles caught between the two trap heights were also tested with the generalized linear mixed model for the two most abundant beetle species. Data were pooled for trap type, site, date, and lure; however, any date/site/block combinations with <10 beetles were eliminated from the analysis. The response distribution for comparing the numbers of the abundant species captured was specified as negative binomial with the link function set as log. Block and site were included as random effects. The trap types and lures for the two most abundant species were pooled and we only compared trap height as a fixed effect. We tested differences between the four treatments in the proportion of beetles captured per subfamily using the *G* goodness-of-fit test (Sokal and Rohlf 1995).

Results

We captured 3,723 beetles representing 72 cerambycid species during the 33-d period that traps were deployed (Table 2). The most numerous species were in the subfamily Cerambycinae with *Neoclytus m. mucronatus* (F.) and *Xylotrechus colonus* (F.) being captured in the largest numbers and almost exclusively in traps baited with the 3R* pheromone (Table 2). *Astylopsis sexgutta* (Say) and *Monochamus carolinensis* (Olivier) were exclusively captured in traps baited with the host volatiles ethanol and α-pinene (Table 2). Both of these species are known to infest conifers (Lingafelter 2007). Traps baited with the 3R* pheromone captured 61 cerambycid species, traps baited with both the pheromone and the host volatiles captured 45 species, and traps baited with the host volatiles alone captured 32 species (Table 2). Low numbers of beetles ($n < 5$) were recorded for 28 of the species (Table 2). Only one nonnative species was collected, *Phymatodes testaceus* (L.), but this species is widely established in Michigan and parts of the United States (Lingafelter 2007). Ten species, represented by 36 specimens, were designated as "uncommon" or "rare" by Lingafelter (2007) (Table 2).

Table 2. Number of cerambycid species captured by trap type (panel or funnel), and height (ground level or in canopy) and proportion of each species attracted to the three lures (3R* pheromone, 3R* pheromone plus host volatiles (ethanol and α-pinene), and host volatiles alone) across all sites organized by subfamily and tribe

Subfamily/tribe	Species	Funnel Canopy	Funnel Ground	Panel Canopy	Panel Ground	% 3R*	%3R* + HV	% HV	Total
Aseminae									
Asemini	*Arhopalus rusticus* (L.)	3	4	3	5	0	20	80	15
Asemini	*Asemum striatum* (L.)	—	8	2	10	10	5	85	20
Cerambycinae									
Anaglyptini	*Cyrtophorus verrucosus* (Olivier)	5	9	7	12	78.79	18.18	3.03	33
Callidiini	*Phymatodes testaceus* (F.)[a]	2	1	2	3	87.50	12.50	0	8
Clytini	*Clytoleptus albofasciatus* (Castelnae & Gory)[b]	—	—	—	2	0	100	0	2
Clytini	*Clytus ruricola* (Olivier)	2	6	5	13	46.15	34.62	19.23	26
Clytini	*Megacyllene caryae* (Gahan)	—	—	1	1	100	0	0	2
Clytini	*Neoclytus a. acuminatus* (F.)	12	23	28	34	69.07	26.80	4.12	97
Clytini	*Neoclytus j. jouteli* Davis[b]	—	—	2	—	50	50	0	2
Clytini	*Neoclytus m. mucronatus*	339	292	618	427	63.90	36.10	0	1676
Clytini	*Neoclytus scutellaris* (Olivier)	1	1	6	3	81.82	18.18	0	11
Clytini	*Xylotrechus colonus* (F.)	37	134	117	365	75.65	23.58	0.77	653
Clytini	*Xylotrechus convergens* LeConte	1	—	—	1	100	0	0	2
Clytini	*Xylotrechus s. sagittatus* (Germar)	4	13	13	32	1.61	9.68	88.71	62
Elaphidiini	*Anelaphus pumilus* (Newman)	2	—	2	1	100	0	0	5
Elaphidiini	*Anelaphus villosus* (F.)	1	2	—	1	75	25	0	4
Elaphidiini	*Elaphidion mucronatum* (Say)	19	4	18	5	47.83	47.83	4.35	46
Elaphidiini	*Parelaphidion aspersum* (Haldeman)	13	3	15	2	57.58	42.42	0	33
Elaphidiini	*Parelaphidion incertum* (Newman)	12	—	8	3	52.17	43.48	4.35	23
Elaphidiini	*Psyrassa unicolor* (Randall)	2	1	1	1	60	40	0	5
Hesperophanini	*Hesperophanes pubescens* (Haldeman)[b]	1	—	—	—	100	0	0	1
Hesperophanini	*Tylonotus bimaculatus* Haldeman[b]	1	2	—	—	66.67	33.33	0	3
Ibidionini	*Heterachthes quadrimaculatus* Haldeman	2	—	—	—	100	0	0	2
Obriini	*Obrium maculatum* (Olivier)	2	1	2	—	60	40	0	5
Obriini	*Obrium rufulum* Gahan	1	—	1	—	100	0	0	2
Tillomorphini	*Euderces picipes* (F.)	15	40	15	46	71.55	25.86	2.59	116
Lamiinae									
Acanthocinini	*Acanthocinus obsoletus* (Olivier)[b]	1	1	1	1	25	25	50	4
Acanthocinini	*Acanthocinus pusillus* Kirby	6	6	17	22	13.73	0	86.27	51
Acanthocinini	*Astylopsis macula* (Say)	2	4	6	4	62.50	31.25	6.25	16
Acanthocinini	*Astylopsis sexguttata* (Say)	62	19	59	32	15.70	7.56	76.74	172
Acanthocinini	*Graphisurus despectus* (LeConte)[b,c]	5	5	5	3	88.89	11.11	0	18
Acanthocinini	*Graphisurus fasciatus* (DeGeer)[c]	12	10	12	13	44.68	6.38	48.94	47
Acanthocinini	*Hyperplatys aspersa* (Say)	—	—	1	3	0	100	0	4
Acanthocinini	*Leptostylus transversus* (Gyllenhal)	3	3	1	2	66.67	11.11	22.22	9
Acanthocinini	*Lepturges angulatus* (LeConte)	15	2	26	3	39.13	60.87	0	46
Acanthocinini	*Lepturges confluens* (Haldeman)	10	—	7	1	61.11	38.89	0	18
Acanthocinini	*Lepturges symmetricus* (Haldeman)[b]	—	—	1	—	100	0	0	1
Acanthocinini	*Sternidius alpha* (Say)[c]	39	7	50	22	52.54	46.61	0.85	118
Acanthocinini	*Sternidius variegatus* (Haldeman)	3	1	2	3	77.78	22.22	0	9
Acanthocinini	*Urgleptes querci* (Fitch)	7	15	5	8	71.43	17.14	11.43	35
Acanthoderini	*Aegomorphus modestus* (Gyllenhal)	1	6	6	4	76.47	17.65	5.88	17
Agapanthiini	*Hippopsis lemniscata* (F.)	—	1	—	6	85.71	14.29	0	7
Desmiphorini	*Eupogonius pauper* LeConte	3	5	10	16	32.35	23.53	44.12	34
Desmiphorini	*Eupogonius tomentosus* (Haldeman)	3	2	2	4	27.27	27.27	45.45	11
Dorcaschematini	*Dorcaschema cinereum* (Olivier)	13	8	10	5	69.44	30.56	0	36
Dorcaschematini	*Dorcaschema nigrum* (Say)	3	1	3	1	100	0	0	8
Monochamini	*Goes pulcher* (Haldeman)[b]	3	—	1	—	25	75	0	4
Monochamini	*Goes pulverulentus* (Haldeman)[b]	—	—	—	1	0	100	0	1
Monochamini	*Hebestola nebulosa* Haldeman[b]	—	1	—	—	0	0	100	1
Monochamini	*Microgoes oculatus* (LeConte)	—	—	—	3	0	0	100	3
Monochamini	*Monochamus carolinensis* (Olivier)	13	9	19	19	0	0	100	60
Monochamini	*Monochamus scutellatus* (Say)	2	1	7	4	0	0	100	14
Phytoeciini	*Oberea praelonga* Casey	—	—	—	1	100	0	0	1
Pogonocherini	*Pogonocherus mixtus* Haldeman	5	1	4	1	0	36.36	63.64	11
Saperdini	*Saperda discoidea* F.	1	—	2	—	100	0	0	3
Saperdini	*Saperda imitans* Felt & Joutel	—	—	1	1	100	0	0	2
Saperdini	*Saperda lateralis* F.	—	—	—	1	100	0	0	1
Saperdini	*Saperda tridentata* Olivier	—	—	4	2	100	0	0	6
Saperdini	*Saperda vestita* Say	1	—	—	1	100	0	0	2
Lepturinae									
Lepturini	*Acmeops proteus* (Kirby)	—	1	—	—	0	0	100	1
Lepturini	*Analeptura lineola* (Say)	—	1	—	—	100	0	0	1
Lepturini	*Bellamira scalaris* (Say)	3	—	4	6	46.15	30.77	23.08	13
Lepturini	*Brachyleptura champlaini* Casey	3	4	15	15	8.11	0	91.89	37
Lepturini	*Brachyleptura rubrica* (Say)	3	6	1	1	72.73	9.09	18.18	11

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Table 2. Continued

Subfamily/tribe	Species	Funnel Canopy	Funnel Ground	Panel Canopy	Panel Ground	% 3R*	%3R* + HV	% HV	Total
Lepturini	*Stictoleptura canadensis* (Olivier)	1	—	—	2	100	0	0	3
Lepturini	*Strangalia famelica solitaria* Haldeman	—	2	—	—	100	0	0	2
Lepturini	*Strangalia luteicornis* (F.)	—	1	1	—	100	0	0	2
Lepturini	*Trachysida aspersa brevifrons* (Howden)	1	—	—	—	0	100	0	1
Lepturini	*Trigonarthris proxima* (Say)	—	2	1	2	60	0	40	5
Lepturini	*Typocerus velutinus* (Olivier)	—	4	—	1	40	60	0	5
Parandrinae									
Parandrini	*Neandra brunnea* (F.)	1	6	—	2	44.44	33.33	22.22	9
Prioninae									
Prionini	*Orthosoma brunneum* (Forster)	—	7	—	2	100	0	0	9

[a] Species are classified as nonnative (Lingafelter 2007).
[b] Species are classified as rare or uncommon.
[c] Species names updated using Bousquet (2009).

The total number of beetles captured differed between trap types, regardless of the lures used and height of the trap (Fig. 1; $F_{3,\ 609} = 9.20$, $P < 0.0001$ for 3R*; $F_{3,\ 312} = 6.13$, $P = 0.0005$ for host volatiles; $F_{3,\ 306} = 6.10$, $P = 0.0005$ for both 3R* and host volatiles). Overall, panel traps captured ≈1.5 times more beetles than funnel traps. There was a significant difference in the average number of species captured per trap in traps baited with 3R* and the host volatiles. Panel traps at ground level captured on average significantly more species than the funnel traps in the canopy and the ground (Fig. 2; $F_{3,\ 532} = 4.61$, $P = 0.0034$ for 3R*; $F_{3,\ 301} = 4.46$, $P = 0.0044$ for host volatiles). Overall, the panel traps captured a total of 63 species and the funnel traps 61 species (Table 2). Eleven species (25 beetles) were captured exclusively in panel traps, whereas 9 species (13 beetles) were captured exclusively in funnel traps.

The height of the traps (i.e., ground level vs. canopy) did not affect the average number of beetles captured overall or the average number of species captured overall (Figs. 1 and 2, respectively). However, for some species, there were clear indications of height preferences. For example, 9 species (17 beetles) were captured exclusively in the canopy traps and 12 species (24 beetles) were captured exclusively in traps at ground level (Table 2). Furthermore, trap height affected the two species captured in greatest number ($F_{1,\ 932} = 6.74$, $P = 0.0096$ for *N. m. mucronatus;* $F_{1,\ 1066} = 73.7$, $P < 0.0001$ for *X. colonus*). Significantly more *N. m. mucronatus* were captured in canopy traps, whereas significantly more *X. colonus* were captured in traps at ground level (Table 2).

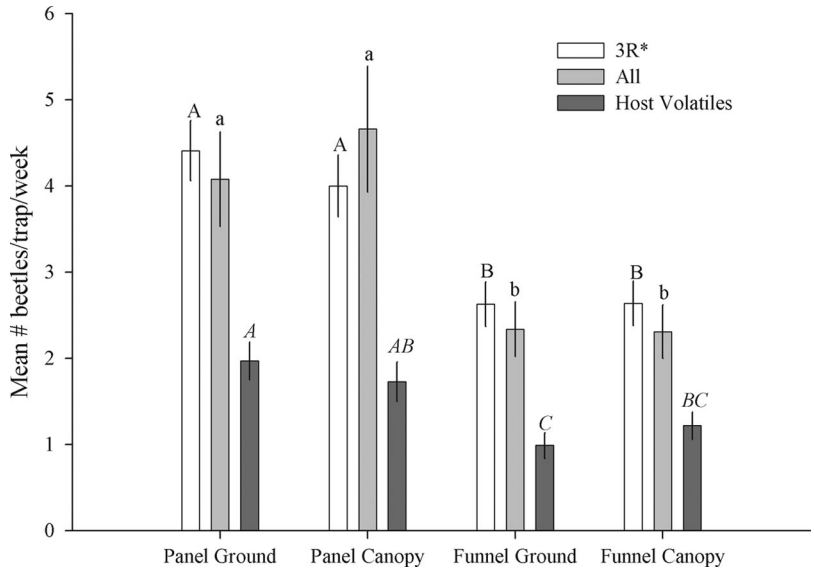

Fig. 1. Mean ± SEM number of cerambycid adults captured per trap type (panel or funnel), trap height (ground or canopy), and lure (host volatiles [$n = 316$], [3R*]-hydroxyhexan-2-one [$n = 640$], or both [$n = 320$]). Differences in treatment means were analyzed separately for each lure used, therefore they are designated differently. Traps baited with (3R*)-hydroxyhexan-2-one are designated with uppercase letters, and traps baited with both lures are designated with lowercase letters, traps baited with the host volatiles are designated with uppercase italics letters.

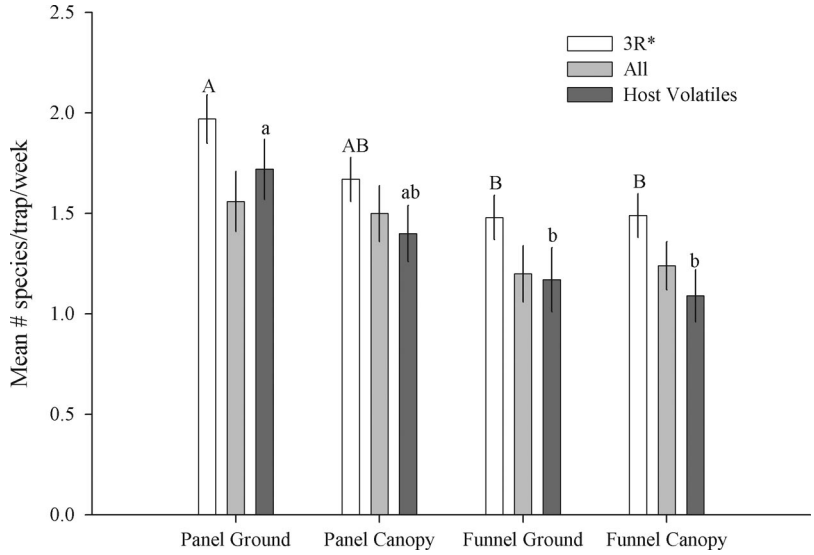

Fig. 2. Mean ± SEM number of cerambycid species captured per trap type (panel or funnel) and lure (host volatiles [$n = 316$], [3R*]-hydroxyhexan-2-one [$n = 640$], or both [$n = 320$]). Differences in treatment means were analyzed separately for each lure used, therefore they are designated differently. Traps baited with (3R*)-hydroxyhexan-2-one are designated with uppercase letters, and traps baited with the host volatiles are designated with lowercase letters.

The number of species captured differed among the trapping sites. More species were captured in hardwood sites (59 species) than in conifer (34 species), residential (41 species), or industrial sites (49). Traps at the two deciduous sites and one industrial site, located in Oakland County, caught the most species (Table 1) whereas traps at the Kellogg Experimental Forest and the other industrial site, located in Ingham County, captured the fewest. Captures peaked during the week of 21 Jun 2010 when the highest proportion (68%) and greatest number of species (49 species) were captured. Temperatures for the two preceding weeks averaged >20°C. The fewest species were caught during the week of 12 July 2010 (37 species).

The subfamilies Cerambycinae and Lamiinae were represented by the greatest number of species (Table 3). Panel traps at ground level and in the canopy captured the largest proportion of cerambycines (Table 3). Slightly more beetles in the subfamily Lamiinae were captured by traps in the canopy, where the largest proportion of beetles was captured (Table 3). We also captured beetles from four other subfamilies of Cerambycidae: Lepturinae, Aseminae, Parandrinae, and Prioninae. A goodness-of-fit test for the proportion of beetles in each subfamily captured per trap type was significant for all the subfamilies (G-test; $P < 0.05$).

Discussion

Trap design can have a major influence on the species and numbers of beetles that are captured and retained (e.g., Chénier and Philogène 1989, Dodds et al. 2010). Both funnel traps and panel traps present a vertical silhouette, but funnel traps have more surfaces on which beetles can alight, and more edges to which beetles can cling instead of falling into the collection cup. Overall, cross-vane panel traps were more effective than funnel traps at capturing cerambycid beetles in large numbers. However, funnel traps still captured a large number of beetles, so for practical purposes, either design would be satisfactory. Other factors, such as cost and durability/field longevity, also need to be factored into the decision as to which trap

Table 3. The total no. of beetles and species from the six subfamilies of Cerambycidae and the proportion of beetles and proportion of species captured in each trap type (panel or funnel) and height (ground level or in canopy) across all sites, summarized from Table 1

Subfamily	Total no. of beetles collected	Total no. of species collected	Panel ground	Panel canopy	Funnel ground	Funnel canopy
Cerambycinae	2,823	24	33.8%:76%	30.6%:72%	18.8%:60%	16.8%:88%
Lamiinae	762	35	24%:80%	34.5%:71.4	13.9%:60%	27.6%:68.6%
Lepturinae	81	11	33.3%:54.5%	27.2%:45.5%	25.9%:72.7%	13.6%:45.5%
Aseminae	33	2	36.4%:100%	12.1%:100%	42.4%:100%	9.1%:50%
Parandrinae	9	1	22.2%:100%	0:0	66.7%:100%	11.1%:100%
Prioninae	9	1	22.2%:100%	0:0	77.8%:100%	0:0

Data for each trap design are reported as percent of the total no. of beetles: percent of the total no. of species for each subfamily in each trap type. Some species were captured in more than one trap type; therefore, the proportion of species does not add up to 100.

type to use. Panel traps are easier to store when not in use and cost about half as much as funnel traps: $23.43 per panel trap versus $51.10 per funnel trap (Contech Enterprises, Inc.). Panel traps also require less Fluon for treatment: ≈37.8 ml undiluted per panel trap versus ≈100 ml undiluted per funnel trap, which adds an additional $4.50 per panel trap and $13.50 per funnel trap, based on current market prices. Our results also demonstrated the importance of trapping cerambycid beetles across a vertical gradient. It only takes ≈5–20 min to hang each canopy trap, versus ≈1 min to hang a panel trap on its reinforcing bar support at ground level. However, despite the extra time, the differences in species composition made the canopy traps worthwhile.

Larval and adult feeding habits may have affected whether beetles were captured in canopy or ground-level traps. For example, larvae of the prionine *O. brunneum*, a species captured exclusively in traps located at ground level, feed in rotting wood and the adults emerge from and remain associated with host material at ground level, providing a possible explanation for why no specimens were caught in the canopy. In contrast, many lamiine species are girdlers and/or chew on branches before laying their eggs (Yanega 1996) and most were captured by traps in the canopy. For example, the larvae of *Sternidius alpha* (Say) feed in branches of hardwood species and 75% of the beetles captured were in traps located in the canopy (Table 2; Yanega 1996). Furthermore, four of the 10 species designated as "rare" or "uncommon" (Lingafelter 2007) were captured exclusively in canopy traps. These species may truly be present only at low densities, but alternatively, their designation as rare or uncommon may simply reflect the fact that previous studies have primarily or exclusively sampled beetles at ground level. Improvements to trapping methods could change the status of these rare or uncommon species. Overall, our data suggest that to maximize the effectiveness of surveys, traps are needed in both the canopy and at ground level to capture species that specialize in different vertical strata and microhabitats.

Males of the two most abundant species captured in our study, *X. colonus* and *N. m. mucronatus*, produce aggregation pheromones that include (*R*)-3-hydroxyhexan-2-one as a major component (Lacey et al. 2007, 2009). Both sexes of these species were captured almost exclusively in traps baited with this compound. Although the two species share hosts and pheromone components, the majority of *X. colonus* were captured at ground level whereas most *N. m. mucronatus* were captured in the canopy. This evidence of resource partitioning suggests one mechanism by which the two species can share a pheromone component without substantial cross-attraction to heterospecifics.

Traps baited with the conifer host volatiles captured many conifer-feeding cerambycid species in the conifer stands. One species in the subfamily Lepturinae, *Brachyleptura champlaini* Casey, was captured in moderate numbers ($n = 37$) in conifer stands. The larvae of this species feed in *Pinus* and adults were captured almost exclusively at the coniferous forest sites in traps baited with the host volatiles. Similarly, the Asemines, *Arhopalus rusticus* (L.), and *Asemum striatum* (L.), and the three species of *Monochamus* (Lamiinae) were also captured exclusively at the coniferous forest sites. Conversely, the two most abundant hardwood-feeding species, *X. colonus* and *N. m. mucronatus*, were captured exclusively at sites with hardwood trees present.

On the logical assumption that the trap design, location, and site combination that captures the largest diversity of cerambycids is most likely to result in capture of a new invading species, then using cross-vane panel traps deployed at both the canopy and ground level appears to be the most effective method of surveillance. Whereas we captured the most species in forested areas with large amounts and diversity of host material, it is unclear whether newly introduced, nonnative cerambycids are more likely to become established in forested sites farther away from the likely points of entry, than in urban sites with transportation hubs. Installing traps in industrial areas, and particularly around airports, ports, or warehouses where shipping containers are opened, may facilitate early detection of recent immigrants before their populations build and spread into forests.

Many species in our study were represented by only a few individuals, but this was not unexpected given the limited number of attractants deployed. Conversely, the large number of species attracted to the single pheromone component, or the pheromone + host volatiles combination, demonstrates how broadly this pheromone may be shared among cerambycine species. There is no question that trapping with a larger number of known cerambycid pheromones will further increase the numbers of species and individuals caught, and the overall efficiency of surveys in sampling the resident cerambycid fauna. Sampling with a greater diversity of pheromone lures may also reveal more complex interactions. For example, we found that racemic 3-hydroxyhexan-2-one, which attracts many cerambycine species, may inhibit beetles from other subfamilies or even competing species in the same subfamily (E.E.G., unpublished data). This study and other recent studies (e.g., Hanks et al. 2007, Millar et al. 2009, Sweeney et al. 2010, Mitchell et al. 2011) demonstrate the wealth of chemical ecology to be found in the Cerambycidae, the richness and diversity of which has been recently studied. Our study also demonstrates that cerambycid chemical ecology can be readily exploited in the development of detection and monitoring methods for this large and important family of insects.

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