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Considering species richness and rarity when selecting optimal survey traps: comparisons of semiochemical baited flight intercept traps for Cerambycidae in eastern North America

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Abstract

1 We compared standard multiple-funnel, modified multiple-funnel, intercept panel and canopy malaise (SLAM) traps with top and bottom collecting cups for their effectiveness (species richness, rarity, abundance) at capturing Cerambycidae in eastern North America.

2 Experiments were conducted in New York, Louisiana, Massachusetts and Georgia in 2011 and 2012. A combination of pheromones and host volatiles chosen to match local forest types were used as lures.

3 Species richness tended to be higher in SLAM and modified funnel traps than standard funnel and intercept panel traps. SLAM traps also captured the highest number of species, unique species, rare (species accounting for ≤ 1% of total cerambycids at a site) and singleton species at each site.

4 Individual-based rarefaction and sample-based species accumulation curves suggested that SLAM traps are more effective for capturing cerambycid species. For many estimates, modified funnel and funnel traps were lower than SLAM traps but greater than intercept panel traps for describing cerambycid communities.

5 Modified funnel and SLAM traps generally captured the highest abundance of cerambycids but the response of the individual subfamily and species varied by trap type.

6 SLAM traps should be considered as a strong tool to describe cerambycid communities when used in conjunction with pheromones and host volatiles.

Keywords Cerambycidae, rarity, species estimation, species richness, survey, trapping, traps.

Introduction

Cerambycidae (Coleoptera) are an economically and ecologically important family of insects found in many parts of the world. Although native species can occasionally cause damage to trees or wood products (Gardiner, 1975; Post & Werner, 1988), invasive cerambycids have become increasingly problematic as a result of the expansion of global trade (Haack, 2006). The cryptic nature of cerambycids allows for easy transport in nursery stock, solid wood packing material and wood products. This behaviour, coupled with increased global trade linked to invasive species introductions (Vilà & Pujadas, 2001; McNeely, 2006; Lin *et al.*, 2007; Marini *et al.*, 2011), makes the likelihood of future introductions high.

Several species of cerambycids have been successful invaders of new environments where they have killed or damaged trees in urban and forest settings. The Asian longhorned beetle [*Anoplophora glabripennis* (Motschulsky)] has successfully established on hardwood trees in urban areas in North America and Europe (Haack *et al.*, 2010) and recently was documented in forested environments (Dodds & Orwig, 2011). *Tetropium fuscum* (F.) has successfully established in spruce forests in Nova Scotia, Canada, where it threatens stressed and weakened

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spruce (Flaherty *et al.*, 2011, 2013). *Phoracantha semipunctata* (F.) and *Phoracantha recurva* Newman have caused considerable damage to exotic eucalypts planted in California (Paine & Millar, 2002). In Europe, 19 exotic cerambycids have been detected, with two species established in natural environments (Cocquempot & Lindelöw, 2010). Five exotic cerambycid species have been found in Israel, with two species established (Friedman *et al.*, 2008). Although agreements are in place to minimize the global movement of organisms in wood products (FAO, 2002), it is likely that further introductions and subsequent detections of Cerambycidae will occur.

Invasive species garner attention from natural resource managers, although the majority of cerambycids are innocuous and only a few are considered pest species. Cerambycids play important ecological roles. Both adults and immature developmental stages are an important food source for wildlife (Linsley, 1959; Solomon, 1969; Hanks *et al.*, 1998), larval activity in downed wood is an important component of decay processes (Edmonds & Eglitis, 1989) and several cerambycid species have been suggested as indicator species for biological diversity assessments (Nilsson *et al.*, 2001). Some species alter their habitat and influence the saproxylic community present in trees (Buse *et al.*, 2008).

The goals of specific trapping efforts can include: (i) detection of invasive species; (ii) description of arboreal insect communities; and (iii) detection of endangered or red-listed species. Regardless of the goal of survey efforts, it is critical that optimal trapping methodologies are employed to ensure survey success. Various trap types exist for trapping wood-inhabiting insects, although few have been tested in terms of community level sampling of cerambycids. Traps commonly deployed for large-scale exotic species surveys (Brockerhoff *et al.*, 2006; Rabaglia *et al.*, 2008), such as funnel and intercept panel traps, have become the *de facto* traps for monitoring cerambycids, with a few studies comparing the two trap types for effectiveness for specific species (Graham *et al.*, 2012; Miller *et al.*, 2013). Other trap types have been used to capture cerambycids (Vance *et al.*, 2003; Bouget *et al.*, 2009; Dodds *et al.*, 2010), although comparisons of community-level estimates among trap types are currently lacking.

Two factors that are especially relevant for community-level trapping efforts are total species richness and rare species captured. Tools used to assess species richness, such as taxon sampling curves (Gotelli & Colwell, 2001) and nonparametric richness estimators (Chao, 1984, 2005), could be helpful in assessing trap efficacy. Although not generally used in this manner, these tools are valuable because they focus on measuring or predicting the number of species in a given habitat or, in this case, a trap type. The number of species captured is a particularly important variable when comparing traps used in exotic species surveys because a trap catching the most species is more important to these surveys than a trap catching high abundance of fewer species.

Cerambycids respond to semiochemicals including host volatiles and bark beetle pheromones (Chenier & Philogene, 1989; Allison *et al.*, 2001, 2004; Miller, 2006; Miller *et al.*, 2011). Recent advancements in cerambycid pheromone identifications provide new opportunities to use new compounds in conjunction with other semiochemicals to further test trap types (Silk *et al.*, 2007; Mitchell *et al.*, 2011; Hanks *et al.*, 2012). The present study aimed to test trap types in four eastern North American forests to determine optimal traps for sampling cerambycid communities.

Materials and methods

Four sites were used to assess response of flying cerambycids to trap types. Sampling occurred in 2011 in the Finger Lakes Region of New York on the Arnot Experimental Forest and in central Louisiana on the Kisatchie National Forest. In 2012, sampling occurred in Brimfield State Forest in southwestern Massachusetts and the Scull Shoals Experimental Forest in central Georgia. Each site was sampled for only one season. Aerial canopy malaise traps (SLAM, MegaView Science, Taiwan), 10-unit modified funnels (Miller *et al.*, 2013) and intercept panel traps (APTIV Inc., Portland, Oregon) were tested at each site (Fig. 1). Standard 12-unit funnel traps (Contech Enterprises, Canada; Synergy Semiochemicals, Canada) were also tested in Massachusetts and Georgia. Modified funnel traps had the

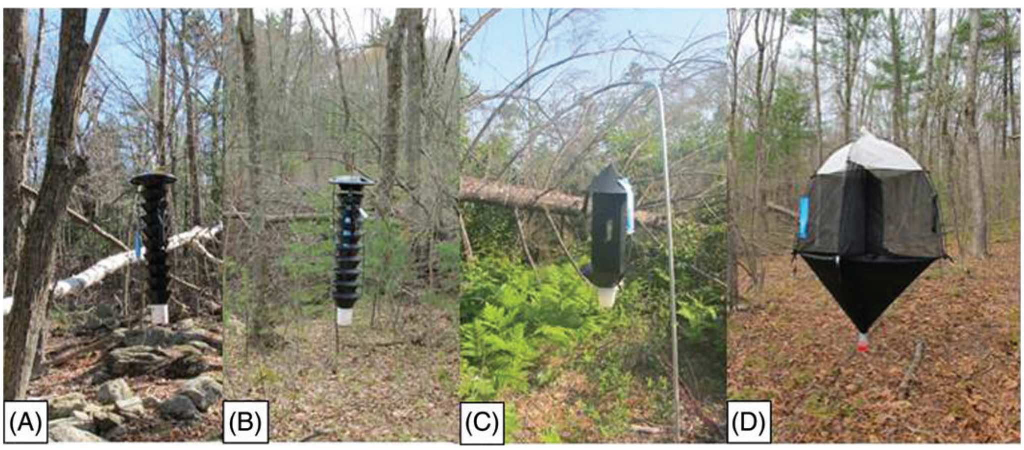

Figure 1 Standard multiple-funnel (A), modified funnel (B), intercept panel (C) and SLAM traps (D) used to survey Cerambycidae in eastern North America. This version of the SLAM trap has a top and bottom collecting cup.

bottom diameter of each funnel expanded from 5 to 12 cm and the lowest funnel where cups attach from 5 to 7.5 cm (Miller *et al.*, 2013). The estimated trapping surface area of each trap was 3.2 m^2 for SLAM; 0.46 m^2 for 10-unit modified funnel; 0.71 m^2 for intercept panel; and 0.56 m^2 for standard funnel. Trapping surface area estimates for SLAM and intercept panel traps only included the vertical surface area and not the tops or bottoms of traps.

Lures

Lure components were selected for each site based on regional fauna and forest type in an attempt to optimize the number of cerambycid species collected. A mix of host volatiles and cerambycid pheromones were always used, and, in one location (Massachusetts), a racemic ipsenol bubblecap lure (Contech Enterprises, released at approximately 0.2 mg/day) was added as a kairomone for cerambycids (Billings & Cameron, 1984; Miller *et al.*, 2011; Allison *et al.*, 2013). For cerambycid pheromones, racemic 3-hydroxy-2-hexanone (hereafter referred to as hydroxyketone) was purchased from Bedoukian Research Inc. (Danbury, Connecticut) and a racemic blend of 2*R*, 3*R*-2,3-hexane diols (hereafter referred to as *R*R**-hexane diols) were synthesized at Atlantic Forestry Centre (Canada) and both chemicals were loaded into release devices at Contech Enterprises. Both the hydroxyketone and *R*R**-hexanediols have been shown to attract a number of cerambycid species (Hanks & Millar, 2013). All traps at every site were baited with an ultra-high release (UHR) ethanol pouch (150 mL; Contech Enterprises) and a hydroxyketone lure (1400 mg; Contech Enterprises), with release rates of approximately 0.6 g/day and 20 mg/day, respectively, at 20 °C. These were the only compounds used to bait traps in New York. UHR α-pinene pouches (200 mL; Contech Enterprises) with a release rate of approximately 2 g/day were used in Louisiana and Massachusetts, and a lure that emitted *R*R*-hexanediols at 1–2 mg/day (150 mg; Contech Enterprises) was used in Georgia. All traps within a site were baited with identical compounds.

Trapping protocols

At all sites except Georgia, the intercept panel and funnel traps were treated with sprayable Teflon Non-stick Dry-film Lubricant (Dupont, Wilmington, Deleware) once at the beginning of the experiment (Allison *et al.*, 2011). Traps were either suspended from rope tied between trees (> 1 m from each tree) or hung from conduit poles so that collecting cups were approximately 0.5 m above the ground. At each site, treatments were replicated 10 times in a randomized complete block design, with at least 15 m spacing between traps and 30 m spacing between blocks. Collecting cups contained propylene glycol (Prestone® RV antifreeze, FRAM Group, Lake Forest, Illinois; or Splash RV & Marine Antifreeze, Fox Packaging Inc., St Paul, Minnesota) to capture and preserve insects. Propylene glycol and captured insects were filtered through paper paint filters, labeled, placed in plastic sample bags and frozen until processed. Cerambycids were sorted from each sample and identified to species in accordance with Lingafelter (2007). Voucher specimens from all sites were deposited in the Forest Insect Collection at the U.S. Forest Service Durham Field Office.

New York: Arnot Experimental Forest

Replicates were split evenly between an *Acer saccharum* Marsh. stand and a mixed-hardwood stand. The *A. saccharum* stand was managed for maple syrup production and contained few other tree species in the overstory. Stand management practices resulted in limited coarse woody debris present throughout the stand. The mixed hardwood stand was also *A. saccharum* dominated but with *Fagus grandifolia* Ehrh., *Prunus serotina* Ehrh., *Tilia americana* L., *Acer rubrum* L., *Quercus rubra* L. and *Fraxinus americana* L. present in the overstory. The mixed hardwood stand was recently thinned and significant coarse woody debris was left on site. This included tops of trees and large diameter lower bole portions. The *A. saccharum* and mixed-hardwood stands were separated by approximately 1.25 km of contiguous forest.

Three trap types were set up 7 July and run to 13 October 2011: (i) top and bottom collecting SLAM; (ii) intercept panel trap; and (iii) 10-unit modified multiple-funnel trap. Each SLAM trap had a collecting cup attached to the top of traps to catch insects that moved upward and a bottom collecting cup that was attached to a nylon or mesh funnel hooked onto the upper trap frame (Fig. 1D). Ethanol lures were changed monthly and the hydroxyketone lures were changed after 8 weeks.

Louisiana: Kisatchie National Forest

A mixed-pine stand on the Kisatchie National Forest was used to test trap types in Louisiana. The stand was dominated by *Pinus palustris* Mill., *Pinus echinata* Mill. and *Pinus taeda* L., with limited *Quercus falcata* Michx. and *Nyssa sylvatica* Marsh. present in the overstory. The stand was managed with prescribed fire on a 3–5-year rotation. Few intermediate or overtopped trees were present as a result of the prescribed fire. Coarse woody debris was also limited by the high frequency of fire in the stand.

The same trap types tested in New York were also deployed in Louisiana except the SLAM traps did not have the optional bottom collecting apparatus and only captured insects in the top collecting cup. All traps were baited with an UHR ethanol pouch, α-pinene pouch and a hydroxyketone lure. Traps were set up 24 June and run to 20 October 2011. Lures were changed every 4–6 weeks.

Massachusetts: Brimfield State Forest

In June, 2011 an EF3 tornado impacted a 63-km long swath of western Massachusetts. Portions of Brimfield State Forest and an adjacent property managed by the U.S. Army Corp of Engineers were within the tornado path and suffered significant damage to some forested areas. The forested area within the tornado path was severely impacted, with most trees snapped, twisted or blown over. Several forest types had formerly covered this area, although the majority of stands were mixed hardwood, with *Pinus* L. spp. and *Tsuga canadensis* (L.) Carr present at lower densities. Hardwood tree species present included *F. americana*, *Quercus* L. spp., *Betula* L. spp. and *Acer* L. spp. The majority of overstory trees throughout the tornado path were destroyed and downed material remained on site. Forests adjacent to the tornado path varied from unaffected to limited damage (scattered trees down, damaged crowns) present.

Trap types tested in Massachusetts included: (i) top and bottom collecting SLAM; (ii) intercept panel; (iii) 10-unit modified funnel; and (iv) standard 12-unit multiple-funnel. Traps were baited with UHR ethanol and α-pinene lures, ipsenol and the hydroxyketone. α-Pinene and ethanol were changed every 4 weeks, ipsenol lures every 6 weeks, and the hydroxyketone lure every 8 weeks. Insects were collected from 19 June to 16 October 2012 with all samples pooled for analysis. Ten replicates of the four trap types were split evenly between the tornado blow down and adjacent intact forests.

Georgia: Oconee National Forest

Two mixed-pine hardwood stands on the Scull Shoals Experimental Forest in Oconee National Forest in Oglethorpe County were used to test trap types in Georgia. The stands were dominated by *P. taeda* and *P. echinata*, with *Quercus alba* L. and *Q. falcata* also common in the stands. *Carya tomentosa* (Poir.) Nutt. and *Liquidambar styraciflua* L. were present in low numbers throughout the stands. These stands experienced an early spring fire several months before sampling that resulted in low levels of downed wood. The two trapping sites were approximately 1 km apart, separated by contiguous forest of the same composition.

Traps tested in Georgia included: (i) top collecting SLAM; (ii) intercept panel; (iii) 10-unit modified funnel; and (iv) standard 12-unit multiple-funnel. Intercept panel traps were obtained from Contech Enterprises. Intercept panel, modified funnel and standard funnel traps were not treated with Teflon in Georgia. Traps were baited with two UHR ethanol lures, and one lure each of hydroxyketone and *R*R**-hexanediols. The hydroxyketone and hexanediol lures were replaced once after 3 weeks. Insects were collected from 12 July to 20 August 2012. Ten replicates of the four trap types were set up in two stands.

Statistical analysis

Trap catches from each site were pooled over the entirety of the trapping period for all analyses. Species for which more than 50 specimens were captured were analyzed separately. Total cerambycids, species richness and individual species comparisons were analyzed using a generalized linear mixed model (PROC GLIMMIX, version 9.3; SAS Institute, Cary, North Carolina) via maximum likelihood estimation with replicates as blocks. Replicates were random factors and trap types were fixed effects in each model. Data were modelled using the negative binomial function with log link. Tukey's honestly significant difference test was used to compare differences in catches among the trap types.

Trap collections by trap type were pooled for the entire sampling period for all species richness estimates. Individual based rarefaction, Chao 1 nonparametric abundance-based species richness estimators and species accumulation curves were used to investigate species richness. Rarefaction curves calculate the number of species detected per number of specimens collected and allow comparison of treatments (i.e. trap types) that may contain different numbers of specimens (Magurran, 2004; Olszewski, 2004; Buddle *et al.*, 2005). Individual based rarefaction curves were calculated for trap types using PAST (Hammer *et al.*, 2001). Chao 1 nonparametric abundance-based species richness estimates (Chao, 1984, 2005) were calculated using SPADE (Chao & Shen, 2010). These estimates use the ratio of singletons to doubletons to estimate the number of missing species. Finally, species accumulation curves were used to investigate the cumulative number of species captured during the sampling periods. Species accumulation curves were created using SDR IV (Seaby & Henderson, 2006). One hundred randomizations of data were performed for each curve to counter the effect of capture rate and order (Colwell & Coddington, 1994). Rarefaction and species accumulation curves were not calculated for traps from Georgia because the collection period was much shorter than those used at the other sites.

Because of the interest in rare species and the possibility that rarity could also represent the establishment phase of an invading population, special consideration was paid to assessing how effective traps were at capturing rare species. Two approaches were taken to investigate rare species. First, a species was considered rare when it tallied ≤ 1% of total trap catches at a site (Maurer & McGill, 2011). To determine this subset, a species list with abundances was generated for the site by combining all trap collections together. Any species representing ≤ 1% of the total abundance were then defined as rare. The percentage of singletons by trap type at each site was also investigated. Singletons are commonly considered to represent rare species in community level sampling (Novotný & Basset, 2000). These definitions of rarity pertain to trap catches only and do not necessarily correspond to rarity in a natural habitat.

Results

New York

In the deciduous forest sampled in New York, 1439 cerambycid specimens were captured from 35 species. Two species, *Neoclytus mucronatus* (F.) and *Xylotrechus colonus* F., accounted for 67% of the captured cerambycids. Nineteen (54%) species were captured less than five times, whereas nine (26%) were captured only once. Twenty-four species accounting for only 6.3% of total cerambycids captured were categorized as rare species.

SLAM traps captured more total species and unique species than other trap types (Table 1), although mean species richness did not differ significantly among trap types ($F_{2,18} = 2.1$; $P = 0.16$). SLAM traps captured 71% of the rare species, with intercept panel (50%) and modified funnel (46%) traps capturing fewer (Fig. 2A). This same pattern was found for singletons, where SLAM traps captured 66% of singletons, with intercept panel (22%) and modified funnel (11%) traps capturing fewer (Fig. 2B).

Individual-based rarefaction curves suggested that SLAM traps detected more species per number of individuals collected than did other trap types (Fig. 3A). This occurred even though

Table 1 Species richness and abundance (mean ± SE) of cerambycids captured in three trap types in New York

Variable	Modified funnel	Intercept panel	SLAM
Mean number of species (NS)	10.3 ± 1.2	7.6 ± 1.0	9.5 ± 1.2
Species richness	22	23	28
Unique species	3	3	7
Chao 1 estimate	22.8 ± 1.4	26.0 ± 3.4	39.0 ± 8.9
Abundance	616	478	345
Mean number of Cerambycidae	59.4 ± 8.6[a]	43.9 ± 6.4[ab]	32.5 ± 4.9[b]
Cerambycinae	53.4 ± 7.6[a]	41.3 ± 6.0[a]	25.0 ± 3.8[b]
Clytus ruricola (NS)	3.1 ± 0.6	2.4 ± 0.5	3.1 ± 0.6
Neoclytus mucronatus	17.8 ± 2.8[a]	14.3 ± 2.3[a]	8.0 ± 1.4[b]
Phymatodes aereus	2.7 ± 0.9[a]	2.9 ± 1.0[a]	0.4 ± 0.2[b]
Xylotrechus colonus	21.4 ± 4.5[a]	17.3 ± 3.7[ab]	11.0 ± 2.4[b]
Lamiinae	5.3 ± 1.1[a]	1.9 ± 0.5[b]	7.1 ± 1.4[a]

Means followed by the same superscript letter within a row are not significantly different (Tukey's HSD, $P > 0.05$). NS denotes comparisons that were not significantly different.

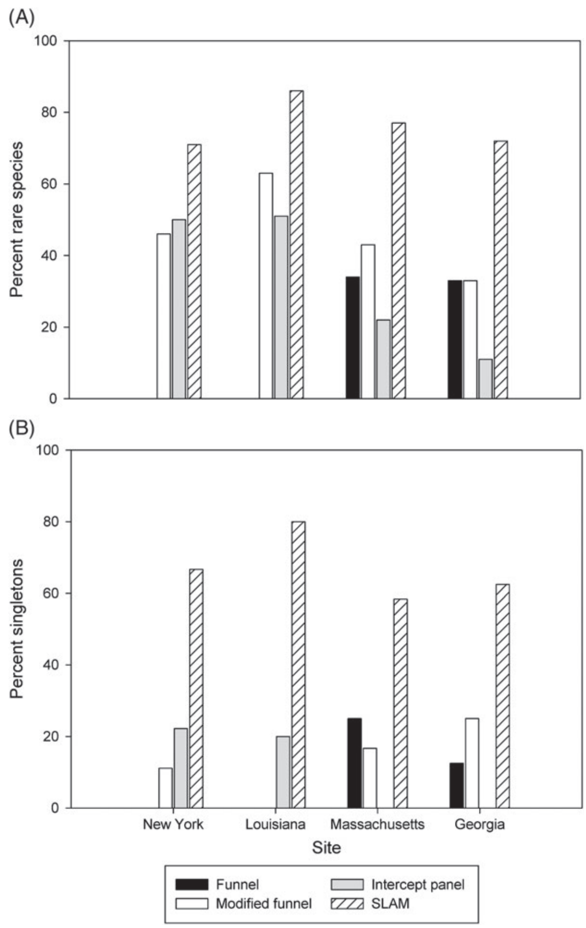

Figure 2 The percentage of (A) rare species and (B) singletons captured by trap type in New York, Louisiana, Massachusetts and Georgia.

SLAM traps captured the fewest specimens. SLAM traps similarly detected more species per trapping effort than did modified funnel or intercept panel traps (Fig. 4A). Chao 1 estimates of total cerambycid species richness were highest for SLAM traps followed by intercept panel and modified funnel (Table 1).

There were significant differences in the mean number of cerambycids captured in the three trap types ($F_{2,18} = 9.14$; $P = 0.002$) (Table 1). Modified funnel traps captured more cerambycids than SLAM traps, although neither trap was different from intercept panel traps. There were significant differences in subfamily response to trap types. Cerambycinae captures were significantly higher in modified funnel and intercept panels than SLAM traps ($F_{2,18} = 14.45$; $P < 0.001$) (Table 1). More Lamiinae were captured in modified funnel and SLAM traps than intercept panel traps ($F_{2,18} = 7.57$; $P = 0.004$) (Table 1).

Most cerambycid species varied in response to trap type as well. Modified funnel and intercept panel traps generally captured the highest number of individual species, including *N. mucronatus* ($F_{2,18} = 7.29$; $P = 0.005$), *Phymatodes aereus* (Newman) ($F_{2,18} = 7.74$; $P = 0.004$) and *X. colonus* ($F_{2,18} = 4.77$; $P = 0.022$) (Table 1). The lone exception of those statistically tested was *Clytus ruricola* (Olivier) where no differences in response to trap type ($F_{2,18} = 0.47$; $P = 0.63$) were found (Table 1).

Louisiana

In Louisiana, 7768 cerambycid specimens from 42 species were captured. Four species from two genera, *Neoclytus scutellaris* (Olivier), *N. mucronatus*, *Xylotrechus sagittatus* (Germar) and *X. colonus* accounted for 88% of all cerambycids captured. Sixteen species (38%) were captured five or fewer times, whereas five (12%) were captured only once. Thirty-five species accounting for only 5% of total catches were categorized as rare species.

SLAM traps captured more total species and unique species than did modified funnel or intercept panel traps (Table 2). However, no significant differences in the mean number of cerambycid species captured in trap types was found ($F_{2,18} = 1.8$; $P = 0.2$) (Table 2). The percentage of rare species captured was greatest for SLAM traps (86%), followed by modified funnel (63%) and intercept panel traps (51%) (Fig. 2A). Only SLAM traps (80%) and intercept panel traps (20%) captured singletons in Louisiana (Fig. 2B).

As in New York, rarefaction curves indicated that SLAM traps detected more species per number of specimens collected

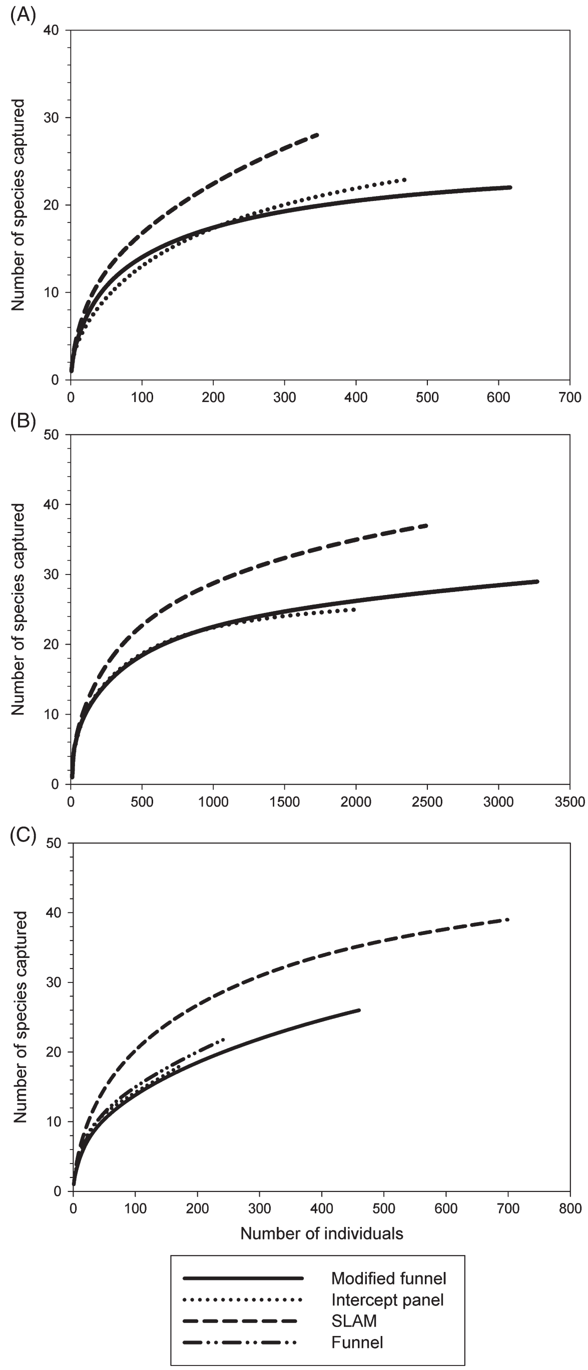

Figure 3 Individual based rarefaction curves for (A) New York, (B) Louisiana and (C) Massachusetts.

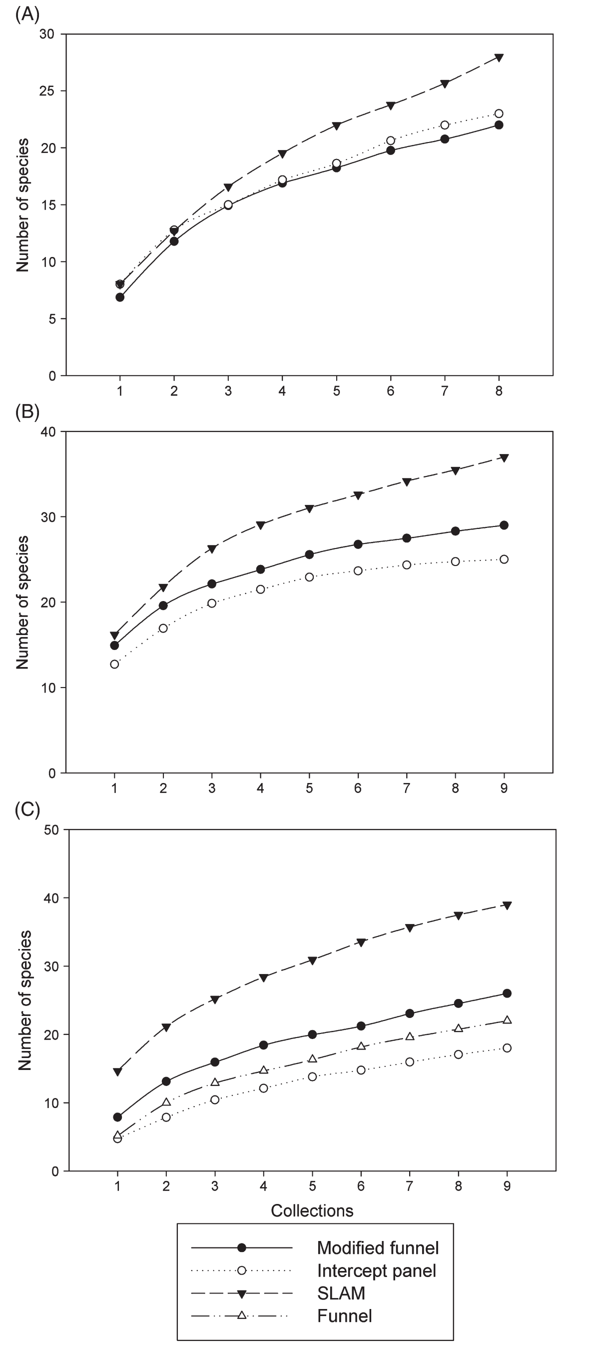

Figure 4 Species accumulation curves for (A) New York, (B) Louisiana and (C) Massachusetts.

than did the other trap types (Fig. 3B). Similarly, SLAM traps detected more species per trapping effort than the other trap types (Fig. 4B). Chao 1 estimates of total cerambycid species richness were also highest for SLAM traps, with modified funnel and intercept panel traps predicted to capture fewer species (Table 2).

Modified funnel traps captured higher mean number of cerambycids than intercept panel traps ($F_{2,18} = 7.15$; $P = 0.005$) (Table 2). There were no significant differences in the mean number of cerambycids captured between SLAM traps and intercept panel or modified funnel traps. Trap catches were generally higher in modified funnel and SLAM traps compared with intercept panel traps for Lamiinae ($F_{2,18} = 6.61$; $P = 0.007$) and Cerambycinae ($F_{2,18} = 7.20$; $P = 0.005$) (Table 2).

The relative performance of the different traps in terms of mean number of individuals captured per trap varied among species (Table 2). No differences in mean catches among the three traps

Table 2 Species richness, and abundance (mean ± SE) of cerambycids captured in three trap types in Louisiana

Variable	Modified funnel	Intercept panel	SLAM
Mean number of species (NS)	15.3 ± 1.2	13.2 ± 1.1	16.4 ± 1.3
Species richness	29	25	37
Unique species	1	1	11
Chao 1 estimate	34.0 ± 5.5	26.0 ± 1.8	43.0 ± 5.4
Abundance	3276	2000	2492
Mean number of Cerambycidae	318.1 ± 37.0[a]	194.3 ± 22.8[b]	240.2 ± 28.1[ab]
Cerambycinae	302.7 ± 36.1[a]	183.4 ± 22.0[b]	225.2 ± 26.9[ab]
Elaphidion mucronatum (NS)	8.9 ± 1.7	6.6 ± 1.3	6.4 ± 1.3
Knulliana cincta	13.4 ± 2.4[a]	2.7 ± 0.7[b]	1.8 ± 0.5[b]
Neoclytus mucronatus	81.1 ± 9.1[a]	47.5 ± 5.5[b]	36.7 ± 4.4[b]
Neoclytus scutellaris	123.7 ± 20.1[a]	65.1 ± 10.7[b]	134.4 ± 21.9[a]
Xylotrechus colonus	8.7 ± 1.9[b]	4.7 ± 1.1[b]	18.6 ± 3.7[a]
Xylotrechus sagittatus	62.0 ± 8.2[a]	53.6 ± 7.2[a]	17.7 ± 2.6[b]
Lamiinae	10.0 ± 1.6[ab]	6.1 ± 1.1[b]	13.8 ± 2.1[a]
Acanthocinus obsoletus (NS)	3.8 ± 0.9	2.9 ± 0.7	4.4 ± 1.0

Means followed by the same superscript letter within a row are not significantly different (Tukey's HSD, $P > 0.05$). NS denotes comparisons that were not significantly different.

Table 3 Species richness, and abundance (mean ± SE) of cerambycids captured in four trap types in Massachusetts

Variable	Modified funnel	Funnel	Intercept panel	SLAM
Mean number of species	17.2 ± 1.9[b]	12.2 ± 1.5[bc]	10.1 ± 1.3[c]	28.1 ± 2.8[a]
Species richness	26	22	18	39
Unique species	3	3	0	13
Chao 1 estimate	33.5 ± 6.4	37.0 ± 12.9	54.0 ± 25.6	48.0 ± 8.1
Abundance	460	247	172	699
Mean number of Cerambycidae	42.9 ± 8.6[ab]	23.9 ± 4.9[bc]	15.6 ± 3.3[c]	61.3 ± 12.1[a]
Cerambycinae	32.3 ± 7.7[ab]	18.4 ± 4.5[bc]	10.9 ± 2.7[c]	37.8 ± 9.0[a]
Neoclytus mucronatus	21.7 ± 5.2[a]	12.7 ± 3.1[ab]	7.0 ± 1.8[b]	16.8 ± 4.1[a]
Neoclytus scutellaris	3.1 ± 1.5[ab]	1.3 ± 0.7[bc]	0.9 ± 0.5[c]	8.2 ± 3.7[a]
Xylotrechus colonus	2.3 ± 0.5[ab]	1.1 ± 0.3[b]	1.6 ± 0.4[ab]	3.5 ± 0.7[a]
Xylotrechus sagittatus (NS)	2.7 ± 0.8	1.8 ± 0.6	1.0 ± 0.4	1.4 ± 0.5
Lamiinae	7.2 ± 1.6[b]	3.4 ± 0.9[b]	3.9 ± 1.0[b]	21.3 ± 4.3[a]
Astylopsis sexguttata	2.8 ± 0.7[ab]	0.9 ± 0.3[b]	1.3 ± 0.4[b]	4.0 ± 1.0[a]
Monochamus carolinensis (NS)	1.4 ± 0.6	0.9 ± 0.4	0.7 ± 0.3	0.9 ± 0.4
Urographis fasciatus	0.5 ± 0.3[b]	0.2 ± 0.2[b]	0.4 ± 0.3[b]	3.9 ± 1.9[a]

Means followed by the same superscript letter within a row are not significantly different (Tukey's HSD, $P > 0.05$). NS denotes comparisons that were not significantly different.

were found for *Acanthocinus obsoletus* (Olivier) ($F_{2,18} = 1.08$; $P = 0.36$) and *Elaphidion mucronatum* (Say) ($F_{2,18} = 1.06$; $P = 0.36$). Modified funnel traps captured more *Knulliana cincta* (Drury) ($F_{2,18} = 26.37$; $P < 0.0001$) and *N. mucronatus* ($F_{2,18} = 16.52$; $P < 0.0001$) than either intercept panel or SLAM traps. More *X. colonus* ($F_{2,18} = 17.42$; $P < 0.0001$) were captured in SLAM traps than the other two trap types. The opposite was true, however, for *X. sagittatus* ($F_{2,18} = 27.58$; $P < 0.0001$) where more were captured in modified funnel and intercept panel traps compared with SLAM traps. *Neoclytus scutellaris* was captured at higher numbers in modified funnel and SLAM traps compared with intercept panel traps ($F_{2,18} = 10.58$; $P < 0.001$).

Massachusetts

In Massachusetts, a total of 1578 cerambycid specimens from 47 species were captured. *Neoclytus mucronatus* and *N. scutellaris* accounted for 58% of the cerambycids captured. Other common species included *Monochamus carolinensis* (Olivier) (3.9%), *Astylopsis sexguttata* (Say) (6.1%) and *A. obsoletus* (2.4%). Twenty-six (55.3%) species were captured less than five times, with 12 (25.5%) captured only once. Thirty-five species accounted for only 8.7% of total specimens captured and were categorized as rare species.

SLAM traps captured more total species and unique species than the other three trap types tested (Table 3). SLAM traps also captured significantly higher mean species richness than did the modified funnel, funnel and intercept panel traps ($F_{3,27} = 28.9$; $P < 0.0001$) (Table 3). Modified funnel and funnel traps captured significantly higher mean species richness than intercept panel traps. SLAM traps captured 77% of rare species, whereas the three other traps captured between 22% and 43% of rare species (Fig. 2A). SLAM traps (58%) also captured the highest percentage of singletons, followed by funnel (25%), modified funnel (17%) and intercept panel (0%) (Fig. 2B).

Table 4 Species richness, and abundance (mean ± SE) of cerambycids captured in four trap types in Georgia

Variable	Modified funnel	Funnel	Intercept panel	SLAM
Mean number of species	4.7 ± 0.7^{ab}	4.3 ± 0.7^{ab}	2.7 ± 0.5^{b}	6.2 ± 0.8^{a}
Species richness	10	10	6	17
Unique species	2	1	0	7
Chao 1 estimate	11.0 ± 1.8	13.0 ± 4.5	6.5 ± 1.3	39.5 ± 19.4
Abundance	466	226	119	1292
Mean number of Cerambycidae	45.3 ± 7.9^{b}	21.1 ± 3.8^{c}	10.9 ± 2.1^{d}	130.2 ± 22.1^{a}
Cerambycinae	44.7 ± 7.7^{b}	20.3 ± 3.7^{c}	10.7 ± 2.1^{d}	129.4 ± 21.9^{a}
Neoclytus acuminatus	11.4 ± 1.2^{b}	3.5 ± 0.6^{c}	3.4 ± 0.6^{c}	21.0 ± 1.9^{a}
Neoclytus mucronatus	24.5 ± 5.2^{a}	9.4 ± 2.1^{b}	4.7 ± 1.2^{b}	23.3 ± 5.0^{a}
Neoclytus scutellaris	6.1 ± 1.8^{b}	5.0 ± 1.5^{b}	2.0 ± 0.7^{c}	56.2 ± 15.1^{a}
Xylotrechus colonus	1.7 ± 0.5^{b}	0.8 ± 0.3^{b}	0.2 ± 0.1^{c}	25.4 ± 3.3^{a}

Means followed by the same superscript letter within a row are not significantly different (Tukey's HSD, $P > 0.05$).

Similar to results in New York and Louisiana, the SLAM traps detected more cerambycid species per total number of specimens collected (Fig. 3C) and per trapping effort (Fig. 4C). Chao 1 estimates of total cerambycid species richness were highest for intercept panel traps followed by SLAM, standard funnel and funnel traps (Table 3).

There were significant differences among the trap types in the mean number of cerambycids captured in the four trap types ($F_{3,27} = 14.2$; $P < 0.0001$) (Table 3). SLAM traps captured significantly more cerambycids than did intercept panel and funnel traps, although in similar numbers as the modified funnel. For taxonomical categories lower than family, cerambycid captures were significantly different for Cerambycinae ($F_{3,27} = 8.9$; $P < 0.001$) and Lamiinae ($F_{3,27} = 18.5$; $P < 0.0001$) (Table 3). SLAM traps were always one of the traps that captured the most cerambycids grouped by subfamily. Modified funnel traps were equally effective as SLAM traps for Cerambycinae.

Relative performance of the different trap types varied among species. *Astylopsis sexguttata* ($F_{3,27} = 6.3$; $P = 0.002$), *N. mucronatus* ($F_{3,27} = 5.5$; $P = 0.005$), *N. scutellaris* ($F_{3,27} = 12.2$; $P < 0.0001$), *Urographis fasciatus* DeGeer ($F_{3,27} = 6.4$; $P = 0.002$) and *X. colonus* ($F_{3,27} = 5.1$; $P = 0.006$) captures all varied by trap type, with SLAM traps and modified funnel traps generally capturing the most cerambycids (Table 3). *Monochamus carolinensis* ($F_{3,27} = 1.4$; $P = 0.3$) and *X. sagittatus* ($F_{3,27} = 2.5$; $P = 0.08$) captures did not differ among the trap types (Table 3).

Georgia

In Georgia, 2103 cerambycid specimens from 22 species were captured during the sampling period. Three species of *Neoclytus* Thomson accounted for 84% of total catches. Thirteen species (59%) were captured five or fewer times, whereas eight (36%) were captured only once. Eighteen species accounting for only 2.5% of total catches were categorized as rare species.

SLAM traps captured higher numbers of species and unique species in Georgia (Table 4). The mean number of cerambycid species detected per trap was greatest for SLAM traps, intermediate for modified funnel and standard funnel traps, and lowest for intercept panel traps ($F_{3,27} = 4.5$; $P = 0.01$) (Table 4). The percentage of rare species detected followed a similar trend with most in the SLAM traps (72%), followed by the funnel (33%), modified funnel (33%) and intercept panel (11%) traps (Fig. 2A). SLAM traps (63%) also captured the most singletons, followed by the modified funnel (25%), funnel (12%) and intercept panel (0%) (Fig. 2B). Chao 1 estimates of total species richness of cerambycids were highest in SLAM traps, followed by funnel, modified funnel and intercept panel traps (Table 4).

Mean catch per trap of cerambycids was significantly greater in SLAM traps than in modified funnel, funnel and intercept panel traps ($F_{3,27} = 46.44$; $P < 0.0001$) (Table 4). Modified funnels captured the next highest numbers, with intercept panel traps capturing the fewest cerambycids. SLAM traps also captured significantly more Cerambycinae ($F_{3,27} = 48.0$; $P < 0.0001$) than other trap types (Table 4).

In three of four species examined [*Neoclytus acuminatus* (F.) ($F_{3,27} = 45.53$; $P < 0.0001$), *N. scutellaris* ($F_{3,27} = 42.38$; $P < 0.0001$) and *X. colonus* ($F_{3,27} = 57.3$; $P < 0.0001$)], SLAM traps captured more individuals than other trap types (Table 4). Modified funnel and SLAM traps caught similar numbers of *N. mucronatus* ($F_{3,27} = 16.0$; $P < 0.0001$) (Table 4).

Discussion

The development of improved trapping technology for arboreal insects has received renewed attention with the expansion of exotic species surveys, biological diversity inventories and the need to protect threatened or endangered species (Sweeney *et al.*, 2004; Brockerhoff *et al.*, 2006; Francardi *et al.*, 2006; Hyvärinen *et al.*, 2006; Bouget *et al.*, 2009; Dodds *et al.*, 2010; Graham *et al.*, 2012; Allison *et al.*, 2014). Cerambycidae are often primary targets of these efforts, however, the trapping methodology has often relied on traps that were developed for other purposes such as mass-trapping efforts (Lindgren, 1983; Lindgren & Fraser, 1994; Czokajlo *et al.*, 2001). Although multiple-funnel and intercept panel traps are effective at catching some cerambycids (McIntosh *et al.*, 2001; Morewood *et al.*, 2002; Sweeney *et al.*, 2004), the effectiveness of these traps for surveying the larger cerambycid communities present at a site has been rarely studied (but see Graham *et al.*, 2012; Miller *et al.*, 2013). The present study focused on determining the optimal trap for surveying cerambycid communities, with special attention being paid to species richness and rare species over strict abundance estimates.

Species richness, unique species and rare species

There were slight differences among the trap types in the mean number of species captured. Although not always statistically significant, SLAM traps generally captured the highest mean species richness among trap types and intercept panel traps generally captured the fewest species. SLAM traps targeting cerambycids have not previously been compared with other trap types but, in a study comparing a similar top collecting canopy malaise trap, no differences were found between these and multiple-funnel and intercept panel traps in terms of mean species richness captured (Dodds *et al.*, 2010). Intercept panel traps have been reported to capture slightly more cerambycid species than multiple-funnel traps when baited with lures similar to those used in our experiments (Graham *et al.*, 2012), although Miller *et al.* (2013) found little difference between the trap types. Intercept panel traps are recommended for the collection of woodborers where abundance is an important measure (McIntosh *et al.*, 2001; Morewood *et al.*, 2002). Our results suggest that trap types other than intercept panels should be considered if community-level description of the cerambycid fauna is the goal, as in exotic species surveys or biological inventories.

Trends observed for mean species richness were also found for pooled estimates of species richness and unique species (i.e. a species only captured in a single trap type). SLAM traps captured a higher total species richness and unique species than other trap types at every site, even when sometimes catching a lower total abundance of cerambycids. Increased abundance often leads to increased species richness (Bock *et al.*, 2007), although SLAM traps were apparently unaffected by this relationship. SLAM traps captured between 54% and 85% of unique species at each site compared with 0–23% of the unique species captured by the other trap types. Intercept panel traps generally captured the lowest number of species and unique species. Top collecting malaise traps have been previously documented to capture higher arboreal insect species richness and unique species compared with other traps tested in a northeastern U.S. forest (Dodds *et al.*, 2010). The exact mechanisms responsible for increased species richness in top collecting traps are unknown, although these traps may allow for a soft landing by insects and persistence on traps for longer periods as a result of trap materials (i.e. fine mesh). This may facilitate movement and capture in top collecting cups. SLAM traps are designed to exploit positive phototaxis (i.e. the top portions of the traps are white, whereas the lower portions are black). Insects that are phototactic likely travel upward toward brighter trap portions and end up captured in top collecting cups. The surface area is much larger on SLAM traps and this may also facilitate higher catches of cerambycids than other trap types. SLAM traps in New York and Massachusetts also had a bottom collecting cup, whereas SLAM traps in Louisiana and Georgia did not. However, few unique species were captured in bottom collecting cups of traps in New York and Massachusetts. Vance *et al.* (2003) found higher species richness in top collecting cups compared with bottom cups of canopy malaise traps at the same time as finding similar numbers of unique species in each collecting cup. The bottom collecting cup of SLAM traps at our study sites were often blocked by debris, likely influencing capture efficacy in the cup.

Total species richness and unique species provide important information on trap efficacy. Species defined as rare are also important to consider when evaluating traps. Traps that are effective at capturing rare species may be especially relevant to monitoring efforts for endangered or red-listed cerambycid species. In addition, an exotic species in the establishment phase of invasion would be present at low numbers, and a trap that excels at surveying rare species may be beneficial for detecting these establishing populations early in the invasion process. Various methods have been used to categorize species based on perceived rarity (Gaston, 1994; Novotný & Basset, 2000; Basset *et al.*, 2008). We investigated rarity using a percentage of total captures cut-off (i.e. species making up ≤ 1% of total catches) and the presence of singletons in captures. These approaches were based on a species list generated for each site. A 1% cut-off for rare species was logical based on frequency distributions of trap catches and also based on previous cerambycid trapping experience. SLAM traps were more effective at catching rare species defined by either method at each site than all other trap types. SLAM traps captured between 71% and 86% of all rare species at a site, whereas other trap types captured 11–63%. Similarly, SLAM traps captured between 58% and 80% of the singletons, whereas other trap types captured 0–25%. Consequently, SLAM traps should be considered for surveys where describing the cerambycid community and/or monitoring populations of rare or threatened species is the goal.

Estimating species richness

Species richness estimates were investigated using several methods, including rarefaction, species accumulation curves and nonparametric species estimators. Rarefaction and species accumulation curves were not implemented for Georgia collections because of the relatively short sampling period. Rarefaction estimates were relatively consistent among traps in New York, Louisiana and Massachusetts. SLAM traps captured more species per number of individuals collected than other trap types, often by a wide margin. In most cases, individual rarefaction curves were slowly increasing, suggesting that more species were present in the area than those we detected. However, rarefaction curves for intercept panel and modified funnel traps were close to asymptote in New York and Louisiana.

Species accumulation curves are useful for investigating the efficiency of sampling efforts (Bonar *et al.*, 2011). Sample based species accumulation curves demonstrated that not only did SLAM traps consistently capture higher numbers of species than the other trap designs, but also they did so with less sampling effort. At each site, failure to reach asymptote suggested that, even at a density of 10 traps per site, some cerambycid species present at the sites were not detected. In Louisiana, however, it appeared that the modified funnel and intercept panel traps had almost reached asymptote and that additional traps would not detect many more species.

Chao 1 is a nonparametric method that uses rare species to estimate species richness (Magurran, 2004). Chao 1 provides a minimum estimate of species richness (Chao, 1984; Gotelli & Colwell, 2011). These estimates can be useful in assessing sampling completeness by assuming they represent a completed sampling inventory (Borges & Brown, 2003; Coddington *et al.*, 2009). All Chao 1 species richness estimates were higher than observed species richness at each site, suggesting that further sampling may have yielded more species. Using Chao 1 estimates to investigate sampling completeness resulted in a wide-range of estimated trapping completeness for SLAM (43–86%), funnel (59–77%), modified funnel (76–96%) and intercept panel (33–96%) traps. High percentage completeness represents traps that caught a greater proportion of the predicted number of species available for a trap type at a site.

Cerambycidae abundance in traps

With the exception of traps from New York, general patterns in mean cerambycid abundance by trap type were evident. Modified funnel and SLAM traps captured higher mean cerambycid abundance than other trap types. Standard funnel traps generally fell between SLAM and modified funnel and intercept panel traps in their effectiveness at capturing cerambycids. Intercept panel traps were generally out-competed by the other trap types, even though they were previously reported to be more effective than other trap types for cerambycids (McIntosh *et al.*, 2001; Morewood *et al.*, 2002; Dodds *et al.*, 2010; Graham *et al.*, 2012; but see also Allison *et al.*, 2014). Discrepancies in these results may be attributed to differences in lure composition and surfactant treatments. Modified funnel, funnel and intercept panel traps used in Georgia were not treated with surfactants and this may have affected abundance-based comparisons for family, subfamily and species among traps from this site.

Modified funnel traps were the most effective traps for catching beetles in the Cerambycinae subfamily. SLAM traps also caught larger numbers of Cerambycinae compared with other trap types at all sites except New York. Intercept panel traps captured more Cerambycinae than SLAM traps in New York. The response of individual Cerambycinae species to trap type varied but, generally, SLAM and modified funnel traps captured larger numbers of *Neoclytus* spp., *Xylotrechus* spp, and other species than other trap types. Three sites had sufficient Lamiinae species to statistically analyze and SLAM and/or modified funnels captured the largest abundance of specimens among the trap types. The Lamiinae species *A. sexguttata* and *U. fasciatus* were captured in larger numbers in SLAM traps relative to other trap types, whereas trap type had no effect on *A. obsoletus* and *M. carolinensis*. Modified funnels were also more effective than intercept panel or standard funnels for capturing *A. sexguttata*.

Conclusions

Testing various trap types in four locations in eastern North America with an array of semiochemicals provided important information helpful for selecting traps when targeting cerambycids. Previous studies have often provided conflicting results on trapping recommendations or were focused more on abundance comparisons instead of community level metrics. By testing various semiochemicals in multiple locations, some clear patterns of optimal trap type for cerambycids were found. Although there were slight differences among trap types for mean catches and individual species comparisons, it was clear that SLAM traps outperformed the others in community level estimates, including species richness, unique species and rare species.

SLAM traps captured the most species, unique species and rare species, suggesting that these traps could be important components of invasive species detection programmes and biological diversity inventories. Modified funnel traps also showed promise for sampling cerambycid communities and can easily be made from existing stores of standard funnel traps. Modified funnel traps captured a higher abundance than standard funnel traps, and marginal increases in species richness and unique species were found. Intercept panel traps should generally be avoided when community level sampling is the survey objective. When targeting a specific species, as in the case of some invasive species survey or delimitation efforts, care should be taken to select the best trap for a given species. Our results in conjunction with those of others (McIntosh *et al.*, 2001; Morewood *et al.*, 2002; Holland, 2006; Allison *et al.*, 2014) suggest there is variation in the response of individual cerambycid species to trap type.

The primary limitation of SLAM traps for wider incorporation into surveys is their cost. SLAM traps are expensive compared with multiple-funnel and intercept traps and their durability over multiple seasons is questionable, particularly in very exposed areas. However, the incorporation of these traps, even at low densities, would be beneficial in exotic species surveys or biological diversity inventories. Use in high-risk areas, such as port environs, may be especially beneficial for detecting invasive cerambycids before widespread establishment in new environments occurs.

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