Ipsenol, Ipsdienol, Ethanol, and α-Pinene: Trap Lure Blend for Cerambycidae and Buprestidae (Coleoptera) in Pine Forests of Eastern North America

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ABSTRACT In 2007–2008, we examined the flight responses of wood-boring beetles (Coleoptera: Cerambycidae and Buprestidae) to multiple-funnel traps baited with the pine volatiles, ethanol, and α-pinene [85% (–)], and the bark beetle pheromones, racemic ipsenol and racemic ipsdienol. Experiments were conducted in mature pine stands in Canada (Ontario and New Brunswick) and the United States (Arkansas, Florida, Michigan, New Hampshire, North Carolina, Ohio, Tennessee, and Wisconsin). At each location, traps were deployed in 10 replicate blocks of four traps per block. The trap treatments were: 1) blank control; 2) ipsenol and ipsdienol; 3) ethanol and α-pinene; and 4) a quaternary blend of ipsenol, ipsdienol, ethanol, and α-pinene. Traps baited with the quaternary blend caught the greatest numbers of *Acanthocinus nodosus* (F.), *Acanthocinus obsoletus* (Olivier), *Acmaeops proteus* (Kirby), *Astylopsis sexguttata* (Say), *Rhagium inquisitor* (L.) (Cerambycidae), and *Buprestis lineata* (F.) (Buprestidae). Traps baited with ethanol and α-pinene caught the greatest numbers of *Arhopalus rusticus* (LeConte), *Asemum striatum* (L.), *Tetropium* spp., *Xylotrechus sagittatus* (Germar) (Cerambycidae), and *Buprestis maculipennis* Gory (Buprestidae) with minimal interruption by ipsenol and ipsdienol. Our results suggest that multiple-funnel traps baited with the quaternary lure blend of ipsenol, ipsdienol, ethanol, and α-pinene are effective for trapping various species of wood-boring beetles in pine forests of eastern North America, and may have utility in detection programs for adventive species in North America and overseas.

KEY WORDS Cerambycidae, Buprestidae, detection, adventive, exotic

Adventive (= non-native, exotic, introduced, nonindigenous, and alien) species of bark and wood-boring insects are transported globally, entering new locales via such pathways as solid wooden packing material and live plants, adversely affecting ecosystems, industry, and private landowners (Allen and Humble 2002, Humble and Allen 2006, Wheeler and Hoebeke 2009, Aukema et al. 2010, Liebhold et al. 2012). For example, the Asian longhorn beetle, *Anoplophora glabripennis* (Motschulsky) (Coleoptera: Cerambycidae) is a native pest of hardwood trees in China, causing yearly losses >US$1 billion per year (Hu et al. 2009). Numerous introductions of *A. glabripennis* have been discovered in eastern Canada and the United States in the past 20 yr, as well as several countries in Europe (Haack et al. 2010), with potential losses of >30% of urban trees in the United States (Nowak et al. 2001, MacLeod et al. 2002). For the period 1996–2008, the costs of eradication efforts against *A. glabripennis* in Canada and the United States totaled >US$400 million (Haack et al. 2010).

Native wood borers are an important component of forested ecosystems with critical roles in nutrient cycling and food web dynamics (Hanks 1999, Allison et al. 2004, Lee et al. 2014). At times, some species can present challenges for forest managers. High larval densities can stress or kill trees, either directly from girdling or indirectly through wind breakage at stem locations weakened by larval feeding (U.S. Department of Agriculture [USDA] 1985, Solomon 1995). Brooks (1923) reported mortality levels of 25% in saplings of oak (*Quercus* spp.) and American chestnut [*Castania dentata* (Marshall) Borkhausen] infested with the oak sapling borer, *Goes tesselatus* Haldeman over a 10-yr period in West Virginia. Unusually high population

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levels of the red oak borer, *Enaphalodes rufulus* (Haldeman) began to appear in 1999 throughout the Ozark Mountain region of Arkansas and Missouri in association with a complex decline phenomenon in oak–hickory forests (Stephen et al. 2001, Haavik et al. 2012). Across four stands in northern Arkansas, 51–75% of red oaks (*Q. rubra* L.) were dead or dying, and associated with large numbers of *E. rufulus* (Heitzman et al. 2007).

Even at low population levels, activities by cerambycids can adversely affect timber values. Tunnels in wood created by feeding larvae of various species can significantly reduce wood product value (degrade), particularly in high-value lumber (USDA 1985, Post and Werner 1988, Solomon 1995, Allison et al. 2004). Degrade losses caused by *E. rufulus* in living oak trees can amount to 40% of timber value (Donley and Acciavatti 1980). In three studies, Morris (1977) found that the combined tunneling activity by five species of Cerambycidae resulted in a 15% degrade to oak lumber in the South, amounting to yearly losses of US$29.5 million in 1970. In Alberta, lumber value loss in white spruce logs, *Picea glauca* (Moench) Voss from larval feeding by *Monochamus scutellatus* (Say) can amount to 30% (Cerezke 1975, 1977).

Additionally, adventive species of wood borers can vector phytopathogenic microorganisms, some of which can be newly acquired and vectored by native species (Humble and Allen 2006). *Monochamus* species can vector the pinewood nematode, *Bursaphelenchus xylophilus* (Steiner and Buhrer) Nickel (Tylenchida: Aphenlenchoididae), native to North America (Allison et al. 2004, Akbulut and Stamps 2012). The pine wilt disease caused by pinewood nematodes (vectored by the Asian species, *Monochamus alternatus* Hopkins) has resulted in extensive tree mortality in China, Korea, and Japan (Evans et al. 1996, Yang 2003, Mamiya 2003, Vicente et al. 2012). The pinewood nematode, first noted in Portugal in 1999, is now vectored by the European species, *Monochamus galloprovincialis* (Olivier) (Sousa et al. 2001, Vicente et al. 2012). The high risk associated with introduction of the pinewood nematode has led to importation bans placed on pine products from the United States (Wingfield et al. 1982; Evans et al. 1996; Bolla and Wood 2003; Dwinell 1997, 2004).

Detection of new adventive species is one of four components that should be included in any comprehensive management program for adventive species of wood-boring beetles (Chornesky et al. 2005, Coulston et al. 2008, Klepzig et al. 2010, Liebhold et al. 2012). The other three components include: 1) phytosanitation of solid wood packing material and live hosts; 2) early eradication of newly discovered species; and 3) long-term management of established species. Early detection of beetles is critical in countering impacts of adventive species on native trees and forests, particularly with concerns over efficacy issues regarding phytosanitation protocols (Haack et al. 2014).

Effective lures are the most important component of early detection programs. Programs in North America and overseas have typically targeted bark and ambrosia beetles with traps baited with host volatiles. In the United States, for example, two national programs are administered by the USDA (Animal and Plant Health Inspection Services–Cooperative Agricultural Pest Survey [CAPS] and the Forest Service–Early Detection

Table 1. Locations, predominant pine species, brands of antifreeze, and trapping dates for each of 10 experiments on flight responses of wood-boring beetles to multiple-funnel traps baited with host volatiles and bark beetle pheromones in eastern North America

Exp.	Location	Coordinates	Predominant tree species	Brand of RV antifreeze	Trapping dates
1	Ouachita National Forest, Yell Co., Arkansas	35.040 N, 93.668 W	*Pinus taeda* L.	Splash[a]	23 June–17 Sept. 2008
2	Austin Cary Memorial Forest, Alachua Co., Florida	29.742 N, 82.201 W	*P. taeda*	Easy Going[b]	23 April–16 July 2008
3	Kellogg Research Forest, Kalamazoo Co., Michigan	42.358 N, 85.375 W	*Pinus resinosa* Aiten	SuperTech[c]	17 May–7 Sept. 2007
4	Acadia Research Forest, Sunbury Co., New Brunswick, Canada	44.993 N, 66.342 W	*P. resinosa*	Prestone Low Tox[d]	23 May–28 Aug. 2007
5	Bear Brook State Park, Merrimack Co., New Hampshire	43.139 N, 71.367 W	*Pinus strobus* L.	Prestone Low Tox	15 June–20 Sept. 2007
6	Nantahala National Forest, Cherokee Co., North Carolina	35.093 N, 84.134 W	*Pinus echinata* Miller	Peak[e]	4 June–27 Aug. 2008
7	Blue Rock State Park, Muskingum Co., Ohio	39.823 N, 81.835 W	*P. strobus*	Meijer[f]	15 May–7 Aug. 2008
8	Canadian Forces Base Borden, Simcoe Co., Ontario, Canada	44.318 N, 79.941 W	*P. resinosa*	Custom blend[g]	12 June–4 Sept. 2007
9	Cherokee National Forest, Johnson Co., Tennessee	36.374 N, 81.949 W	*P. strobus*	Peak	13 June–4 Sept. 2007
10	La Crosse County Forest, La Crosse Co., Wisconsin	44.059 N, 91.073 W	*P. resinosa*	Peak	10 June–2 Sept. 2008

[a] Splash RV & Marine Antifreeze, Fox Packaging Inc., St. Paul, MN.
[b] Easy Going, CAMCO Mfg. Inc., Greensboro, NC.
[c] SuperTech RV & Marine Antifreeze, Wal-Mart, Bentonville, AR.
[d] Prestone Low Tox Antifreeze, Prestone Products Corp., Danbury, CT.
[e] Peak RV & Marine Antifreeze, Old World Industries, Northbrook, IL.
[f] Meijer Marine & RV Antifreeze, Meijer Distribution Inc., Grand Rapids, MI.
[g] 50:50 Blend of water and propylene glycol (Brenntag Canada Inc., Toronto, ON, Canada).

and Rapid Response program [EDRR]), using traps baited with ethanol and α-pinene (Rabaglia et al. 2008, Jackson et al. 2010). Effective, broad-spectrum lures are required for other groups of wood-boring insects such as longhorn beetles that are commonly intercepted at ports-of-entry in North America and overseas (Allen and Humble 2002, Aukema et al. 2010, Haack et al. 2014).

Our goal is to help develop survey programs that maximize the diversity of target species detected with minimal numbers of traps and lures, thereby reducing program costs (Hanks et al. 2012). Wood-boring species that typically infest pine trees are attracted broadly to host volatiles, bark beetle pheromones, and their combinations (Allison et al. 2004). In southeast United States, traps baited with a binary blend of two host volatiles, ethanol, and α-pinene are attractive to various species of wood borers: *Acanthocinus nodosus* F., *Acanthocinus obsoletus* (Olivier), *Arhopalus rusticus* (LeConte), *Asemum striatum* (L.), *Monochamus titillator* (F.) complex [with *Monochamus carolinensis* (Olivier)], *Prionus pocularis* Dalman, *Xylotrechus integer* (Haldeman) and *Xylotrechus sagittatus* (Germar) (Cerambycidae), and *Buprestis lineata* F. (Buprestidae) (Miller 2006).

Bark beetle pheromones such as ipsenol and ipsdienol can enhance attraction of *Monochamus* species to traps baited with host volatiles (Billings 1985; Allison et al. 2001, 2003; de Groot and Nott 2004; Pajares et al. 2004; Ibeas et al. 2006; Costello et al. 2008). In the southeast United States, traps baited with the quaternary blend of ethanol, α-pinene, ipsenol, and ipsdienol were more effective than the binary combinations of ethanol and α-pinene or ipsenol and ipsdienol for the following species: *Ac. nodosus*, *Ac. obsoletus*, *Astylopsis arcuata* (LeConte), *Astylopsis sexguttata* (Say), *M. scutellatus*, *M. titillator* complex, *Rhagium inquisitor* (L.) (Cerambycidae), as well as the buprestids *Buprestis consularis* Gory and *B. lineata* (Miller et al. 2011).

The objective of the current study was to evaluate the attractiveness of the quaternary lure blend to various species of native wood borers over a broad geographic range in eastern North America. Consistent results over a broad range of hosts can minimize concerns by managers about geographic variation in responses, as well as document responses by species not previously encountered in southeastern studies. Knowledge about effective lures for North American species of wood borers are critically needed for detection programs in countries outside of North America that monitor for invasions by North American species, particularly as we are unable to predict the consequences of wood borer introductions in ecosystems outside of their current range.

Materials and Methods

In 2007–2008, we conducted separate trapping experiments in stands of mature pine at each of 10 locations in eastern Canada and eastern United States, using the same randomized complete block design (Table 1). At each location, we deployed 40 multiple-funnel traps (Contech Enterprises Inc., Victoria, BC, Canada, or Synergy Semiochemicals Corp., Burnaby, BC, Canada, for any given location) set in 10 replicate blocks of four traps per block. The number of blocks was reduced to nine in Ohio owing to a processing error in the laboratory after the experiment was completed. Traps with 12 funnels were used in Michigan, New Brunswick, New Hampshire, Ohio, and Wisconsin, while 8-unit traps were used at the remaining locations. Traps were spaced 10–20 m apart within blocks, with replicate blocks spaced $\geq$10 m apart. Each trap was suspended between trees by rope or on metal conduit stands such that each trap was >2 m from any tree and the bottom of each trap was 0.5–1.0 m above ground level. At each location, traps were deployed during the summer months for a period of ~12 wk (Table 1).

Each collection cup contained 150–200 ml of antifreeze solution (a.i., propylene glycol) as a killing and preservation agent (Miller and Duerr 2008). Catches were collected every 2–3 wk with new antifreeze solution added on each occasion. Various brands of antifreeze solutions were used in the trapping studies (Table 1). All brands contained solutions of propylene glycol and water with either a pink or green dye; in Ontario, we used a blend without dye. The concentrations of propylene glycol in the commercial brands ranged from 6 to 37%; none of the brands contained ethanol (verified by examination of product labels and the associated Material Safety Data Sheets).

Contech Enterprises Inc. supplied ultra-high-release (UHR) plastic pouch lures containing either ethanol (150 ml) or α-pinene (200 ml), each with chemical purities >95%. The enantiomeric composition of α-pinene was 85% (–). The release rate of ethanol from ethanol UHR pouches was 0.6 g/d at 25–28°C, whereas α-pinene was released at 2–6 g/d from α-pinene UHR pouches at 25–28°C (as determined by weight loss). Bubble-cap lures containing either racemic ipsenol or racemic ipsdienol [chemical purities >95%, enantiomeric composition 50:50 (+)/(–)] were obtained from ConTech Enterprises Inc. in 2007 and Synergy Semiochemicals Corp. in 2008. Ipsenol and ipsdienol were released from bubblecaps at 0.1–0.3 mg/d at 22–25°C (as determined by the manufacturers).

At each location, one of the following four treatments was allocated randomly to each of the four traps within each block: 1) blank control, 2) ethanol + α-pinene, 3) ipsenol + ipsdienol, and 4) ethanol + α-pinene + ipsenol + ipsdienol. Cerambycidae and Buprestidae species were identified using Bright (1987), Chemsak (1996), Lingafelter (2007), and Paiero et al. (2012). Species names and authors were verified with Integrated Taxonomic Information System (ITIS) (2015). Voucher specimens of all species were deposited in the University of Georgia Collection of Arthropods, Georgia Museum of Natural History, University of Georgia (Athens, GA).

Analyses were conducted on total cumulative numbers of insects captured per trap. Trap catch data were transformed by ln (Y + 1) to ensure homoscedasticity

Table 2. Total numbers of longhorn beetles (Cerambycidae) captured at 10 locations in eastern North America (2007–2008)

Species	Arkansas	Florida	Michigan	New Brunswick	North Carolina	New Hampshire	Ohio	Ontario	Tennessee	Wisconsin	Total
CERAMBYCIDAE											
Acanthocinus nodosus (F.)	43	30	–	–	3	–	–	–	–	–	76
Acanthocinus obsoletus (Olivier)	133	530	126	8	91	32	3	30	17	75	1,045
Acmaeops discoideus (Haldeman)	–	–	–	–	1	–	14	–	–	–	15
Acmaeops proteus (Kirby)	–	–	–	106	–	44	–	8	–	8	166
Aegomorphus modestus (Gyllenhal)	3	4	1	–	3	–	–	–	7	–	18
Analeptura lineola (Say)	–	–	1	–	–	1	–	1	–	–	3
Ancylocera bicolor (Olivier)	–	3	–	–	–	–	–	–	–	–	3
Anelaphus inermis (Newman)	–	14	–	–	–	–	–	–	–	–	14
Anelaphus parallelus (Newman)	–	–	–	–	–	1	8	–	–	–	9
Anelaphus pumilus (Newman)	–	–	–	7	–	–	–	–	–	–	7
Anelaphus villosus (F.)	–	2	7	–	1	3	4	–	2	–	19
Anoplodera pubera (Say)	–	–	1	–	–	–	–	–	–	–	1
Anthophylax attenuatus (Haldeman)	–	–	–	7	–	–	–	–	–	–	7
Arhopalus rusticus (L.)	8	37	–	–	21	–	9	–	22	2	99
Asemum striatum (L.)	–	–	156	761	–	88	206	14	1	303	1,529
Astylopsis arcuata (LeConte)	–	12	–	–	–	–	–	–	1	–	13
Astylopsis sexguttata (Say)	12	43	112	4	56	14	25	26	129	88	509
Ataxia crypta (Say)	–	7	–	–	–	–	–	–	–	–	7
Ataxia hubbardi Fisher	1	–	–	–	–	–	–	–	–	–	1
Bellamira scalaris (Say)	–	–	3	–	3	–	1	7	–	1	15
Brachyleptura champlaini Casey	–	–	7	–	4	1	2	–	3	1	18
Brachyleptura circumdata (Olivier)	–	–	–	–	–	–	–	–	–	1	1
Brachyleptura rubrica (Say)	–	–	2	–	4	–	–	–	2	1	9
Brachyleptura vagans (Olivier)	–	–	–	–	–	2	–	1	–	2	5
Callimoxys spp.	–	1	–	–	–	–	–	–	–	–	1
Clytus ruricola (Olivier)	–	–	50	–	–	18	–	26	–	6	100
Cyrtophorus verrucosus (Olivier)	–	–	53	–	8	–	24	–	1	8	94
Eburia quadrigeminata (Say)	–	1	–	–	–	–	–	–	–	–	1
Ecyrus dasycerus (Say)	–	6	–	–	1	–	–	–	–	–	7
Elaphidion mucronatum (Say)	5	37	2	–	2	–	–	–	1	–	47
Enaphalodes atomarius (Drury)	6	5	–	–	–	–	–	–	–	–	11
Eupogonius pauper LeConte	–	–	3	–	–	–	–	–	2	–	5
Eupogonius tomentosus (Haldeman)	2	–	10	–	–	–	–	–	4	–	16
Gaurotes cyanipennis (Say)	–	–	9	1	–	2	1	–	5	4	22
Graphisurus fasciatus (Degeer)	–	1	1	–	2	–	3	–	–	1	8
Hyperplatys maculata Haldeman	–	–	–	–	1	–	–	–	–	–	1
Idiopidonia pedalis (LeConte)	–	1	–	–	–	–	–	–	–	–	1
Judolia cordifera (Olivier)	–	–	–	–	39	43	15	–	20	–	117
Knulliana cincta (Drury)	–	3	–	–	–	–	1	–	–	–	4
Leptostylopsis planidorsus (LeConte)	–	2	–	–	–	–	–	–	–	–	2
Leptostylus asperatus (Haldeman)	–	1	–	–	1	–	–	–	–	–	2
Leptostylus transversus (Gyllenhal)	–	27	–	–	4	–	10	–	1	–	42
Leptura obliterata (Haldeman)	–	–	–	–	–	1	–	–	–	–	1
Leptura plebeja Randall	–	–	–	1	–	–	–	–	–	–	1
Leptura subhamata Randall	–	–	–	–	–	3	–	–	–	–	3
Lepturopsis biforis (Newman)	–	–	–	–	–	1	–	–	–	–	1
Megacyllene caryae (Gahan)	–	–	–	–	–	–	4	–	–	–	4
Microgoes oculatus (LeConte)	–	–	–	–	1	4	–	16	1	1	23

(*continued*)

Table 2. Continued

Species	Arkansas	Florida	Michigan	New Brunswick	North Carolina	New Hampshire	Ohio	Ontario	Tennessee	Wisconsin	Total
Monochamus carolinensis (Olivier)	–	–	137	1	–	7	72	4	–	–	221
Monochamus notatus (Drury)	–	–	–	4	–	8	–	2	15	–	29
Monochamus scutellatus (Say)	–	–	31	20	1	61	76	30	2	776	997
Monochamus titillator (F.) complex	2,984	824	–	–	283	–	–	–	52	502	4,645
Neandra brunnea (F.)	–	–	7	–	–	–	–	–	1	–	8
Neoclytus acuminatus (F.)	–	1	–	–	–	–	1	–	4	3	9
Neoclytus leucozonus Laporte & Gory	–	–	–	1	–	–	–	–	–	7	8
Neoclytus mucronatus (F.)	56	1	–	–	3	–	–	–	–	–	60
Neoclytus scutellaris (Olivier)	120	36	–	–	–	–	–	–	–	–	156
Obrium rufulum Gahan	–	–	1	–	–	–	–	–	–	–	1
Orthosoma brunneum (Forster)	3	–	7	–	8	2	–	1	3	2	26
Parelaphidion aspersum (Haldeman)	–	3	–	–	–	–	–	–	–	–	3
Phymatodes dimidiatus (Kirby)	–	–	–	3	–	–	–	–	–	1	4
Phymatodes testaceus (L.)	–	–	1	–	–	–	–	–	–	–	1
Pidonia aurata (Horn)	–	–	–	–	1	–	–	–	–	–	1
Pogonocherus penicillatus LeConte	–	–	–	1	–	–	–	–	–	–	1
Prionus imbricornis (L.)	1	–	–	–	1	–	–	–	–	–	2
Prionus laticollis (Drury)	–	–	–	–	4	1	–	–	1	–	6
Prionus pocularis Dalman	–	151	–	–	4	–	–	–	–	7	162
Psenocerus supernotatus (Say)	–	–	4	–	–	–	2	–	–	–	6
Purpuricenus humeralis (F.)	11	–	–	–	1	–	1	–	–	–	13
Purpuricenus paraxillaris MacRae	1	–	–	–	1	–	–	–	–	–	2
Pygoleptura nigrella (Say)	–	–	–	9	–	–	–	–	–	1	10
Rhagium inquisitor (L.)	–	–	–	31	–	5	164	1	–	11	212
Saperda imitans Felt & Joutel	–	–	–	–	–	–	1	1	–	2	4
Saperda lateralis F.	–	–	–	–	1	–	–	–	–	–	1
Saperda puncticollis Say	–	–	1	–	–	–	–	–	–	–	1
Sphenostethus taslei (Buquet)	1	–	–	–	–	–	–	–	–	–	1
Stictoleptura canadensis (Olivier)	–	–	31	20	–	4	–	10	8	1	74
Strangalepta abbreviata (Germar)	–	–	7	2	1	10	–	4	1	5	30
Strangalia luteicornis (F.)	2	4	6	–	2	1	–	–	1	4	20
Strophiona nitens (Forster)	–	–	2	–	–	3	–	–	–	4	9
Styloleptus biustus (LeConte)	–	14	–	–	–	–	–	–	–	–	14
Tetropium spp.	–	–	32	7	–	34	34	108	2	1	218
Trachysida mutabilis (Newman)	–	–	2	4	–	3	–	4	–	2	15
Trigonarthris proxima (Say)	–	–	–	2	3	–	–	3	–	–	8
Typocerus badius (Newman)	–	2	–	–	–	–	–	–	–	–	2
Typocerus lugubris (Say)	–	–	–	–	1	–	–	–	–	–	1
Typocerus lunulatus (Swederus)	–	1	–	–	1	–	–	–	–	–	2
Typocerus velutinus (Olivier)	1	–	2	–	–	2	2	2	12	3	24
Typocerus zebra (Olivier)	1	27	–	–	8	–	–	–	–	–	36
Urgleptes querci (Fitch)	–	–	–	–	–	–	–	2	–	–	2
Xylotrechus colonus (F.)	3	–	5	–	7	2	1	–	1	4	23
Xylotrechus convergens LeConte	–	–	1	–	–	–	–	–	–	–	1
Xylotrechus integer (Haldeman)	–	–	–	14	–	2	–	3	4	–	23
Xylotrechus sagittatus (Germar)	102	1,353	1,039	19	490	124	228	307	280	196	4,138
Xylotrechus undulatus (Say)	–	–	1	1	–	–	–	1	–	–	3
Total number of beetles	3,499	3,184	1,861	1,034	1,068	527	912	612	606	2,034	15,336
Total number of species	22	36	36	24	38	32	27	25	32	34	95

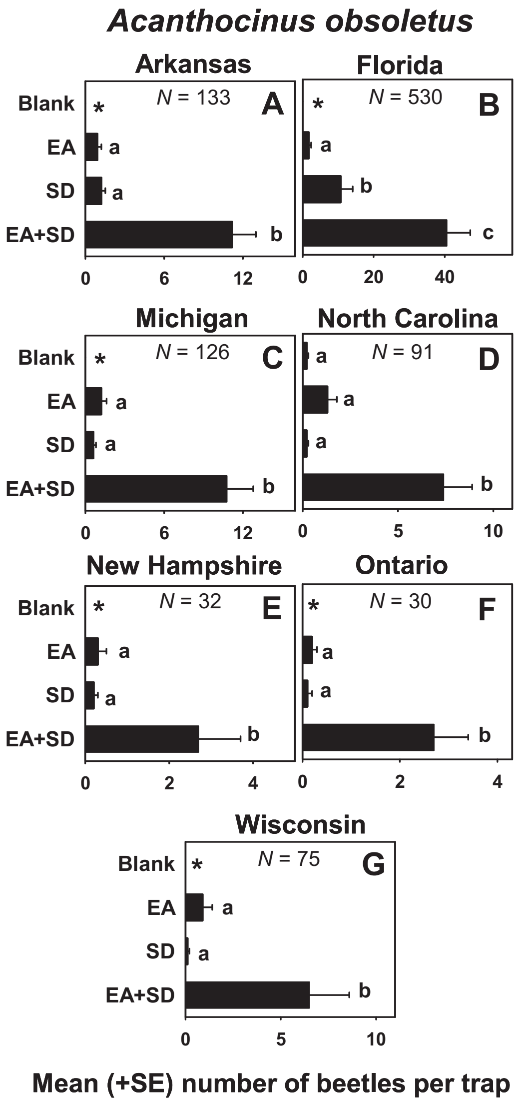

Fig. 1. Mean (+SE) number of *Ac. obsoletus* captured in multiple-funnel traps baited with ethanol + α-pinene (EA), ipsenol + ipsdienol (SD), and all four compounds (EA + SD) in Arkansas (A), Florida (B), Michigan (C), North Carolina (D), New Hampshire (E), Ontario (F), and Wisconsin (G). At each location, means followed by the same letter are not significantly different at $P = 0.05$ (Holm–Sidak test). Treatment with an asterisk had 0 catches. N = Total trap catch of beetles per location.

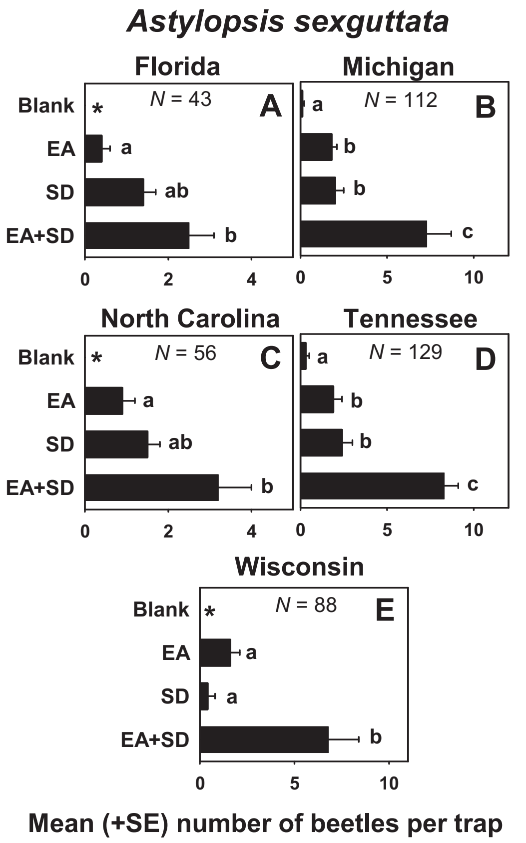

Fig. 2. Mean (+ SE) number of *As. sexguttata* captured in multiple-funnel traps baited with ethanol + α-pinene (EA), ipsenol + ipsdienol (SD), and all four compounds (EA + SD) in Florida (A), Michigan (B), North Carolina (C), Tennessee (D), and Wisconsin (E). At each location, means followed by the same letter are not significantly different at $P = 0.05$ (Holm–Sidak test). Treatment with an asterisk had 0 catches. N = Total trap catch of beetles per location.

(Pepper et al. 1997) for locations where sufficient numbers of individuals ($N \geq 30$) were captured for each species. Normality and homoscedasticity were verified using the Kolmogorov–Smirnov and equal variance tests, respectively, with the SigmaStat (ver. 3.01) statistical package (SYSTAT Software Inc., Point Richmond, CA). To ensure homoscedasticity in our analyses, treatments for some species were omitted from analyses when means and variances for a treatment at a location were both zero (Reeve and Strom 2004). To determine effects of treatments across locations, data were subjected to analysis of variance (ANOVA) with the SYSTAT statistical package (SYSTAT Software Inc.) using the following model components (Model 1): 1) replicate (nested within location); 2) location; 3) treatment; and 4) location × treatment. Data sets with only two nonzero treatment means were not analyzed across locations. To determine treatment effects within locations, trap catch data for each location were subjected to ANOVA with the SigmaStat package using the following model components (Model 2): 1) replicate and 2) treatment. The Holm–Sidak multiple comparison procedure (Glantz 2005) in SigmaStat was used to compare means within a location for each species exhibiting a significant treatment effect ($\alpha = 0.05$).

Results

We captured 15,336 longhorn beetles in our study, representing 95 species of Cerambycidae (Table 2).

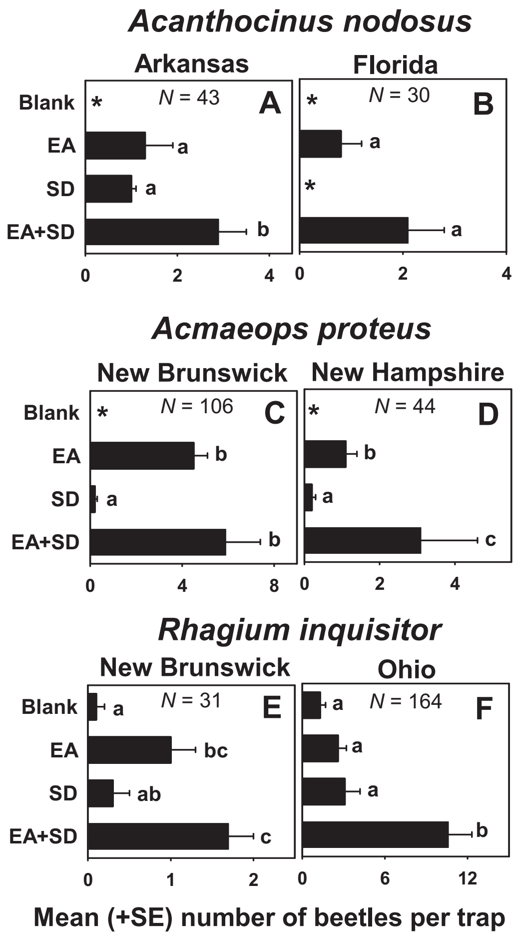

Fig. 3. Mean (+SE) number of *Ac. nodosus* (A and B), *Acm. proteus* (C and D), and *R. inquisitor* (E and F) captured in multiple-funnel traps baited with ethanol + α-pinene (EA), ipsenol + ipsdienol (SD), and all four compounds (EA + SD) in Arizona (A), Florida (B), New Brunswick (C and E), New Hampshire (D), and Ohio (F). At each location, means followed by the same letter are not significantly different at $P = 0.05$ (Holm–Sidak test). Treatment with an asterisk had 0 catches. N = Total trap catch of beetles per location.

Total beetle catches per location ranged from 527 to 3,499 with the number of species ranging from 22 to 38 per location. *Monochamus* species were the most common group, representing 38.4% of total catches of longhorn wood borers. Our results for *Monochamus* spp. have been presented previously and demonstrated a preference by three eastern species, *M. carolinensis*, *M. scutellatus*, and *M. titillator* complex, for traps baited with the quaternary lure blend (Miller et al. 2013).

Five additional species of pine-colonizing cerambycids exhibited a preference for traps baited with the quaternary blend in eastern North America (Figs. 1–3). There was a significant treatment effect on catches of *Ac. obsoletus* and *As. sexguttata* across seven and five locations, respectively (Table 3). At each location, catches of beetles were greatest in traps baited with the quaternary blend (Figs. 1 and 2). There was a significant interaction between treatment and location on catches of both species (Table 3). Mean catches of *Ac. obsoletus* in traps with the binary blend of ipsenol and ipsdienol were greater than those in traps with the binary blend of ethanol and α-pinene in Florida (Fig. 1B) but not at the other six locations (Fig. 1A, C–G). Mean catches of *As. sexguttata* in traps baited with the quaternary blend were greater than those in the binary blend of ipsenol and ipsdienol in Michigan, Tennessee, and Wisconsin (Fig. 2B, D, and E), but not in Florida or North Carolina (Fig. 2A and C).

Ac. nodosus was caught in sufficient numbers for analyses at only two locations (Table 2). In Arkansas, the mean catch of *Ac. nodosus* in traps baited with the quaternary bait blend was greater than that in traps baited with either binary blend; no beetles were caught in the blank control traps (Fig. 3A). In Florida, there was no significant difference between mean catches in traps baited with the quaternary blend and those baited with the binary blend of ethanol and α-pinene; no beetles were captured in blank control traps or in those baited with ipsenol and ipsdienol (Fig. 3B).

There was a significant treatment effect on catches of *Acmaeops proteus* (Kirby) and *R. inquisitor*, although differences occurred between locations (Table 3). For both species at both locations, the greatest catches were in traps baited with the quaternary blend

Table 3. ANOVA of treatment (T), location (L), interaction between treatment and location (T × L), and replicate nested within location (Rep{within L}) on catches of Cerambycidae and Buprestidae (Coleoptera) in eastern North America

Species	Treatment (T)			Location (L)			T × L			Rep {within L}			Error
	df	*F*	*P*	df	*F*	*P*	df	F	P	df	*F*	*P*	df
CERAMBYCIDAE													
Acanthocinus obsoletus	2	163.2	<0.01	6	34.7	<0.01	12	5.8	<0.01	63	1.2	0.19	126
Acmaeops proteus	2	55.8	<0.01	1	19.8	<0.01	2	7.4	<0.01	18	1.7	0.09	36
Asemum striatum	3	190.5	<0.01	4	34.5	<0.01	12	4.4	<0.01	44	1.3	0.11	132
Astylopsis sexguttata	2	14.4	<0.01	4	2.5	<0.01	8	2.0	0.06	45	0.2	0.99	90
Judolia cordifera	3	3.0	0.04	1	0.1	0.98	3	0.9	0.43	18	1.4	0.19	54
Rhagium inquisitor	3	21.5	<0.01	1	68.2	<0.01	3	2.6	0.07	17	1.2	0.29	51
BUPRESTIDAE													
Buprestis lineata	3	94.7	<0.01	3	58.4	<0.01	9	3.4	<0.01	36	1.9	<0.01	108
Chalcophora virginiensis	3	9.6	<0.01	2	15.1	<0.01	6	1.1	0.39	27	2.1	<0.01	81

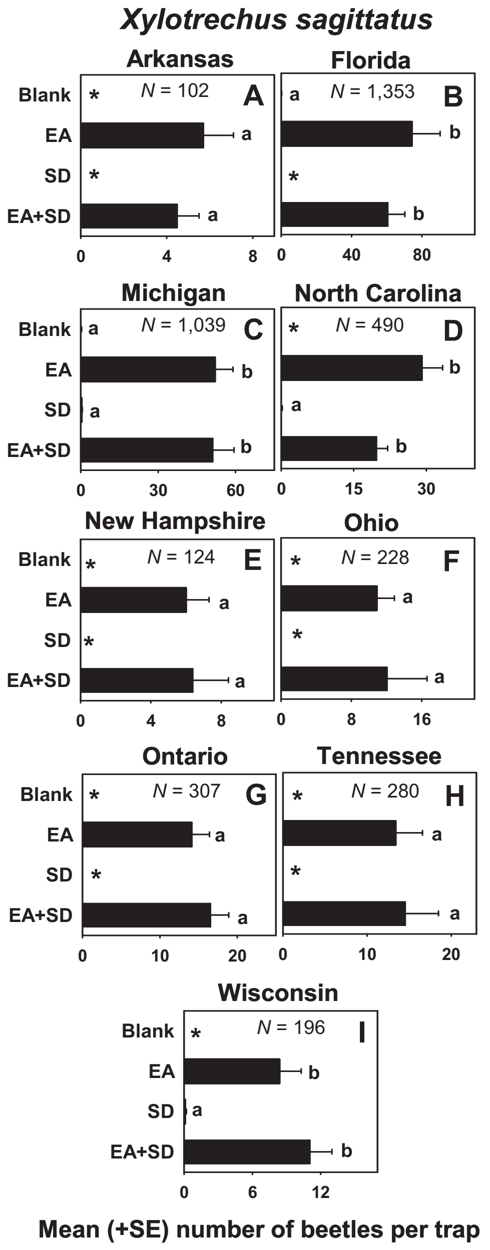

Fig. 4. Mean (+SE) number of *X. sagittatus* captured in multiple-funnel traps baited with ethanol + α-pinene (EA), ipsenol + ipsdienol (SD), and all four compounds (EA + SD) in Arkansas (A), Florida (B), Michigan (C), North Carolina (D), New Hampshire (E), Ohio (F), Ontario (G), Tennessee (H), and Wisconsin (I). At each location, means followed by the same letter are not significantly different at $P = 0.05$ (Holm–Sidak test). Treatments with an asterisk had 0 catches. N = Total trap catch of beetles per location.

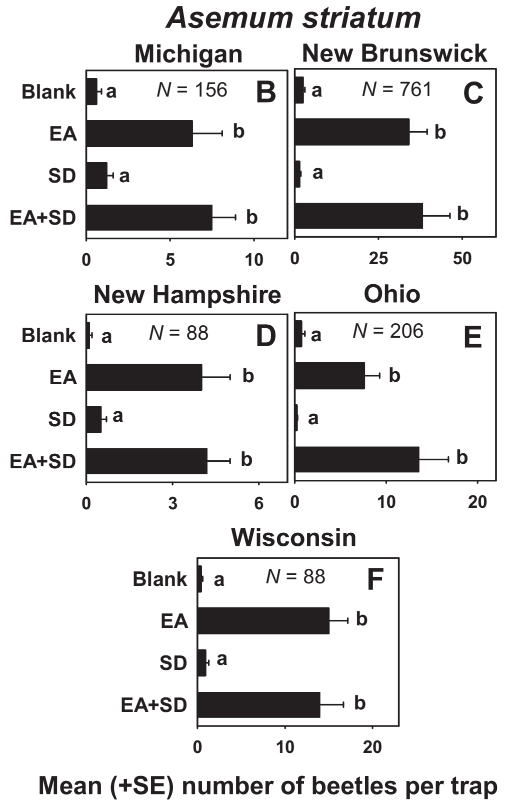

Fig. 5. Mean (+ SE) number of *As. striatum* captured in multiple-funnel traps baited with ethanol + α-pinene (EA), ipsenol + ipsdienol (SD), and all four compounds (EA + SD) in Michigan (A), New Brunswick (B), New Hampshire (C), Ohio (D), and Wisconsin (F). Means followed by the same letter are not significantly different at $P = 0.05$ (Holm–Sidak test). Treatment with an asterisk had 0 catches. N = Total trap catch of beetles per location.

(Fig. 3C–F). The mean catches of *Acm. proteus* and *R. inquisitor* in traps baited with the quaternary blend were different from those in traps baited with the binary blend of ethanol and α-pinene in New Hampshire for *Acm. proteus* and Ohio for *R. inquisitor* but not in New Brunswick for either species (Fig. 3C and D).

The binary blend of ipsenol and ipsdienol had no effect on catches of seven other species of Cerambycidae (Figs. 4–7). *X. sagittatus* was widely distributed across all locations and accounted for 27.0% of total catch (Table 2). At nine locations, mean catches in traps baited with ipsenol and ipsdienol were equal to, or close to, zero, similar to those in blank control traps (Fig. 4). Adding ipsenol and ipsdienol to the blend of ethanol and α-pinene did not enhance or reduce trap catches. The same pattern was observed for *As. striatum* in Michigan, New Brunswick, New Hampshire, Ohio, and Wisconsin (Fig. 5), *Tetropium* spp. in Michigan, New Hampshire, Ohio, and Ontario (Fig. 6A–D), and *Ar. rusticus* in Florida (6E).

In North Carolina, catches of *Judolia cordifera* (Olivier) were greater in traps baited with the quaternary blend than in those baited with ipsenol and ipsdienol (Fig. 7A), whereas there was no significant treatment effect in New Hampshire (Fig. 7B). Catches of

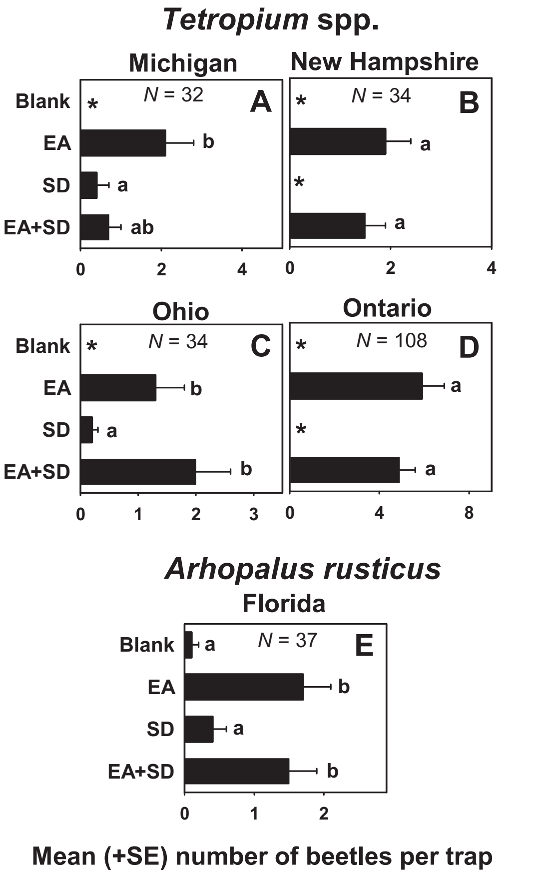

Fig. 6. Mean (+SE) number of *Tetropium* spp. (A–D), and *Ar. rusticus* (E) captured in multiple-funnel traps baited with ethanol + α-pinene (EA), ipsenol + ipsdienol (SD), and all four compounds (EA + SD) in Florida (E), Michigan (A), New Hampshire (B), Ohio (C), and Ontario (D). At each location, means followed by the same letter are not significantly different at $P = 0.05$ (Holm–Sidak test). Treatments with an asterisk had 0 catches. N = Total trap catch of beetles per location.

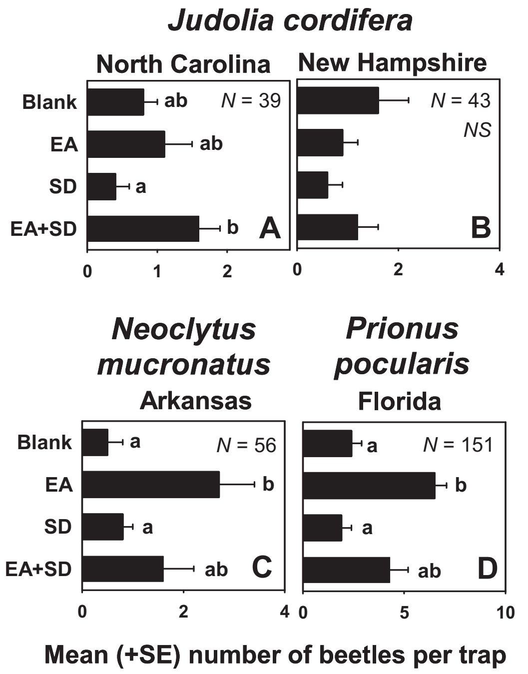

Fig. 7. Mean (+ SE) number of *J. cordifera*. (A and B), *N. mucronatus* (C), and *P. pocularis* (D) captured in multiple-funnel traps baited with ethanol + α-pinene (EA), ipsenol + ipsdienol (SD), and all four compounds (EA + SD) in North Carolina (A), New Hampshire (B), Arkansas (C), and Florida (D). At each location, means followed by the same letter are not significantly different at $P = 0.05$ (Holm–Sidak test). N = Total trap catch of beetles per location.

Neoclytus mucronatus (F.) and *P. pocularis* in Arkansas and Florida, respectively, were greater in traps baited with ethanol and α-pinene than in blank control traps (Fig. 7C and D).

We captured 1,858 metallic wood borers in our study, representing 25 species of Buprestidae (Table 4). Total beetle catches per location ranged from 3 to 795 with the number of species ranging from 1 to 13 per location. *Buprestis* species were the most common group, representing 73.4% of total catches of flat-headed wood borers. There was a significant treatment effect on catches of *B. lineata*, although differences occurred between locations (Table 3). In Arkansas, Florida, and Tennessee, catches in traps baited with the quaternary blend were significantly greater than those in blank control traps but only significantly different from those baited with the binary blends in Arkansas and Florida (Fig. 8A, B, and D). In North Carolina, catches were greatest in traps baited with ethanol and α-pinene and unaffected by the addition of ipsenol and ipsdienol (Fig. 8C). The same was true for *Buprestis maculipennis* Gory in Florida (Fig. 8E).

There was a significant treatment effect on catches of *Chalcophora virginiensis* (Drury), although differences occurred between locations (Table 3). Treatment effects were not discernable in Arkansas and Florida (Fig. 9A and B), whereas in Wisconsin, catches of *C. virginiensis* were greatest in traps baited with ipsenol and ipsdienol with no interruptive effect of ethanol and α-pinene (Fig. 9C). Trap treatments had no effect on catches of *Chrysobothris femorata* (Olivier) in Florida ($F_{3,27} = 0.618$; $P = 0.610$) with an overall mean (±SE) catch of 2.5 ± 0.7 beetles per trap.

Discussion

Our results provide important information on lures for numerous species of North American wood borers that can be used by managers of detection programs outside of North America that monitor for invasions by North American species. In addition to six North American species of *Monochamus* previously reported in Miller et al. (2013), we found that the quaternary blend of ethanol, α-pinene, ipsenol, and ipsdienol was

Table 4. Total numbers of flat–headed wood borers (Buprestidae) captured at 10 locations in eastern North America (2007–2008)

Species	Arkansas	Florida	Michigan	New Brunswick	North Carolina	New Hampshire	Ohio	Ontario	Tennessee	Wisconsin	Total
Acmaeodera spp.	1	–	–	–	–	–	–	–	–	–	1
Acmaeodera tubulus (F.)	–	1	–	–	–	–	–	–	–	–	1
Actenodes acornis (Say)	–	11	–	–	–	–	–	–	–	–	11
Buprestis apricans Herbst	–	6	–	–	–	–	–	–	–	–	6
Buprestis consularis Gory	4	–	–	–	–	–	–	–	–	–	4
Buprestis lineata F.	517	277	–	–	78	–	5	–	138	–	1,015
Buprestis maculativentris Say	15	–	–	–	–	–	–	–	–	–	15
Buprestis maculipennis Gory	2	292	–	–	–	–	–	–	–	–	294
Buprestis rufipes Olivier	1	1	–	–	–	–	–	–	–	–	2
Buprestis salisburyensis Herbst	–	–	–	–	1	–	–	–	–	–	1
Buprestis striata F.	–	–	6	–	–	5	5	5	–	6	27
Chalcophora virginiensis (Drury)	152	104	–	–	–	–	–	1	–	64	321
Chrysobothris spp.	3	–	–	–	–	2	–	–	–	–	5
Chrysobothris chrysoela (Illiger)	–	1	–	–	–	–	–	–	–	–	1
Chrysobothris cribraria Mannerheim	3	–	–	–	–	–	–	–	–	–	3
Chrysobothris dentipes (Germar)	3	–	–	–	–	–	1	–	–	–	4
Chrysobothris femorata (Olivier)	10	100	–	–	–	–	1	–	1	1	113
Chrysobothris harrisi (Hentz)	–	–	–	–	–	1	–	–	–	–	1
Chrysobothris sexsignata Say	–	1	1	–	–	–	4	–	2	–	8
Dicerca divaricata (Say)	–	–	–	–	1	1	3	2	–	–	7
Dicerca lurida (F.)	2	–	–	–	1	–	4	–	–	–	7
Dicerca obscura (F.)	–	1	–	–	–	–	–	–	–	–	1
Dicerca punctulata (Schönherr)	1	–	–	–	–	–	–	—	–	–	1
Dicerca tenebrosa (Kirby)	–	–	–	3	–	–	–	2	–	2	7
Phaenops aeneola (Melsheimer)	–	–	–	–	–	–	–	2	–	–	2
Total no. of beetles	714	795	7	3	81	9	23	12	141	73	1,858
Total no. of species	13	12	2	1	4	4	7	5	3	4	

broadly attractive to five species of eastern Cerambycidae (Figs. 1–3), all known to breed in pines (Lingafelter 2007). Furthermore, the combination of ethanol and α-pinene was attractive to five species of pine-feeding and two species of hardwood-feeding Cerambycidae with minimal interruptive effect of ipsenol and ipsdienol on trap catches (Figs. 4–7). Our findings agree with results from previous studies (Allison et al. 2004, Miller 2006, Miller et al. 2011).

The consistency of our results across such a large geographic area suggest that similar selection pressures may be acting on host finding behaviors by pine-feeding Cerambycidae in pine forests, throughout a range of pine compositions and climates. Wood borers typically colonize stressed, dead, and dying trees (Furniss and Carolin 1980), trees that typically release ethanol (Kelsey 1994, 1996; Kelsey and Joseph 1998, 2003). The monoterpene α-pinene is a major constituent of the oleoresin of most pines (Mirov 1961, Smith 2000). Therefore, it is not surprising that pine-inhabiting species of Cerambycidae are attracted to ethanol and α-pinene (Allison et al. 2004).

Throughout North America, engraver beetles, *Ips* spp. are typically the earliest invaders of recently dead or highly stressed pines, such as lightning-struck trees, or recently downed live trees or limbs (Furniss and Carolin 1980, USDA 1985), producing such pheromones as ipsenol and ipsdienol (Borden 1982; Smith et al. 1993; Allison et al. 2004, 2012a). For some species of Cerambycidae, the presence of ipsenol and ipsdienol in addition to ethanol and α-pinene likely indicates host conditions with high suitability for oviposition and larval development (Allison et al. 2004, Miller et al. 2011); some species require fresh phloem tissues for early larval development (Furniss and Carolin 1980, USDA 1985). The lack of response by some cerambycids to ipsenol and ipsdienol may relate to a broad host range or their use of hosts in a greater state of decay. For example, hosts for *As. striatum* and *Tetropium* spp. include larch and true firs (Lingafelter 2007), none of which serve as hosts for *Ips* species (USDA 1985).

Broad-spectrum lures that attract numerous species such as our quaternary blend are important considerations for managers of early detection programs for adventive species. Managers face an important logistical issue, given the limited funds and operational resources (Hanks et al. 2012). There are hundreds of potential adventive species that could impact our forest resources if they were ever introduced into North America. Should managers deploy separate traps with species-specific lures for all these species at a low number of sites? Or should they deploy a few traps baited with a couple of broad-spectrum lures at numerous sites? At present, managers typically choose the latter in detecting new introductions as part of an integrated detection and response program. Species-specific lures are typically used when an introduction has been confirmed and managers are attempting an eradication or long-term management program.

National detection programs for bark and ambrosia beetles such as EDRR and CAPS typically deploy three

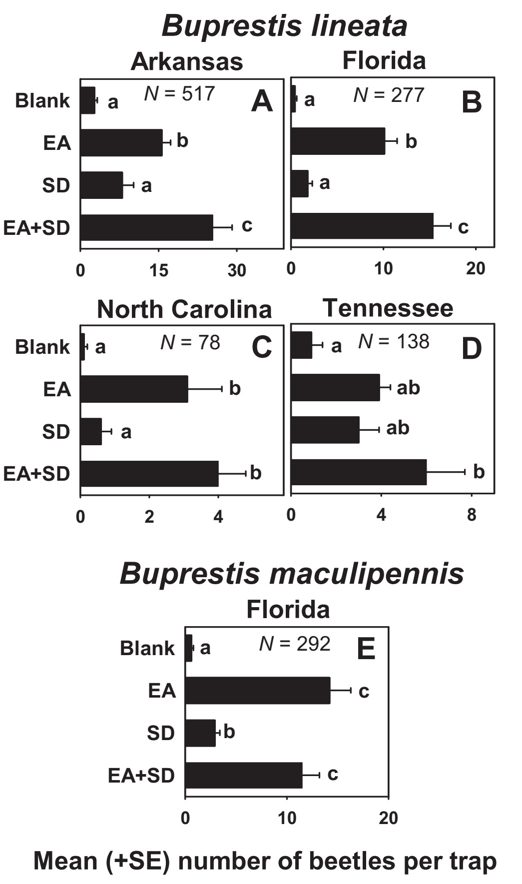

Fig. 8. Mean (+SE) number of *B. lineata* (A–D), and *B. maculipennis* (E) captured in multiple-funnel traps baited with ethanol + α-pinene (EA), ipsenol + ipsdienol (SD), and all four compounds (EA + SD) in Arkansas (A), Florida (B and E), North Carolina (C), and Tennessee (D). At each location, means followed by the same letter are not significantly different at $P = 0.05$ (Holm–Sidak test). N = Total trap catch of beetles per location.

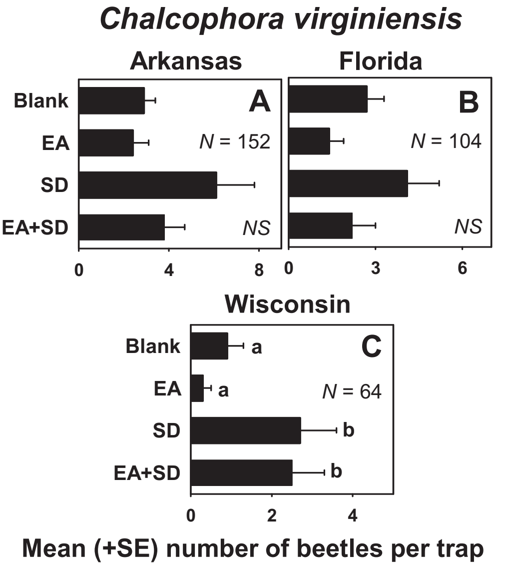

Fig. 9. Mean (+SE) number of *C. virginiensis* captured in multiple-funnel traps baited with ethanol + α-pinene (EA), ipsenol + ipsdienol (SD), and all four compounds (EA + SD) in Arkansas (A), Florida (B), and Wisconsin (C). At each location, means followed by the same letter are not significantly different at $P = 0.05$ (Holm–Sidak test). N = Total trap catch of beetles per location.

traps at each site, each baited with one of the following lure blends: 1) ethanol alone; 2) ethanol and α-pinene; and 3) ipsdienol, *cis*-verbenol, and methylbutenol. The first two lure blends are broadly attractive to bark and ambrosia beetles (Coyle et al. 2005; Miller and Rabaglia 2009; Reding et al. 2011; Kelsey et al. 2013; Ranger et al. 2010, 2011, 2014). The third lure blend is essentially a lure for *Ips typographus* L. (Borden 1982, Byers 2004) rather than a general lure for exotic *Ips* beetles. To be effective as a broad-spectrum lure for *Ips* species, other lures such as ipsdienol and lanierone should likely be added to the blend (Borden 1982; Miller et al. 1997, 2003; Byers 1989, 2004; Allison et al. 2012a).

A similar three-trap system for detection of wood borers such as Cerambycidae and Buprestidae could use traps baited with three different lure blends targeting Cerambycidae broadly. Hanks et al. (2014) used traps baited with various semiochemicals including ethanol, α-pinene, hydroxyketones, hexanediols, monochamol, fuscumol, and fuscumol acetate to determine the flight phenologies of 114 species of Cerambycidae in east central Illinois.

One trap could be baited with the quaternary lure blend of ethanol, α-pinene, ipsenol, and ipsdienol to broadly target the pine wood borer guild. The lure blend attracts ≥15 species of Cerambycidae as well as various metallic wood boring (Figs. 1–9). In Slovenia, Jurc et al. (2012) captured 17 species of Cerambycidae in traps baited with ethanol and α-pinene. In Italy, traps baited with α-pinene, ethanol, ipsenol, ipsdienol, and methylbutenol were efficient at trapping the cerambycids *Acanthocinus griseus* (F.), *Arhopalus syriacus* (L.), and *Monochamus galloprovincialis* (Olivier) (Francardi et al. 2009). Compounds such as ipsenol and α-pinene are important kairomones for *M. galloprovincialis* in Spain and Italy (Pajares et al. 2004, Ibeas et al. 2006, Rassati et al. 2012). Adding monochamol to the mix can enhance captures of *Monochamus* species in North America, China, and Europe (Pajares et al. 2010, Teale et al. 2011, Allison et al. 2012b, Fierke et al. 2012, Macias-Samano et al. 2012, Rassati et al. 2012, Ryall et al. 2015).

The second trap could be baited with a combination of ethanol, fuscumol, fuscumol acetate, and spruce volatiles, targeting beetles associated with spruce forests. Fuscumol is a pheromone used by a native cerambycid species, *Tetropium cinnamopterum* (Kirby) and an adventive one, *Tetropium fuscum* (F.) (Silk et al. 2007), both found in spruce forests with the latter first noted in Nova Scotia in 1999 (Smith and Hurley 2000).

Fuscumol, fuscumol acetate, and spruce volatiles are broadly attractive to numerous species of Cerambycidae (Sweeney et al. 2004, 2006, 2010; Mitchell et al. 2011; Hanks et al. 2012; Hanks and Millar 2013). Sweeney et al. (2014) found that combinations of ethanol, hydroxyketones, fuscumol, fuscumol acetate, and spruce volatiles captured 30 cerambycid species in the Russian Far East.

The third trap could be baited with a blend of hydroxyketones, hexanediols, and ethanol, targeting hardwood species of Cerambycidae (Hanks et al. 2012, Hanks and Millar 2013). In North America, traps baited with hexanediols are attractive to *Anelaphus parallelus* (Newman), *Anelaphus villosus* (F.), *Curius dentatus*, *Dorcaschema alternatum* (Say), *Megacyllene caryae* (Gahan), and *Neoclytus acuminatus* (F.) (Hanks et al. 2012, Hanks and Millar 2013). More than 11 species of Cerambycidae are attracted to traps baited with hydroxyketones (Hanks et al. 2012, Hanks and Millar 2013). In China, traps baited with generic lures of hexanediols and hydroxyketones were broadly attractive to >20 species of Cerambycidae (Wickham et al. 2014). Host volatiles such as ethanol can enhance responses of some species (Hanks and Millar 2013).

A multiple-trap system with several broadly attractive lures could reduce servicing costs and make better use of limited resources, relative to a large number of traps baited with species-specific lures. In light of current issues concerning trap efficiency for early detection of the emerald ash borer, *Agrilus planipennis* Fairmaire (Buprestidae) (Herms and McCullough 2014), we need to clearly state an important and general caveat with respect to trap efficiency in catching Cerambycidae and Buprestidae in pine forests. We have no estimate of population numbers for any of these species. Therefore, we cannot know the proportions of populations caught in baited traps for any species. In the absence of such information, we are inferring that protocols that increase relative numbers of beetles captured in traps should increase relative trap efficiency. We further infer that such protocols would also increase the likelihood of catching those species when population numbers are low, such as in the case of a new introduction of an adventive species. These inferences need to be verified with accurate estimates of trap efficiency so that managers of detection programs can have some measure of confidence in trapping protocols meeting their objectives.

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