

Trap Height Affects Catches of Bark and Woodboring Beetles (Coleoptera: Curculionidae, Cerambycidae) in Baited Multiple-Funnel Traps in Southeastern United States

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Abstract

In north-central Georgia, trap height affected catches of some species of bark and woodboring beetles (Coleoptera) in traps baited with lures used in surveillance programs to detect non-native forest insects. Traps were placed within the canopy and understory of mature oak trees (*Quercus* spp.) with collection cups placed 18–23 m above ground level (AGL), and 0.3–0.5 m AGL, respectively. Traps were baited with ethanol to target ambrosia beetles (Curculionidae: Scolytinae) in one experiment, ethanol + *syn*-2,3-hexanediol + racemic 3-hydroxyhexan-2-one + racemic 3-hydroxyoctan-2-one to target hardwood woodborers (Cerambycidae) in a second experiment, and α -pinene + racemic ipsenol + racemic ipsdienol to target pine bark beetles (Curculionidae) and woodborers (Cerambycidae) in a third experiment. Canopy traps were more effective than understory traps for detecting *Cnestus mutilatus* (Blandford) (Curculionidae), *Neoclytus scutellaris* (Olivier), and *Monochamus titillator* (F.) (Cerambycidae). The reverse was true for *Xylosandrus crassiusculus* (Motschulsky), *Dendroctonus terebrans* (Olivier) (Curculionidae), and *Neoclytus acuminatus* (F.) (Cerambycidae). Catches of a third group which included *Hylobius pales* (Herbst), *Ips grandicollis* (Eichhoff) (Curculionidae), *Neoclytus mucronatus* (F.), and *Anelaphus pumilus* (Newman) (Cerambycidae) were largely unaffected by trap height. Similar patterns were noted for species of Cleridae, Scarabaeidae, Trogossitidae, and Zopheridae but not Histeridae or Tenebrionidae (Coleoptera). Catches of the bee assassin *Apiomerus crassipes* (F.) (Hemiptera: Reduviidae) in traps baited with the hardwood borer blend were greater in canopy traps than in understory traps.

Key words: Cerambycidae, Curculionidae, ambrosia beetle, early detection, Scolytinae

Numerous species of forest insects continue to pose invasive risks to many countries worldwide (Brockhoff and Liebhold 2017, Inward 2019, Meurisse et al. 2019, Yu et al. 2019), necessitating the continued and expanded use of early detection trapping programs for species such as bark and woodboring beetles (Brockhoff et al. 2006, Grégoire and Evans 2007, Sweeney et al. 2016, Anderson et al. 2017, Canadian Food Inspection Agency [CFIA] 2017, Bowers et al. 2018, Rabaglia et al. 2019). Typically in such programs, baited panel or multiple-funnel traps are hung on poles, or ropes strung between trees, with collection cups spaced 0.3–0.5 m above ground level (AGL).

Research on canopy arthropods in the past several decades has documented differences in community structures of forest Coleoptera between canopy and understory environments (Kato et al. 1995, Su

and Woods 2001, Ulyshen and Hanula 2007, Wermelinger et al. 2007, Ulyshen et al. 2010, Graham et al. 2012, Vodka and Cizek 2013, Williams et al. 2017). For example, the diversity of Cerambycidae in eastern Canadian forests of *Acer saccharum* (Marshall) and *Pinus strobus* L. was higher in the canopy than in the understory whereas abundance was higher in the understory than in the canopy (Vance et al. 2003). In southeastern United States, Ulyshen and Sheehan (2019) found that the diversity and abundance of bark and woodboring beetles (Curculionidae, Buprestidae and Cerambycidae) in clear intercept traps increased with trap height whereas those of ambrosia beetles (Curculionidae) decreased with height.

Similar patterns are still apparent when traps are baited with attractants. In China, traps baited with ethanol caught more *Neocerambyx raddei* (Blessig & Solsky) (Cerambycidae) in the

canopy than in the understory (Li et al. 2017). Using funnel traps baited with ethanol + α -pinene + ipsenol + ipsdienol in thinned stands of *P. strobus* and *Pinus resinosa* Solander ex Aiton, Dodds (2014) found that *Ips pini* (Say) (Curculionidae) and *Monochamus carolinensis* (Olivier) (Cerambycidae) were more abundant in canopy traps than in understory traps, whereas *Dendroctonus valens* LeConte, *Gnathotrichus materiarius* (Fitch) (Curculionidae), and *Monochamus scutellatus* (Say) (Cerambycidae) were more common in understory traps. In a stand of *Quercus alba* L. and *Carya ovata* Miller (Koch) in Illinois, Schmeelk et al. (2016) used panel traps baited with hardwood borer pheromones and found that five species of Cerambycidae were more common in canopy traps, whereas three species were more common in understory traps. Flaherty et al. (2019) used traps baited with various pheromones and host volatiles in mixed hardwood-conifer stands in Canada and Poland, and found that trap height significantly affected mean catches or detection rates of 57 target species, with 29 species (13 Cerambycidae, 16 Scolytinae) detected most frequently in the understory and 28 species (3 Buprestidae, 17 Cerambycidae, and 8 Scolytinae) detected most frequently in the canopy. Using green and purple multiple-funnel traps baited with ethanol or ethanol + hardwood beetle pheromone blend, Rassati et al. (2019) found a canopy preference for Cerambycinae and certain species of Laminae but not Lepturinae (Cerambycidae) in hardwood stands in northeast Italy. In the Czech Republic, catches of *Monochamus galloprovincialis* (Olivier) (Cerambycidae) in baited traps placed in the canopy at heights of 18–23 m were seven times greater than those in traps placed at a height of 2 m (Foit et al. 2019).

Species-specific trapping protocols continue to be needed for species that are deemed high risk for invasion (Bowers et al. 2018, Yu et al. 2019). Our goal was to determine the species-specific effects of trap height on catches of bark and woodboring beetles in the southeastern United States in traps baited with lures used in operational surveillance programs for native and exotic species of bark and woodboring beetles worldwide (CFIA 2017, Bowers et al. 2018, Rabaglia et al. 2019). Such data should add weight to generalizations made across taxa and guilds (Vance et al. 2003, Flaherty et al. 2019, Rassati et al. 2019, Ulyshen and Sheehan 2019) as well as identify exceptions to those generalizations. We also determined the effect of trap height on catches of predators and other species associated with bark and woodboring beetles. Various species of insects including beetle predators and ectoparasites are commonly found in association with bark and woodboring beetles in live plants, wood-packaging materials, logs and shipping containers moved between countries (Humble and Allen 2001, Meurisse et al. 2019).

Materials and Methods

Three trapping experiments were conducted in a mature, closed-canopy, mixed-hardwood forest adjacent to the Charlie Elliott Wildlife Center (33.4619 N, 83.7320 W) near Mansfield, GA. The stand consisted primarily of *Q. alba*, *Quercus falcata* Michaux, *Quercus rubra* L., *Carya tomentosa* Sargent, and *Fagus grandifolia* Ehrhart with a few scattered *Pinus echinata* Miller. The heights of dominant trees ranged from 25 to 35 m.

In all three experiments, we used 10-unit multiple-funnel traps that were modified to allow placement of lures within the funnels (Miller et al. 2013). Collection cups contained an aqueous solution of propylene glycol (Splash RV & Marine Antifreeze, Fox Packaging Inc., St. Paul, MN) to kill and preserve insects (Miller and Duerr 2008). In each experiment, pairs of traps were deployed with one

trap in the canopy and the other in the understory; eight pairs in experiment 1 and six pairs in experiments 2 and 3. Canopy traps were hung from branches of oak trees by rope and pulleys (placed by tree climbers) at heights of 18–23 m AGL to bottom of collection cups. Understory traps were hung on ropes strung between trees such that the bottom of collection cups were 0.3–0.5 m AGL. The understory trap in each pair was deployed at a horizontal distance of 3–5 m from a vertical line directly below the canopy trap within the pair. Pairs of traps were spaced 15–25 m apart.

Traps were baited with various lures (Table 1) obtained from Scotts Canada (Delta, BC, Canada). Ethanol is broadly attractive to ambrosia beetles in the southeastern United States (Miller and Rabaglia 2009). Traps baited with the blend of ethanol, *syn*-2,3-hexanediol, 3-hydroxyhexan-2-one, and 3-hydroxyoctan-2-one attract numerous species of Cerambycidae in southeastern hardwood stands (Miller et al. 2017). The host kairomones ethanol and α -pinene, and the bark beetle pheromones ipsenol and ipsdienol are attractive to pine bark and woodboring species in southeastern pine stands (Miller and Asaro 2005, Miller 2006, Miller et al. 2011, Allison et al. 2012).

Traps in experiment 1 were all baited with ethanol (E) to target ambrosia beetles, whereas traps in experiment 2 were baited with ethanol + *syn*-2,3-hexanediol (D6) + 3-hydroxyhexan-2-one (K6) + 3-hydroxyoctan-2-one (K8) to target hardwood borers. In experiment 3, traps were baited with α -pinene (aP) + racemic ipsenol (Is) + racemic ipsdienol (Id) to target pine bark beetles and woodborers. Trapping periods for experiments 1–3 were 29 March–7 June 2016, 30 May–9 October 2014, and 6 August–9 October 2014, respectively. In experiment 2, ethanol lures were replaced once on 31 July, whereas D6, K6, and K8 lures were replaced three times (2 July, 31 July, and 16 September 2014). Lures were not replaced in experiments 1 and 3. Vouchers were retained at USDA Forest Service, Southern Research Station, Athens, GA and deposited in the UGA Collection of Arthropods, University of Georgia, Athens, GA.

For each experiment, data on catches of individual species were summed over the entire trapping period and analyzed by two-tailed paired *t*-test for each species caught in sufficient numbers for analyses ($N \geq 20$) using the SigmaStat (ver. 3.01) statistical package (SYSTAT Software Inc.). Normality was verified using the Shapiro–Wilk test. We used the Wilcoxon Signed Rank test (denoted by asterisk following *P* value) in cases where the data for a species failed the assumption of normality.

Results

Across our three studies, we caught a total of 23,261 bark and woodboring beetles (and associated beetle species) with 67.7% caught in canopy traps (Table 2). A total of 48 species were detected with 87.5% detected in both canopy and understory traps. Three

Table 1. Description of lures used in the study

Code	Compound	Release rate ^a
E	Ethanol UHR	0.5 g/d at 23°C
D6	<i>syn</i> -2,3-hexanediol	1.5 mg/d at 20°C
K6	3-Hydroxyhexan-2-one, racemic	20–25 mg/d at 20°C
K8	3-Hydroxyoctan-2-one, racemic	20–25 mg/d at 20°C
aP	α -Pinene UHR, 75% (-)	1–6 g/d at 23°C
Is	Ipsenol, racemic	0.1–0.2 mg/d at 23°C
Id	Ipsdienol, racemic	0.1–0.2 mg/d at 23°C

All chemical purities >95%.

^aDetermined by manufacturer.

Table 2. Trap catches of common bark and woodboring beetles, and associated species of beetles (Coleoptera), in three experiments comparing catches in baited multiple-funnel traps placed within the tree canopy to those within the understory in a hardwood stand in central Georgia

Family, species	Ground				Canopy				Grand total
	Exp. 1	Exp. 2	Exp. 3	Total	Exp. 1	Exp. 2	Exp. 3	Total	
Bostrichidae									
<i>Xylobiops basilaris</i> (Say)	–	258	–	258	–	116	–	116	374
Buprestidae									
<i>Buprestis lineata</i> F.	–	–	3	3	–	–	2	2	5
Cerambycidae									
<i>Acanthocinus obsoletus</i> (LeConte)	–	–	22	22	–	–	87	87	109
<i>Anelaphus pumilus</i> (Newman)	–	12	–	12	–	14	–	14	26
<i>Astylopsis arcuata</i> (LeConte)	–	–	–	–	–	–	1	1	1
<i>Astylopsis sexguttata</i> (Say)	–	–	–	–	–	–	2	2	2
<i>Cyrtophorus verrucosus</i> (Olivier)	8	1	–	9	–	1	–	1	10
<i>Eudermes pini</i> Olivier	–	6	–	6	–	–	–	–	6
<i>Monochamus titillator</i> (F.)	–	–	108	108	–	–	316	316	424
<i>Neoclytus acuminatus</i> (F.)	5	130	–	135	1	25	–	26	161
<i>Neoclytus jouteli</i> Davis	–	1	–	1	–	21	–	21	22
<i>Neoclytus mucronatus</i> (F.)	2	786	3	791	4	527	–	531	1,322
<i>Neoclytus scutellaris</i> (Olivier)	1	350	1	352	14	687	–	701	1,053
<i>Xylotrechus colonus</i> (F.)	26	39	–	65	2	1	–	3	68
<i>Xylotrechus sagittatus</i> (Germar)	–	–	10	10	–	–	47	47	57
Cleridae									
<i>Chariessa pilosa</i> (Forster)	–	40	–	40	–	38	–	38	78
<i>Thanasimus dubius</i> (F.)	–	–	21	21	–	–	129	129	150
Curculionidae									
<i>Ambrosiodmus obliquus</i> (LeConte)	66	–	6	72	14	–	6	20	92
<i>Ambrosiophilus atratus</i> (F.)	5	–	–	5	–	–	–	–	5
<i>Cyclorhipidion bodoanum</i> (Reitter)	14	–	–	14	4	–	–	47	61
<i>Cnesinus strigicollis</i> LeConte	5	–	–	5	2	–	–	2	7
<i>Cnestus mutilatus</i> (Blandford)	45	118	–	163	462	381	–	843	1,006
<i>Dendroctonus terebrans</i> (Olivier)	–	–	82	82	–	–	12	12	94
<i>Dryoxylon onobaransense</i> (Murayama)	559	34	–	593	27	8	–	35	628
<i>Euwallacea interjectus</i> (Blandford)	6	–	–	6	2	–	–	2	8
<i>Hylobius pales</i> (Herbst)	–	–	30	30	–	–	21	21	51
<i>Hylocurus rudis</i> (LeConte)	28	136	30	194	1	656	14	671	865
<i>Hypothenemus</i> spp.	164	59	–	223	126	36	–	162	385
<i>Ips avulsus</i> (Eichhoff)	–	–	216	216	–	–	852	852	1,068
<i>Ips calligraphus</i> (Germar)	–	–	132	132	–	–	188	188	320
<i>Ips grandicollis</i> (Eichhoff)	–	–	1,593	1,583	–	–	1,818	1,818	3,401
<i>Monarthrum fasciatum</i> (Say)	2	–	–	2	1	–	–	1	3
<i>Monarthrum mali</i> (Fitch)	35	1	–	36	20	37	–	57	93
<i>Pachylobius picivorus</i> (Germar)	–	–	15	15	–	–	20	20	35
<i>Stenoscelis brevis</i> (Boheman)	461	125	–	586	3	–	–	3	589
<i>Xyleborinus saxesenii</i> (Ratzeburg)	316	78	–	394	94	25	–	119	513
<i>Xyleborus</i> spp.	45	–	–	45	1	–	–	1	46
<i>Xylosandrus compactus</i> (Eichhoff)	5	–	–	5	–	–	–	–	5
<i>Xylosandrus crassiusculus</i> (Motschulsky)	257	413	–	670	11	39	–	50	720
<i>Xylosandrus germanus</i> (Blandford)	3	–	–	3	–	–	–	–	3
Histeridae									
<i>Platysoma</i> spp.	–	–	41	41	–	–	29	29	70
Passandridae									
<i>Catogenus rufus</i> (F.)	–	–	1	1	–	–	1	1	2
Scarabaeidae									
<i>Cotinus nitida</i> (L.)	–	–	–	–	–	28	35	63	63
Tenebrionidae									
<i>Corticeus</i> spp.	–	–	42	42	–	–	58	58	100
Trogossitidae									
<i>Temnoscheila virescens</i> (F.)	–	123	32	155	–	61	97	158	313
<i>Tenebroides</i> spp.	–	45	15	60	–	13	17	30	90
Zopheridae									
<i>Lasconotus</i> spp.	–	–	243	243	–	–	906	906	1,149
<i>Namunaria guttulata</i> (LeConte)	–	11	63	74	–	2	9	11	85

species were found only in canopy traps and three species were found only in understory traps. There were significant effects of trap height on catches of: 1) ambrosia beetles, 2) longhorn beetles, 3) bark and snout beetles, and 4) predators and associated species.

Ambrosia Beetles

In experiments 1 and 2, we captured eight species of ambrosia beetles in sufficient numbers for analyses (Table 2). Traps baited with ethanol in experiment 1 caught more *Cyclorhipidion bodoanum* (Reitter) (Coleoptera: Curculionidae) in the canopy than in the understory (Fig. 1A). Similarly, catches of *Cnestus mutilatus* (Blandford) were greater in canopy traps than in understory traps in experiments 1 and 2 (Fig. 1A and B). In contrast, understory traps caught more beetles than canopy traps for the following species: *Ambrosiodmus obliquus* (LeConte), *Dryoxylon onoharaense* (Murayama), *Xyleborinus saxesenii* (Ratzeburg), *Xyleborus* spp., and *Xylosandrus crassiusculus* (Motschulsky). One ambrosia beetle species exhibited disparate results between experiments 1 and 2. In

experiment 1, catches of *Monarthrum mali* (Fitch) were greater in understory traps than in canopy traps (Fig. 1A), whereas the reverse was true for *M. mali* in experiment 2 (Fig. 1B).

In all three experiments, most species of ambrosia beetles were detected in both canopy and understory traps. The exceptions were in experiment 1 where *Ambrosiophilus atratus* (F.), *Xylosandrus compactus* (Eichhoff), and *Xylosandrus germanus* (Blandford) were detected in understory traps but not in canopy traps.

Longhorn Beetles

Seven species of hardwood longhorn beetles (Cerambycidae) were captured in sufficient numbers for analyses in experiment 2 with traps baited with the hardwood cerambycid blend (E + D6 + K6 + K8) (Table 2). Catches of *Neoclytus scutellaris* (Olivier) and *Neoclytus jouteli* Davis were greater in canopy traps than in understory traps, whereas the reverse was true for *Neoclytus acuminatus* (F.) and *Xylotrechus colonus* (F.). Catches of *Neoclytus mucronatus* (F.), and *Anelaphus pumilus* (Newman) were unaffected by trap height (Fig. 2).

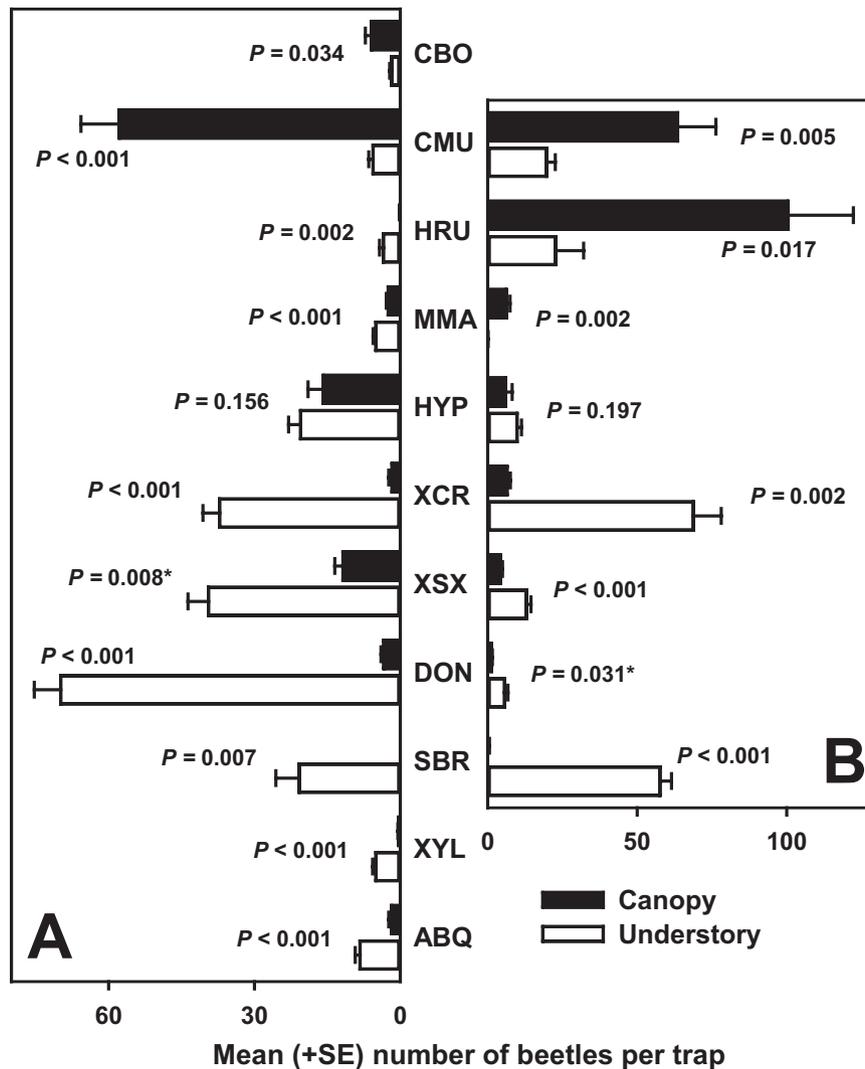


Fig. 1. Effect of height on mean (+SE) catches of snout and ambrosia beetles in multiple-funnel traps baited with ethanol in experiment 1 (A) and ethanol + syn-2,3-hexanediol + 3-hydroxyhexan-2-one + 3-hydroxyoctan-2-one in experiment 2 (B): *Ambrosiodmus obliquus* (ABQ), *Cnestus mutilatus* (CMU), *Cyclorhipidion bodoanum* (CBO), *Dryoxylon onoharaense* (DON), *Hylocurus rudis* (HRU), *Hypothenemus* spp. (HYP), *Monarthrum mali* (MMA), *Stenoscelis brevis* (SBR), *Xyleborinus saxesenii* (XSX), *Xyleborus* spp. (XYL) and *Xylosandrus crassiusculus* (XCR) (Coleoptera: Curculionidae). P = significance level between tree canopy and understory traps for paired t -test except those followed by an asterisk (Wilcoxon Signed Rank test).

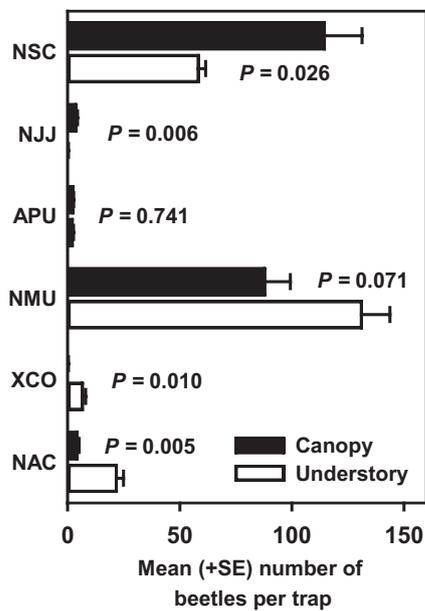


Fig. 2. Effect of height on mean (+SE) catches of hardwood woodborers in multiple-funnel traps baited ethanol + syn-2,3-hexanediol + 3-hydroxyhexan-2-one + 3-hydroxyoctan-2-one in experiment 2: *Anelaphus pumilus* (APU), *Neoclytus acuminatus* (NAC), *N. jouteli* (NJJ), *N. mucronatus* (NMU), *N. scutellaris* (NSC) and *Xylotrechus colonus* (XCO) (Coleoptera: Cerambycidae). *P* = significance level for paired t-test between tree canopy and understory traps.

In experiment 3, three species of pine longhorn beetles responded to traps baited with the softwood lure blend (aP + Is + Id) (Table 2). Trap catches of *Acanthocinus obsoletus* (LeConte), *Monochamus titillator* (F.), and *Xylotrechus sagittatus* (Germar) were all greater in canopy traps than in understory traps (Fig. 3).

In all three experiments, most species of Cerambycidae were detected in both canopy and understory traps. The exceptions were *Cyrtophorus verrucosus* (Olivier) and *Euderces pini* Olivier in experiments 1 and 2, respectively, which were not detected in canopy traps. The exceptions in experiment 3 were *N. mucronatus* and *N. scutellaris* which were not detected in canopy traps, and *Astylopsis arcuata* (LeConte) and *Astylopsis sexguttata* (Say) which were not detected in understory traps.

Bark and Snout Beetles

The snout beetle *Stenoscelis brevis* (Boheman) (Curculionidae) was more prevalent in understory traps than in canopy traps in experiments 1 and 2, (Fig. 1A and B). Trends in catches of *Hylocurus ruidis* (LeConte) differed among the three experiments. In experiment 1, catches of *H. ruidis* were greater in understory traps than in canopy traps (Fig. 1A), whereas the reverse was true in experiment 2 (Fig. 1B). There was no effect of trap height on catches of *H. ruidis* in experiment 3 (Fig. 3). Catches of twig beetles *Hypothenemus* spp. were unaffected by trap height in experiments 1 and 2 (Fig. 1A and B). In experiment 3, catches of *Dendroctonus terebrans* (Olivier) were greater in understory traps than in canopy traps (Fig. 3). Trap height had no effect on catches of the bark beetles *Ips avulsus* (Eichhoff), *I. calligraphus* (Germar), and *I. grandicollis* (Eichhoff), and the snout weevils *Hylobius pales* (Herbst) and *Pachylobius picivorus* (Germar).

In all three experiments, most species of Curculionidae were detected in both canopy and understory traps. The one exception was *S. brevis* in experiment 2 which was not detected in canopy traps.

Predators and Associated Species

Species in nine other families of Coleoptera were caught in sufficient numbers for analyses (Table 2) with most species detected in both canopy and understory traps. The one exception was the eastern June beetle *Cotinus nitida* (L.) (Scarabaeidae) which was collected only in canopy traps (Figs. 4 and 5). In experiment 2, more *Xylobiops basilaris* (Say) (Bostrichidae) were caught in understory traps than in canopy traps (Fig. 4).

The bark beetle predators, *Lasconotus* spp. (Zopheridae) and *Thanasimus dubius* (F.) (Cleridae) were significantly more prevalent in canopy traps than in understory traps, whereas the reverse was true for *Namunaria guttulata* (LeConte), *Corticeus* spp. (Tenebrionidae), *Platysoma* spp. (Histeridae), and *Chariessa pilosa* (Forster) (Fig. 5). Catches of *Tenebroides* spp. and *Temnoscheila virescens* (F.) (Trogossitidae) were greater in understory traps than in canopy traps in experiment 2 (Fig. 4) but not in experiment 3 (Fig. 5). In experiment 2, we caught a total of 127 bee assassins, *Apiomerus crassipes* (F.) (Hemiptera: Reduviidae), in traps baited with the hardwood lure blend (E + D6 + K6 + K8) with more *A. crassipes* caught in canopy traps than in understory traps (Fig. 4).

Discussion

Clearly, trap height can affect beetle catches in traps baited with lures commonly used in detection programs. In at least one experiment, catches of 4 of 15 common species of bark and ambrosia beetles, and 5 of 9 species of longhorn beetles were greater in canopy traps than understory traps (Figs. 1–3). Four of nine predatory species were also more common in canopy traps in at least one experiment (Figs. 4 and 5). The prevalence of these species in canopy traps is likely associated with opportunities for feeding, mating, and oviposition sites. Various species of pine cerambycids are known to feed on twigs and needles of pine trees, whereas some species of bark and ambrosia beetles infest twigs and small branches of mature trees (USDA 1985, Haack 2017). Predators are also more likely to be common in areas preferred by their prey (adult or larval). Not surprisingly, the leaf-feeding species *C. nitida* was only detected in canopy traps (Fig. 4).

The use of canopy traps may be particularly important for target species such as *C. mutilatus* and *M. titillator*. A native pest in Asia, *C. mutilatus* was first detected in northern Mississippi in 1999 (Schieffer and Bright 2004) and has now been reported in numerous states from Texas in the west, to Florida and North Carolina in the east, and Illinois, Indiana, Maryland, New Jersey, and Ohio in the north (Atkinson 2018, Rabaglia et al. 2019). Unlike other species of ambrosia beetles, *C. mutilatus* is more common in the canopy than in the understory, likely allowing for significant wind dispersal (Oliver et al. 2012, Sheehan et al. 2019). The beetle typically infests small-diameter branches and shoots of numerous species (Oliver et al. 2012, Warmund 2012, Olatinwo et al. 2014). As with other species of *Monochamus*, *M. titillator* is a known vector of the pinewood nematode, the causative agent of pine wilt disease, and is recognized as potential invasive pest by various countries (Akbulut and Stamps 2012, Vicente et al. 2012, Eyre and Haack 2017, Bragard et al. 2018, Carnegie et al. 2018). Adult *M. titillator* are commonly found in the canopy of pine trees, feeding on needles and twigs (USDA 1985).

We found an increase of more than 900% in catches of *C. mutilatus* in ethanol-baited traps placed within the canopy compared to those in the understory (Fig. 1A). There was an increase of almost 200% in catches of *M. titillator* for traps in the canopy in experiment 3 (Fig.

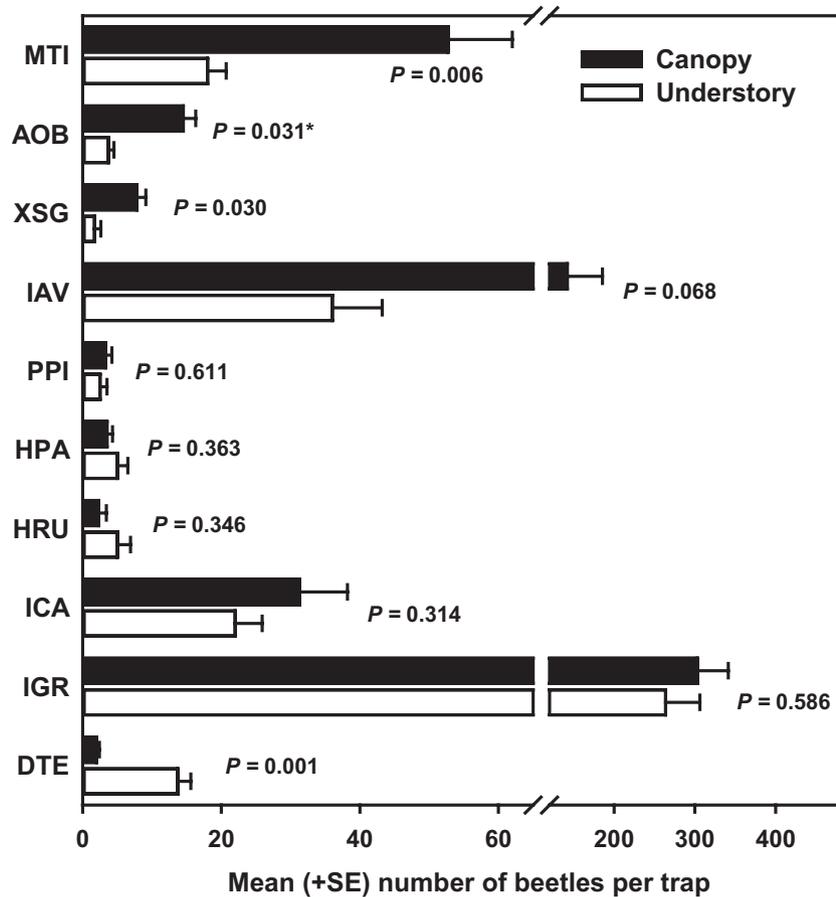


Fig. 3. Effect of height on mean (+SE) catches of pine bark and woodboring beetles in multiple-funnel traps baited with α -pinene + ipsenol + ipsdienol in experiment 3: *Acanthocinus obsoletus* (AOB), *Monochamus titillator* (MTI) and *Xylotrechus sagittatus* (XSG) (Coleoptera: Cerambycidae), *Dendroctonus terebrans* (DTE), *Hylobius pales* (HPA), *Hylocurus rudis* (HRU), *Ips avulsus* (IAV), *I. calligraphus* (ICA), *I. grandicollis* (IGR) and *Pachylobius picivorus* (PPI) (Curculionidae). P = significance level between tree canopy and understory traps for paired t -test except those followed by an asterisk (Wilcoxon Signed Rank test).

3). Early detection programs for exotic insects attempt to detect new arrivals typically at low population levels (Poland and Rassati 2019). If we assume that trap treatments resulting in greater catches of beetles are more effective in detecting those same species when populations are very low, then placing some traps in the canopy should increase the detection probability for species such as *C. mutillatus* and *M. titillator*. This may be particularly important in areas with natural sources of host odors such as ethanol and α -pinene, potentially competing with baited traps in attracting beetles.

The efficacy of canopy traps for some species does not negate the importance of using understory traps in a detection program. In at least one experiment, seven of eight species of ambrosia beetles were more abundant in understory traps than in canopy traps (Fig. 1). The bark beetle, *D. terebrans* and two of nine species of Cerambycidae were also more common in understory traps than in canopy traps (Figs. 2 and 3). The same was true for one predatory species, *N. guttulata* and the bostrichid *X. basilaris* (Figs. 4 and 5).

Our data and those of other authors (Dodds 2014, Schmeelk et al. 2016, Li et al. 2017, Flaherty et al. 2019, Rassati et al. 2019, Foit et al. 2019) provide support for the use of baited canopy traps in detection programs for specific species as well as for guilds of bark and woodboring beetles, and associated species such as bark beetle predators. Typically, detection programs targeting exotic bark and woodboring beetles have used baited traps deployed in the

understory. The lack of canopy traps in such programs has likely been due to various factors such as a lack of supporting data, insufficient program funds, and few cost-effective tools or methods to place traps in the canopy. New tools and tactics have been developed for deploying traps in the canopy in a cost-effective manner (e.g., Hughes et al. 2014). Managers must weigh the costs and benefits of adding or changing protocols in trapping programs for early detection of bark and woodboring beetles; trap height is only one of many factors that warrant consideration by managers (Poland and Rassati 2019).

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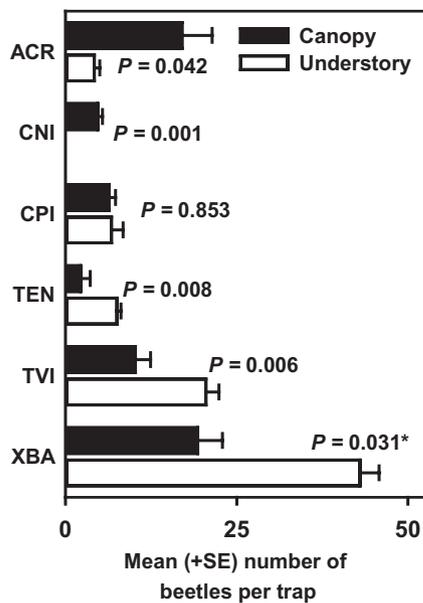


Fig. 4. Effect of height on mean (+SE) catches of species associated with hardwood woodborers in multiple-funnel traps baited ethanol + *syn*-2,3-hexanediol + 3-hydroxyhexan-2-one + 3-hydroxyoctan-2-one in experiment 2: *Apiomerus crassipes* (ACR) (Hemiptera: Reduviidae), *Chariessa pilosa* (CPI) (Coleoptera: Cleridae), *Cotinus nitida* (CNI) (Scarabaeidae), *Temnoscheila virescens* (TVI), *Tenebroides* spp. (TEN) (Trogossitidae) and *Xylobiops basilaris* (XBA) (Bostrichidae). *P* = significance level between tree canopy and understory traps for paired *t*-test except those followed by an asterisk (Wilcoxon Signed Rank test).

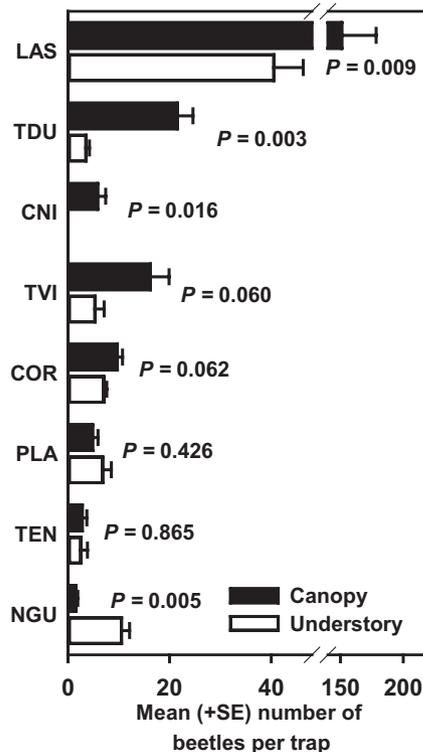


Fig. 5. Effect of height on mean (+SE) catches of species associated with pine bark and woodboring beetles in multiple-funnel traps baited with α -pinene + ipsenol + ipsdienol in experiment 3: *Corticus* spp. (COR) (Tenebrionidae), *Cotinus nitida* (CNI) (Scarabaeidae), *Lasconotus* spp. (LAS), *Namunaria guttulata* (NGU) (Zopheridae), *Platysoma* spp. (PLA) (Histeridae), *Temnoscheila virescens* (TVI), *Tenebroides* spp. (TEN) (Trogossitidae) and *Thanasimus dubius* (TDU) (Cleridae). *P* = significance level for paired *t*-test between tree canopy and understory traps.

suitable. The USDA is an equal opportunity provider, employer, and lender.

References Cited

- Akbulut, S., and W. T. Stamps. 2012. Insect vectors of the pinewood nematode: a review of the biology and ecology of *Monochamus* species. For. Pathol. 42: 89–99.
- Allison, J. D., J. L. McKenney, D. R. Miller, and M. L. Gimmel. 2012. Role of ipsdienol, ipsenol, and *cis*-verbenol in chemical ecology of *Ips avulsus*, *Ips calligraphus*, and *Ips grandicollis* (Coleoptera: Curculionidae: Scolytinae). J. Econ. Entomol. 105: 923–929.
- Anderson, C., S. Low-Choi, P. Whittle, S. Taylor, C. Gambley, L. Smith, P. Gillespie, H. Löcker, R. Davis, and B. Fominiak. 2017. Australian plant biosecurity surveillance systems. Crop Protect. 100: 8–20.
- Atkinson, T. H. 2018. Bark and ambrosia beetles of Southeastern U.S. (incl. Florida). *Cnestus mutilatus* (Blandford 1894) (introduced). (http://www.barkbeetles.info/regional_chklist_target_species.php?lookUp=2188) (accessed 8 March 2019).
- Bowers, J., L. Jackson, and R. Zink. 2018. Cooperative Agricultural Pest Survey (CAPS) 2019 National Pest Surveillance Guidelines. US Department of Agriculture–Animal and Plant Health Inspection Services–Plant Protection and Quarantine, Raleigh, NC (<https://caps.ceris.purdue.edu/pest-surveillance-guidelines/2019>) (accessed 8 March 2019).
- Bragard, C., K. Dehnen-Schultz, F. Di Serio, P. Gonthier, M.-A. Jacques, J. A. J. Miret, A. F. Justesen, A. MacLeod, C. S. Magnusson, J. A. Navas-Cortes, et al. 2018. Pest categorization of non-EU *Monochamus* spp. EFSJ 16: 5435.
- Brockerhoff, E. G., and A. M. Liebhold. 2017. Ecology of forest insect invasions. Biol. Invasion. 19: 3141–3159.
- Brockerhoff, E. G., J. Bain, M. Kimberley, and M. Knížek. 2006. Interception frequency of exotic bark and ambrosia beetles (Coleoptera: Scolytinae) and relationship with establishment in New Zealand and worldwide. Can. J. Forest. Res. 36: 289–298.
- Canadian Food Inspection Agency (CFIA). 2017. Plant protection survey report 2015–2017. CFIA, Ottawa, ON, Canada. (<http://publications.gc.ca/site/eng/9.831610/publication.html>) (accessed 4 April 2019).
- Carnegie, A. J., T. Venn, S. Lawson, M. Nagel, T. Wardlaw, N. Cameron, and I. Last. 2018. An analysis of pest risk and potential economic impact of pine wilt disease to *Pinus* plantations in Australia. Aust. For. 81: 24–36.
- Dodds, K. J. 2014. Effect of trap height on captures of arboreal insects in pine stands of northeastern United States of America. Can. Entomol. 146: 80–89.
- Eyre, D., and R. A. Haack. 2017. Invasive cerambycid pests and biosecurity measures, pp. 563–618. In Q. Wang (ed.), *Cerambycidae of the world. Biology and pest management*. CRC Press, Taylor & Francis, Boca Raton, FL.
- Flaherty, L., J. M. Gutowski, P. Mayo, T. Mokrzycki, G. Pohl, P. Silk, R. Webster, C. Hughes, K. Van Rooyen, and J. Sweeney. 2019. Pheromone-enhanced lure blends and multiple trap heights improve detection of bark and wood-boring beetles potentially moved in solid wood packaging. J. Pest Sci. 92: 309–325.
- Foit, J., V. Čermák, V. Gaar, K. Hradil, V. Nový, and P. Rolincová. 2019. New insights into the life history of *Monochamus galloprovincialis* can enhance surveillance strategies for the pinewood nematode. J. Pest Sci. 92: 1203–1215.
- Graham, E. E., T. M. Poland, D. G. McCullough, and J. G. Millar. 2012. A comparison of trap type and height for capturing cerambycid beetles (Coleoptera). J. Econ. Entomol. 105: 837–846.
- Grégoire, J.-C., and H. F. Evans. 2007. Damage and control of BAWBILT organisms: an overview, pp. 19–37. In F. Lieutier, K. R. Day, A. Battisti, J.-C. Grégoire, and H. F. Evans (eds.), *Bark and wood boring insects in living trees in Europe, a synthesis*. Springer, Dordrecht, the Netherlands.
- Haack, R. A. 2017. Feeding biology of cerambycids, pp. 105–132. In Q. Wang (ed.), *Cerambycidae of the world. Biology and pest management*. CRC Press, Taylor & Francis, Boca Raton, FL.
- Hughes, C. C., R. C. Johns, and J. D. Sweeney. 2014. A technical guide to installing beetle traps in the upper crown of trees. J. Acad. Entomol. Soc. 10: 12–18.

- Humble, L. M., and E. A. Allen. 2001. Implications of nonindigenous introductions in forest ecosystems, pp. 45–51. In A. M. Liebhold, M. L. McManus, I. S. Otvos, and S. L. C. Fosbroke (eds.), *Proceedings—integrated management and dynamics of forest defoliating insects*. US Department of Agriculture–Forest Service Gen. Tech. Rep. NE-277.
- Inward, D. J. G. 2019. Three new species of ambrosia beetles established in Great Britain illustrate unresolved risks from imported wood. *J. Pest Sci.* doi:10.1007/s10340-019-01137-1.
- Kato, M., T. Inque, A. A. Hamid, T. Nagamitsu, M. B. Merdek, A. R. Nona, T. Itino, S. Yamane, and T. Yumoto. 1995. Seasonality and vertical structure of light-attracted insect communities in a dipterocarp forest in Sarawak. *Res. Popul. Ecol.* 37: 59–79.
- Li, Y., Q. Meng, P. Silk, W. Gao, P. Mayo, and J. Sweeney. 2017. Effect of semiochemicals and trap height on catch of *Neocerambyx raddei* in Jilin province, China. *Entomol. Exp. Appl.* 164: 94–101.
- Meurisse, N., D. Rassati, B. P. Hurley, E. G. Brockerhoff, and R. A. Haack. 2019. Common pathways by which non-native forest insects move internationally and domestically. *J. Pest Sci.* 92: 13–27.
- Miller, D. R. 2006. Ethanol and (-)-alpha-pinene: attractant kairomones for some large wood-boring beetles in southeastern USA. *J. Chem. Ecol.* 32: 779–794.
- Miller, D. R., and C. Asaro. 2005. Ipsenol and ipsdienol attract *Monocharmus titillator* (Coleoptera: Cerambycidae) and associated large pine woodborers in southeastern United States. *J. Econ. Entomol.* 98: 2033–2040.
- Miller, D. R., and D. A. Duerr. 2008. Comparison of arboreal beetle catches in wet and dry collection cups with Lindgren multiple funnel traps. *J. Econ. Entomol.* 101: 107–113.
- Miller, D. R., and R. J. Rabaglia. 2009. Ethanol and (-)-alpha-pinene: attractant kairomones for bark and ambrosia beetles in the southeastern US. *J. Chem. Ecol.* 35: 435–448.
- Miller, D. R., C. Asaro, C. M. Crowe, and D. A. Duerr. 2011. Bark beetle pheromones and pine volatiles: attractant kairomone lure blend for longhorn beetles (Cerambycidae) in pine stands of the southeastern United States. *J. Econ. Entomol.* 104: 1245–1257.
- Miller, D. R., C. M. Crowe, B. F. Barnes, K. J. Gandhi, and D. A. Duerr. 2013. Attaching lures to multiple-funnel traps targeting saproxylic beetles (Coleoptera) in pine stands: inside or outside funnels? *J. Econ. Entomol.* 106: 206–214.
- Miller, D. R., C. M. Crowe, J. D. Sweeney, P. D. Mayo, and P. J. Silk. 2017. Interactions between 2,3-hexanediol and 3,2-hydroxyketone lures on trap catches of hardwood beetles in Georgia. *J. Econ. Entomol.* 110: 2119–2128.
- Olatinwo, R., D. Streett, and C. Carlton. 2014. Habitat suitability under changing climatic conditions for the exotic ambrosia beetle, *Cnestus mutilatus* (Curculionidae: Scolytinae: Xyleborini) in the southeastern United States. *Ann. Entomol. Soc. Am.* 107: 782–788.
- Oliver, J., N. Youssef, J. Basham, A. Bray, K. Copley, F. Hale, W. Klingeman, M. Comb, and W. Haun. 2012. Camphor shot borer: a new nursery and landscape pest in Tennessee. Tennessee State University Cooperative Extension Research Paper 21.
- Poland, T. M., and D. Rassati. 2019. Improved biosecurity surveillance on non-native forest insects: a review of current methods. *J. Pest Sci.* 92: 37–49.
- Rabaglia, R. J., A. I. Cognato, E. R. Hoebeke, C. W. Johnson, J. R. Labonte, M. E. Carter, and J. J. Vlache. 2019. Early detection and rapid response: a ten-year summary of the USDA Forest Service Program of Surveillance for non-native bark and ambrosia beetles. *Am. Entomol.* 65: 29–42.
- Rassati, D., L. Marini, M. Marchioro, P. Rapuzzi, G. Magnani, R. Poloni, F. Di Giovanni, P. Mayo, and J. Sweeney. 2019. Developing trapping protocols for wood-boring beetles associated with broadleaf trees. *J. Pest Sci.* 92: 267–279.
- Schieffer, T. L., and D. E. Bright. 2004. *Xylosandrus mutilatus* (Blandford), an exotic ambrosia beetle (Coleoptera: Curculionidae: Scolytinae: Xyleborini) new to North America. *Coleop. Bull.* 58: 431–438.
- Schmeelk, T. C., J. G. Millar, and L. M. Hanks. 2016. Influence of trap height and bait type on abundance and species diversity of cerambycid beetles captured in forests of east-central Illinois. *J. Econ. Entomol.* 109: 1750–1757.
- Sheehan, T. N., M. D. Ulyshen, S. Horn, and E. R. Hoebeke. 2019. Vertical and horizontal distribution of bark and woodboring beetles by feeding guild: is there an optimal trap location for detection? *J. Pest Sci.* 92: 237–241.
- Su, J. C., and S. A. Woods. 2001. Importance of sampling along a vertical gradient to compare the insect fauna in managed forests. *Environ. Entomol.* 30: 400–408.
- Sweeney, J. D., P. J. Silk, V. Grebennikov, and M. Mandelshtam. 2016. Efficacy of semiochemical-baited traps for detection of Scolytinae species (Coleoptera: Curculionidae) in the Russian Far East. *Eur. J. Entomol.* 113: 84–97.
- Ulyshen, M. D., and J. L. Hanula. 2007. A comparison of the beetle (Coleoptera) fauna captured at two heights above the ground in a North American temperate deciduous forest. *Am. Midl. Nat.* 158: 260–278.
- Ulyshen, M. D., and T. N. Sheehan. 2019. Trap height considerations for detecting two economically important forest beetle guilds in southeastern US forests. *J. Pest Sci.* 92: 253–265.
- Ulyshen, M. D., S. Horn, J. L. Hanula. 2010. Response of beetles (Coleoptera) at three heights to the experimental removal of an invasive shrub, Chinese privet (*Ligustrum sinense*), from floodplain forests. *Biol. Invasion.* 12: 1573–1579.
- US Department of Agriculture–Forest Service (USDA). 1985. Insects of eastern forests. US Department of Agriculture–Forest Service Misc. Publ. No. 1426.
- Vance, C. C., K. R. Kirby, J. R. Malcolm, and S. M. Smith. 2003. Community composition of longhorned beetles (Coleoptera: Cerambycidae) in the canopy and understorey of sugar maple and white pine stands in south-central Ontario. *Environ. Entomol.* 32: 1066–1074.
- Vicente, C., M. Espada, P. Vieira, and M. Mota. 2012. Pine wilt disease: a threat to European forestry. *Eur. J. Plant Pathol.* 133: 89–99.
- Vodka, Š., and L. Cizek. 2013. The effects of edge-interior and understorey-canopy gradients on the distribution of saproxylic beetles in a temperate lowland forest. *Forest. Ecol. Manag.* 304: 33–41.
- Warmund, M. 2012. *Cnestus mutilatus*, another exotic pest on the move. *Missouri Environ. Garden* 18: 3.
- Wermelinger, B., P. F. Flückiger, M. K. Obrist, and P. Duelli. 2007. Horizontal and vertical distribution of saproxylic beetles (Col., Buprestidae, Cerambycidae, Scolytinae) across sections of forest edges. *J. Appl. Entomol.* 131: 104–114.
- Williams, D. T., N. Straw, N. Fielding, M. Jukes, and J. Price. 2017. The influence of forest management systems on abundance and diversity of bark beetles (Coleoptera: Curculionidae: Scolytinae) in commercial plantations of Sitka spruce. *Forest Ecol. Manag.* 398: 196–207.
- Yu, Y., Z. Chi, J. Zhang, P. Sun, C. Wang, and X. Pan. 2019. Assessing the invasive risk of bark beetles (Curculionidae: Scolytinae and Platypodinae). *Ann. Ent. Soc. Am.* 112: 451–457.