

Forest Entomology

Evaluation of Trapping Schemes to Detect Emerald Ash Borer (Coleoptera: Buprestidae)

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Abstract

Management responses to invasive forest insects are facilitated by the use of detection traps ideally baited with species-specific semiochemicals. Emerald ash borer, *Agrilus planipennis* Fairmaire, is currently invading North American forests, and since its detection in 2002, development of monitoring tools has been a primary research objective. We compared six trapping schemes for *A. planipennis* over 2 yr at sites in four U.S. states and one Canadian province that represented a range of background *A. planipennis* densities, canopy coverage, and ash basal area. We also developed a region-wide phenology model. Across all sites and both years, the 10th, 50th, and 90th percentile of adult flight occurred at 428, 587, and 837 accumulated degree-days, respectively, using a base temperature threshold of 10°C and a start date of 1 January. Most trapping schemes captured comparable numbers of beetles with the exception of purple prism traps (USDA APHIS PPQ), which captured significantly fewer adults. Trapping schemes varied in their trap catch across the gradient of ash basal area, although when considering trap catch as a binary response variable, trapping schemes were more likely to detect *A. planipennis* in areas with a higher ash component. Results could assist managers in optimizing trap selection, placement, and timing of deployment given local weather conditions, forest composition, and *A. planipennis* density.

Key words: *Agrilus planipennis*, invasive species, pest management, sampling, semiochemical, survey and detection

Detection and monitoring efforts are critically important in invasive species management programs as they guide and support decisions on regulatory and outreach activities, implementation of eradication efforts, population suppression or pest control tactics, or electing to

take no action (Britton et al. 2010, Liebhold et al. 2016). Sensitive monitoring devices that can detect and track newly established, low-density populations are critical for minimizing damage from destructive invasive pests (Mercader et al. 2013) and for management

programs that seek to extirpate or slow the spread of an invasive species (Liebhold and Tobin 2008, Liebhold et al. 2016). Past work has highlighted the relationship between the detectability of a non-native species and the success of subsequent management programs (Pluess et al. 2012, Tobin et al. 2014).

Emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae) is an invasive woodborer native to Asia that became established in southeast Michigan, USA by the early 1990s and was detected in 2002 (Cappaert et al. 2005, Siegert et al. 2014). Hundreds of millions of ash (*Fraxinus* spp.) have been killed to date as this invader continues to spread, and some native ash species could be effectively eliminated as overstory components of North American forests (Herms and McCullough 2014, McCullough 2019). Currently, the most effective means to detect and monitor low density *A. planipennis* populations involves girdling small ash trees (i.e., 10–15 cm diameter at breast height, DBH) in spring and then debarking the trees in autumn to assess larval presence and density (Mercader et al. 2013, Siegert et al. 2017, McCullough 2019). Use of girdled trees, however, can be problematic where ash trees are scarce or when multi-year surveys are needed for *A. planipennis* detection (McCullough et al. 2009a).

Many previous studies have focused on developing or improving artificial traps and lures for *A. planipennis* and an exhaustive review is beyond the scope of this paper. Briefly, past research has addressed the effects of trap shape, color, placement, and semiochemical lures on trap efficiency (e.g., Crook et al. 2008, 2009, 2012; Francese et al. 2008, 2010, 2011; de Groot et al. 2008; Crook and Mastro 2010; McCullough et al. 2011; Poland et al. 2011; Poland and McCullough 2014, Ryall 2015; Ryall et al. 2015; Silk and Ryall 2015; Poland et al. 2019; Silk et al. 2019; Parker et al. 2020). Other studies have examined the influence of *A. planipennis* density, tree condition and stand-level variables on trap efficiency (e.g., McCullough et al. 2009a,b; McCullough et al. 2011; Poland and McCullough 2014). While this research has improved detection and monitoring tools for *A. planipennis*, variable trap captures and detection rates among trap types under different conditions present challenges for selecting optimal traps and implementing effective regulatory and management programs (Herms and McCullough 2014, McCullough 2019).

The objective of this study was to compare trapping schemes for *A. planipennis*. We used trapping schemes designed by three research groups engaged in developing *A. planipennis* detection methods: USDA APHIS PPQ, Natural Resources Canada-Canadian Forest Service, and Michigan State University and the USDA Forest

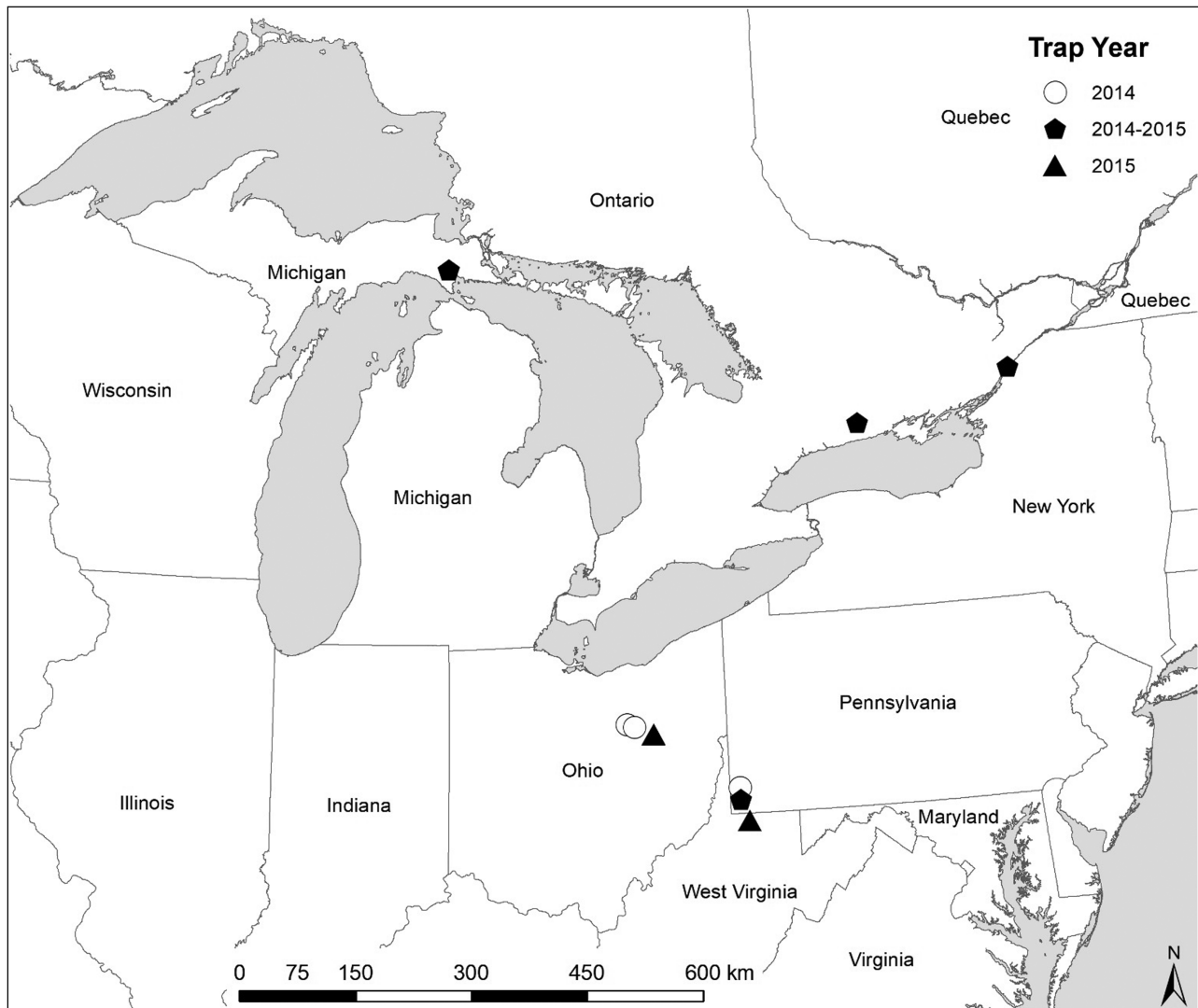


Fig. 1. Location of study sites in 2014 and 2015. Study sites were along or near the edge of the expanding distribution of *A. planipennis*.

Service. We tested the trapping schemes across a range of site conditions with different ash densities and *A. planipennis* invasion histories over a broad spatial scale. The overarching goal of this research was to inform detection, monitoring, and sampling protocols for *A. planipennis*. Several previous studies have quantified cumulative degree-days for the adult flight period at regional sites using a minimum base temperature threshold of 10°C and a starting date of 1 January (e.g., Poland et al. 2011, Tluczek et al. 2011). Thus, a secondary objective of this study was to evaluate the robustness of using a minimum base temperature threshold of 10°C and a starting date of 1 January for characterizing the flight period of males and females across a broader geographical scale (~39.5 to 46.0° N latitude).

Materials and Methods

Study Locations

To evaluate effectiveness of traps for initial detection and monitoring of low density *A. planipennis* populations, we established study locations along or near the edge of its expanding distribution in Ohio (2014–2015), Pennsylvania (2014–2015), the Upper Peninsula of Michigan (2014–2015), Ontario (2014–2015), and West Virginia (2015) (Fig. 1). It was subsequently determined that sites in Ohio in 2014 were within an area already well infested with *A. planipennis* (see results). At each study location, we established two study sites (> 15 km apart), with each site consisting of four moderately homogeneous replicate blocks with six trapping schemes deployed randomly in each block, for a total of 192 traps deployed across 32 blocks in each year.

The diverse study locations included privately owned tree farms, park or recreation areas, forest openings (abandoned gravel pit), and forest edges (e.g., pipeline or utility rights-of-way). Stand structure and species composition were measured in six 0.0405 or 0.0126 ha plots per block with one plot at each trap location. In each plot, we identified and measured the DBH of all woody stems ≥ 5 cm. Total basal area was estimated as a measure of canopy cover, and the proportion of basal area consisting of *Fraxinus* spp. was calculated. We also visually examined and qualitatively rated canopy condition of ash trees to quantify the number of ash trees rated as poor or dead (>75% canopy loss) whether due to *A. planipennis* or other factors.

Trapping Schemes

Trapping schemes used in this study were developed previously by (1) USDA APHIS PPQ; (2) Natural Resources Canada-Canadian Forest Service; and (3) Michigan State University and the USDA Forest Service. Each group submitted two trapping schemes for a total of six schemes for evaluation. Trapping schemes are described below and shown in Fig. 2. A trapping scheme was defined as a combination of trap design including shape and color, the semiochemical(s) used as lures, and deployment instructions including trap height. All schemes included a commercially available, green leaf volatile lure (GLV; (3Z)-hexenol) (de Groot et al. 2008). A total of three different commercial GLV lures were specified by the research groups for their respective schemes. To measure release rates of GLV lures, five replicates of each lure type were deployed in full sun and full shade environments in Pineville, LA (Rapides Parish, LA), and mass loss was measured after 30 d. Generally, release rates are strongly driven by temperature (Teske et al. 2014); maximum and minimum daily temperatures from Pineville, LA (U.S. Climate Data 2015) were used to generate a mean temperature of 26.4°C for the 30 d time period from 23 May 2015 to 22 June 2015.

One trapping scheme supplied by USDA APHIS PPQ was a 12-unit multifunnel trap made with plastic colored a dark shade of green (Sabic green, 530 nm, 48% relative reflectance; values approximated from Francese et al. 2011; Chemica USA, Durant, OK) and surface-treated with the fluoropolymer Fluon (AGC Chemicals, Exton, PA), diluted to 50%, to increase slipperiness.

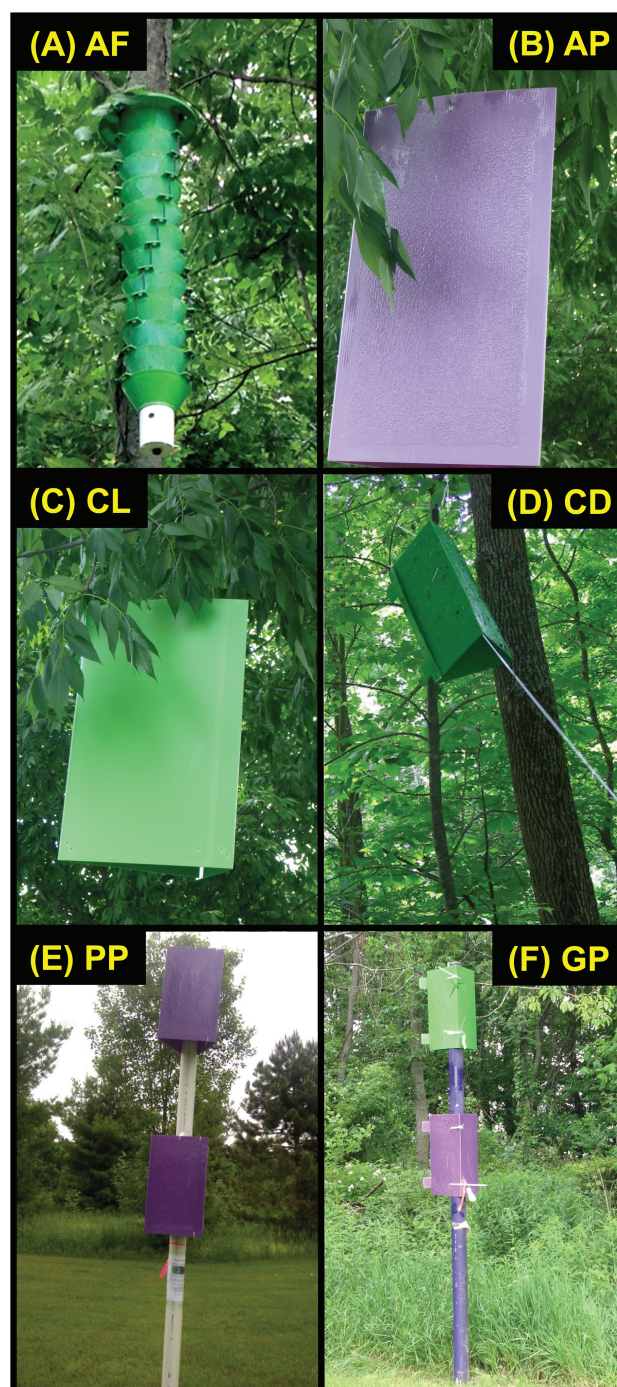


Fig. 2. Trapping schemes evaluated in this study: green multifunnel trap (A, AF) and purple prism trap (B, AP) (USDA APHIS PPQ); light green prism trap (C, CL) and dark green prism trap (D, CD) (Natural Resources Canada, Canadian Forest Service); and purple-purple double-decker trap (E, PP) and green-purple double-decker trap (F, GP) (Michigan State University-USDA Forest Service).

Multifunnel traps were hung from a branch in the lower-to-mid canopy of an ash tree, ~5–8 m above the ground, and insects were captured in collection cups filled with ~150–200 ml of propylene glycol as a surfactant and preservative. Each multifunnel trap had a surface area of ~0.5 m², and was baited with one GLV pouch lure (release rate at 30 d = 40 mg day⁻¹ shade, 30 mg day⁻¹ sun; Scentry Biologicals, Inc., Billings, MT). The second trapping scheme supplied by USDA APHIS PPQ was a purple prism trap (Sabic purple, 420 nm, 21.7% and 670 nm, 13.6%; [Francese et al. 2013b](#)); with a surface area of ~0.65 m² coated with clear Tangle-Trap Sticky Coating (The Scotts Company LLC, Marysville, OH), which was also hung in the lower-to-mid canopy of an ash tree, ~5–8 m above the ground, and baited with the same GLV lure (release rate @ 30 d = 40 mg day⁻¹ shade, 30 mg day⁻¹ sun; Scentry Biologicals, Inc., Billings, MT).

Two trapping schemes developed by Natural Resources Canada-Canadian Forest Service were comprised of green prism traps coated with clear Tangle-Trap Sticky Coating (The Scotts Company LLC, Marysville, OH). One scheme was a darker green panel (Sabic green, reflectance values as before, Synergy Semiochemical Corp., Burnaby British Columbia, Canada). This scheme was deployed with a Synergy GLV (3Z-hexenol) lure (release rate @ 30 d = 74 mg day⁻¹ shade, 154 mg day⁻¹ sun; Synergy Semiochemicals Corp.) and a short range *A. planipennis* pheromone lure (3Z-lactone) ([Silk et al. 2011](#), [Parker et al. 2020](#)) supplied as a 3 mg load in a red rubber septum, which released ~80 µg day⁻¹ at 20°C (Sylvar Technologies Inc.). The other scheme was a lighter green panel (YA green, 540 nm, 64% relative reflectance; values approximated from [Francese et al. 2010](#), Sylvar Technologies Inc., Fredericton, New Brunswick, Canada) deployed with a Sylvar GLV lure (release rate @ 30 d = 104 mg day⁻¹ shade, 109 mg day⁻¹ sun; Sylvar Technologies Inc.) and the same *A. planipennis* pheromone lure as above. Both trapping schemes had a surface area of ~0.65 m² and were hung in the upper canopy of an ash with a preference for branches that were in direct sunlight.

Trapping schemes developed by Michigan State University and the USDA Forest Service were double-decker traps consisting of two prism traps (Great Lakes IPM, Inc., Vestaburg, MI) mounted at ~1.8 m and ~3 m high on a 3 m tall PVC pipe (10 cm in diameter) supported by sliding the pipe over an ~2.1 m T-post ([McCullough and Poland 2017](#)). One scheme used two dark purple prisms (Sabic purple, reflectance values as before) and the other scheme used a dark green prism (Sabic green, reflectance values as before) on top and a light purple prism on the bottom (Sabic purple, reflectance values as before). Prism surfaces were coated with clear Tangle-Trap Sticky Coating. The total trapping surface for each scheme was ~1.3 m² and both schemes were deployed with two GLV bubble caps on each prism (release rate per bubble cap @ 30 d = 22 mg day⁻¹ shade, 20 mg day⁻¹ sun; Contech, Inc., Victoria, British Columbia, Canada). Traps were placed in full sun ~5 m from the edge of a stand or in an open area near ash trees to exploit behavioral preferences of *A. planipennis* ([Yu 1992](#), [McCullough et al. 2009a](#)) and to ensure visual cues (prism color) and olfactory cues (volatiles) were not obscured by surrounding trees ([McCullough and Poland 2017](#)).

Most traps were deployed according to the specifications of the respective developers (i.e., height within tree, distance from edge of stand, sun exposure) with some variation depending on site conditions. For example, some blocks of traps at study sites in Pennsylvania and West Virginia were located in partially shaded areas within mature hardwood stands when there were no ash trees

at the forest edge. To account for variation in trap deployment, both block and site were considered as random effects in the analysis.

Sampling Protocol

Traps were deployed at each study site and year just prior to the estimated initial emergence of adult *A. planipennis* (e.g., [Poland et al. 2011](#), [Tluczek et al. 2011](#)). Initial deployment dates were 26–29 May (WV sites), 2–5 June (PA and OH sites), and 23–26 June (MI and Ontario sites). Traps were checked for EAB once or twice per wk (PA and WV sites), once per wk (OH sites) or once every 2 wk (MI and ON sites) throughout the 12-wk duration of the experiment, with frequency varying based on travel logistics. All lures were replaced after 6 wk. During each trap check, specimens were removed from the collection cups from multifunnel traps, or from the surfaces of the prism traps using forceps or a spackle knife, after which Tangle-Trap Sticky Coating was re-applied to the panel. Beetles captured on sticky prisms were soaked in Histo-Clear II (National Diagnostics, Atlanta, GA) to remove Tangle-Trap Sticky Coating and all beetles were sexed. We counted the number of male and female adults per trapping scheme, collection date, and study location.

Phenological Analysis

For each year at each study location, daily maximum and minimum air temperatures were obtained from the closest weather station ([National Centers for Environmental Information 2017](#)), while excluding stations located at commercial airports due to heat island effects. All weather stations were within 15 km of their paired study location. Degree-days were estimated by applying the sine wave method ([Allen 1976](#)) to daily maximum and minimum temperatures with a minimum base temperature threshold of 10°C. Cumulative degree-days were summed for each year and study location beginning on 1 January. We then used an exponential model to fit the cumulative proportion of trap catch (males and females combined) for each study location and year (P_b) over accumulated degree-days (D) according to:

$$P_b = \exp(-\exp(-rD + b)), \quad (1)$$

in which r and b are the rate of increase and lag, respectively ([Tobin et al. 2008](#)). We also considered phenology for males and females separately by fitting Eq. 1 to the proportion of males and the proportion of females, respectively. Nonlinear model fits were conducted in R version 3.5.2 ([R Core Team 2018](#)). To test for differences in the flight phenology between males and females, we used a linearizing transformation applied to the cumulative proportion of males (P_m) or females (P_f) according to:

$$P'_i = \ln\left(\frac{P_i}{(1 - P_i)}\right), \quad (2)$$

where i = male or female, and P'_i is the transformed proportion for males or females ([Brown and Mayer 1988](#)). Equation 2 omits the extreme tails of the flight period (i.e., the period before the start of flight, or $P_i = 0$, and the period after which all beetles have been trapped for the year, or $P_i = 1$). Linearizing the proportions and excluding the extreme tails allowed us to test for homogeneity between the flight periods of males and females. We considered the main effects of cumulative degree-days and sex (a test of y -intercept homogeneity), and their interaction (a test of slope homogeneity), in a linear regression model in R version 3.5.2 ([R Core Team 2018](#)).

Analysis of Trapping Scheme Effectiveness

We first examined trapping scheme effectiveness across all sites and blocks irrespective of *A. planipennis* density. The total number of trapped adults was standardized by trap surface area (m²), which varied by scheme. For each trapping scheme, the total number of adults per m² was transformed using $\log_{10}(y+1)$ to satisfy the assumptions of normality and used as the response variable. Site and block were considered as random effects in a randomized block design. We tested the significance of the main effects of trapping scheme, total basal area in the block as a measure of canopy coverage, the proportion of the total basal area in each block that was ash, and the proportion of ash trees in each block rated as poor or dead. In addition, we tested for interactions between trapping scheme and the other main effects in a linear mixed effects model using lme4 (Bates et al. 2015) in R version 3.5.2 (R Core Team 2018). *P*-values for main and interaction effects were estimated using lmerTest based on a Type III analysis of variance and using the Satterthwaite method for estimating degrees of freedom. Post-hoc tests were also conducted in lmerTest based on least squares means (Kuznetsova et al. 2019).

To evaluate the effectiveness of traps for early detection of low-density populations, we also analyzed trap catch separately for a subset of 31 of the 64 blocks in which the total number of captured adults was ≤ 100 across all trapping schemes during a particular year; the number of blocks used from each location and year are noted in Table 1. This threshold was considered characteristic of low-density populations based upon previous work (Marshall et al. 2009, McCullough et al. 2011, Francese et al. 2013a, Crook et al. 2014, Poland and McCullough 2014, Burr et al. 2018). We analyzed the same main and interaction effects using the same response variable and statistical procedures described above with site and block included as random effects.

We also used the low-density subset of data to test the significance of main and interaction effects when considering a binomial distribution for the response variable. In this case, we scored a trapping scheme as a '1' if at least one adult was trapped and 0 otherwise. We tested the significance of the same main and interaction effects with site and block as random effects as before using glmer (Bates et al.

2015) in R version 3.5.2 (R Core Team 2018). Significance of effects was based on *z* values in logistic regression.

Results

Total numbers of *A. planipennis* adults captured by trapping schemes varied by location and ranged from 75 to 1,588 per year, with a mean ($\pm$ SE) of 736 (139) and a median ($\pm$ IQR) of 488 (1069). Trap catch was generally highest in Ohio, and lowest in Michigan and Ontario, when averaged across all blocks and trapping schemes (Table 1). Total basal area per block ranged from 1.73 to 37.10 m²/ha, with a mean ($\pm$ SE) of 17.52 (2.92) m²/ha, while the proportion of the basal area comprised of ash per block ranged from 0.20 to 0.69, with a mean ($\pm$ SE) of 0.39 (0.05). Blocks where ash accounted for a relatively high proportion of total basal area (i.e., >0.5) tended to be in locations with low canopy coverage (<12 m²/ha), reflecting study locations established in parks or other open areas chosen for their high ash presence. Relatively low proportions of ash (i.e., <0.3) tended to be in blocks with intermediate canopy coverage (12–25 m²/ha), while blocks with high canopy coverage (>30 m²/ha) tended to have 30–36% of basal area in ash. The proportion of ash trees rated as poor or dead per block ranged from 0.00 to 0.60 with a mean ($\pm$ SE) of 0.09 (0.01). Collectively, the study locations represented a range of canopy coverage, presence of ash, and background *A. planipennis* abundance (Table 1).

Phenological Analysis

Cumulative degree-days for the phenological occurrence of *A. planipennis* males, females, and males and females combined across all sites and years are given in Fig. 3. Males were trapped significantly before females (interaction effect between degree-days and sex: $F = 8.2$; $df = 1,173$; $P < 0.01$). Estimated degree-day accumulation (base temperature threshold = 10°C) for 50% flight was 577 for males and 650 for females (587 weighted mean). The predicted degree-day accumulation for different flight percentiles of males, females, and all adults are given in Table 2 with the corresponding parameter estimates from Eq. 1.

Table 1. Characteristics of study locations in Michigan, Ohio, Ontario, Pennsylvania, and West Virginia in 2014 and 2015

Study location	Year	Study site number	Mean ($\pm$ SE) total basal area (m ² ha ⁻¹)	Mean ($\pm$ SE) proportion basal area in ash	Total ash stems rated as dead/dying (N ash stems)	Total number of trapped adults	Number of low density blocks
Michigan	2014	1	22.72 (3.17)	0.27 (0.08)	9 (65)	255	3
Michigan	2014	2	37.10 (1.97)	0.36 (0.02)	11 (83)	594	1
Michigan	2015	1	22.72 (3.17)	0.27 (0.08)	9 (65)	302	3
Michigan	2015	2	19.02 (3.22)	0.26 (0.07)	0 (57)	124	4
Ontario	2014	1	4.80 (1.99)	0.58 (0.06)	0 (64)	305	3
Ontario	2014	2	1.73 (0.27)	0.69 (0.05)	0 (102)	272	4
Ontario	2015	1	4.80 (1.99)	0.58 (0.06)	0 (64)	866	0
Ontario	2015	2	1.73 (0.27)	0.69 (0.05)	0 (102)	350	3
Ohio	2014	1	24.60 (4.31)	0.29 (0.08)	103 (173)	991	1
Ohio	2014	2	NA ^a	NA ^a	NA ^a	1,201	0
Ohio	2015	1	31.08 (2.98)	0.30 (0.05)	24 (98)	1,563	0
Ohio	2015	2	32.72 (2.97)	0.32 (0.03)	45 (126)	1,398	1
Pennsylvania	2014	1	19.67 (2.65)	0.25 (0.03)	20 (83)	377	3
Pennsylvania	2014	2	16.18 (1.16)	0.23 (0.04)	5 (49)	75	4
Pennsylvania	2015	1	11.91 (1.79)	0.53 (0.09)	15 (47)	1,588	0
West Virginia	2015	2	12.02 (2.84)	0.20 (0.01)	2 (38)	1,494	1

Means and totals for each study site in each study location and year are based upon four blocks. Also indicated are the number of low-density blocks in each study site used to measure trapping scheme effectiveness in the subset analysis.

^aData were unavailable as the site was harvested following *A. planipennis* trapping but prior to stand measurements.

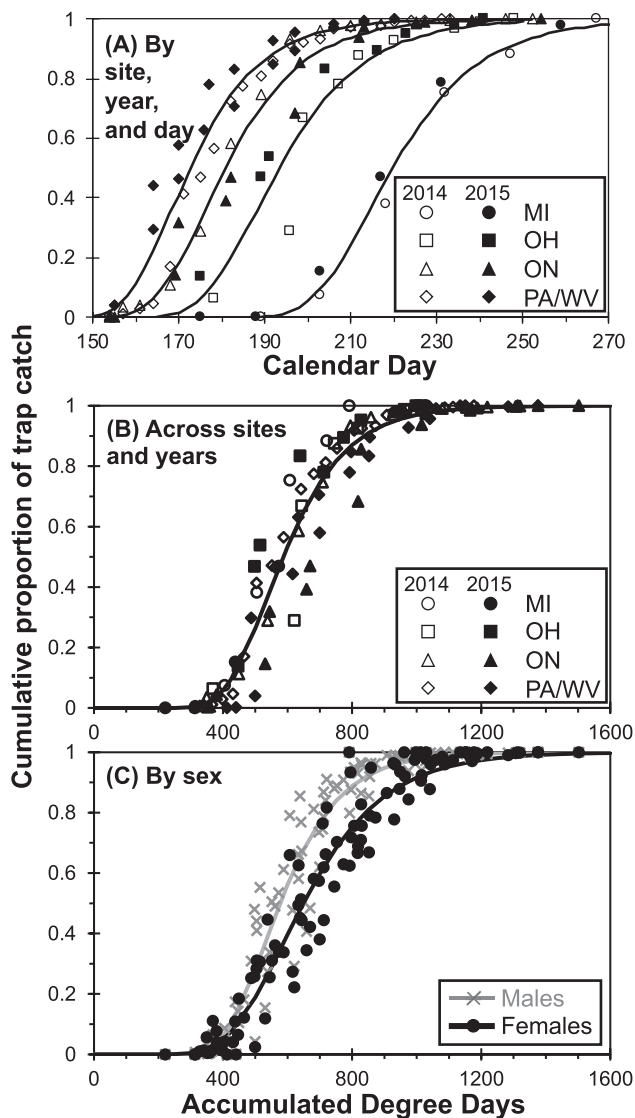


Fig. 3. Cumulative proportion of trap catch over calendar day at each site and year (A). Cumulative proportion of trap catch of all adults (B) and by sex (C) across all sites and years over accumulated degree-days from 1 January in each year (base temperature threshold = 10°C).

Analysis of Trapping Scheme Effectiveness

When considering all blocks regardless of the number of *A. planipennis* adults trapped, the main effects of trapping scheme ($F = 8.14$; $df = 5, 336$; $P < 0.01$) and the proportion of the basal area in ash ($F = 12.54$; $df = 1, 285$; $P < 0.01$) were significant predictors of the number of adults captured per m^2 of trap surface. The interaction between trapping scheme and the proportion of the basal area in ash ($F = 3.26$; $df = 5, 336$; $P < 0.01$) was also significant. Main effects of basal area ($F = 0.08$; $df = 1, 200$; $P = 0.78$) and the proportion of ash trees rated as poor or dead ($F = 0.79$; $df = 1, 161$; $P = 0.37$) were not significant. Interactions between trapping scheme and basal area ($F = 0.59$; $df = 5, 336$; $P = 0.71$) and trapping scheme and the proportion of ash trees rated as poor or dead ($F = 0.45$; $df = 5, 336$; $P = 0.82$) were also not significant. All trapping schemes trapped similar numbers of adults across all blocks with the exception of the purple prism trapping scheme (USDA APHIS PPQ), which trapped significantly fewer ($P < 0.01$; Fig. 4A). Also, with the exception of the purple prism trapping scheme (USDA APHIS PPQ), trap catch increased with higher proportions of basal area in ash (Fig. 4B).

Table 2. Parameter estimates for adult males, females, and combined, and the estimated accumulated degree-days (from 1 January, base temperature threshold = 10°C) at corresponding flight percentiles

Sex	Parameter estimates ^a		Accumulated degree-days at flight percentile:				
	<i>r</i>	<i>b</i>	10th	25th	50th	75th	90th
Males	0.0079	4.1960	426	490	577	688	815
Females	0.0059	3.4568	446	532	650	799	969
Combined	0.0076	4.0642	428	496	587	704	837

^aProportion of trap catch = $\exp(-\exp(-r \text{ Accumulated Degree-days} + b))$, Eq. 1.

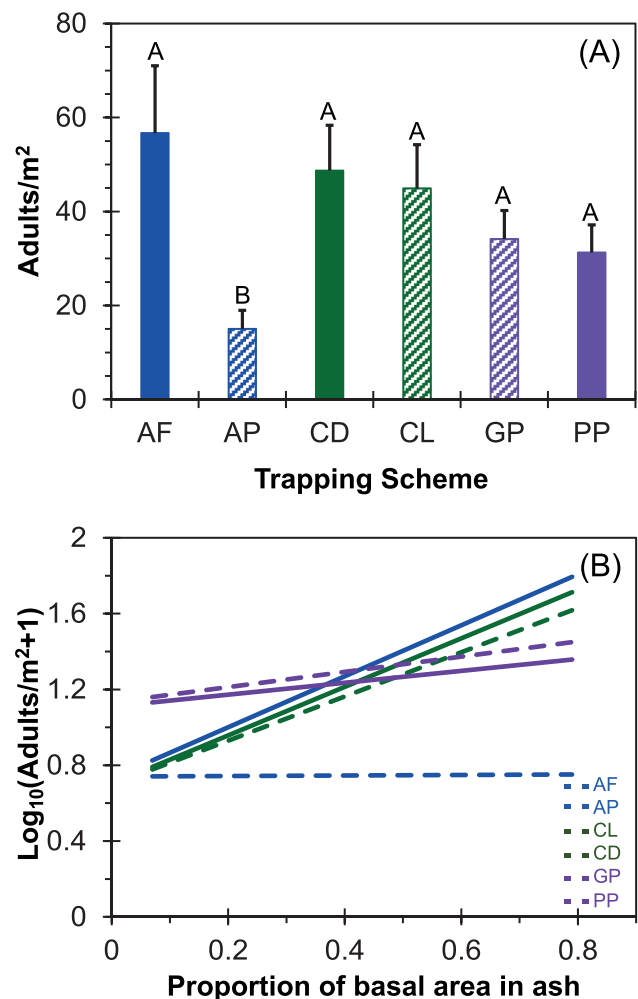


Fig. 4. (A) Mean number of trapped adults per m^2 by trapping scheme across 2014–2015 and study locations; different letters denote significant differences based on least squares means in lmerTest (Kuznetsova et al. 2019) ($P < 0.05$). (B) Linear regressions of the transformed numbers of adults trapped per m^2 by trapping scheme and by the proportion of basal area in ash per block. Trapping schemes: green multifunnel trap (AF) and purple prism trap (AP) (USDA APHIS PPQ); light green prism trap (CL) and dark green prism trap (CD) (Natural Resources Canada, Canadian Forest Service); and purple-purple double-decker trap (PP) and green-purple double-decker trap (GP) (Michigan State University-USDA Forest Service).

When considering only low-density blocks (i.e., ≤ 100 *A. planipennis* adults across all trapping schemes), the significant main effects were trapping scheme ($F = 8.88$; $df = 5, 167$; $P < 0.01$)

and the proportion of the basal area in ash ($F = 5.06$; $df = 1, 62$; $P < 0.01$). Main effects of basal area ($F = 0.003$; $df = 1, 54$; $P = 0.96$) and the proportion of ash stems rated as poor or dead ($F = 2.71$; $df = 1, 38$; $P = 0.11$) were not significant. None of the interaction effects were significant (all $P > 0.09$). All trapping schemes trapped similar numbers of adults, except the purple prism trapping scheme (USDA APHIS PPQ), which captured significantly fewer adults ($P < 0.01$; Fig. 5A). Also, trap catch in low-density blocks increased with higher proportions of basal area in ash ($P < 0.01$; Fig. 5B).

When considering trap catch as a binary response (i.e., whether or not at least one adult was trapped), the main effects of trapping scheme (z value = 3.39; $P < 0.01$) and proportion of basal area in ash (z value = 2.87; $P < 0.01$) were significant. No other main or interaction effects were significant (all $P > 0.1$). Increases in the proportion of the basal area in ash were associated with an increased probability of at least one *A. planipennis* adult being trapped in the block (Fig. 6). At least one adult *A. planipennis* was trapped by at least one trapping scheme in every low-density block. The green-purple

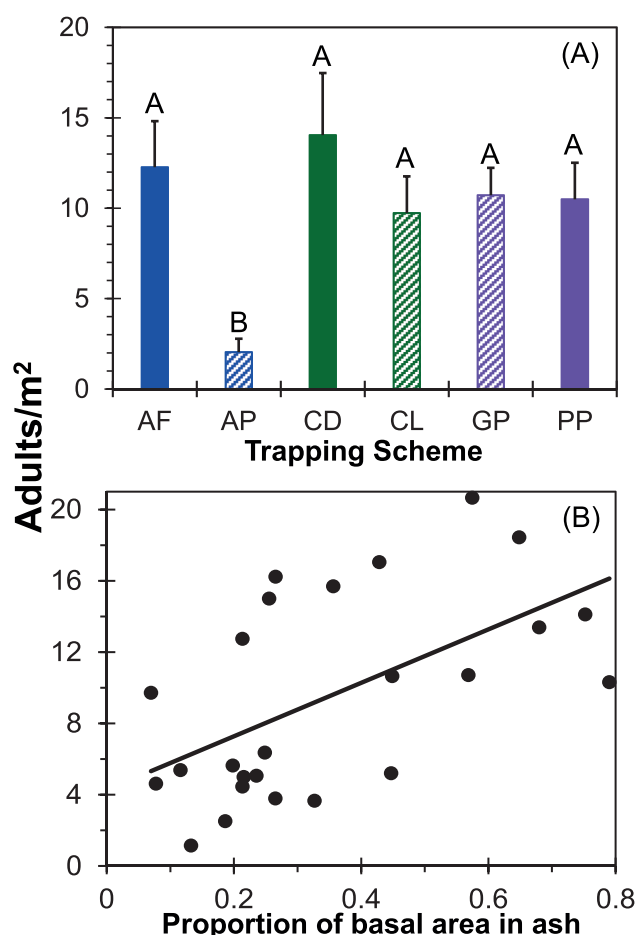


Fig. 5. (A) Mean number of trapped adults per m² by trapping scheme across 2014–2015 and study locations when considering only low-density blocks (e.g., ≤ 100 *A. planipennis* adults across all trapping schemes in the block); different letters denote significant differences based on least squares means in lmerTest (Kuznetsova et al. 2019) ($P < 0.05$). (B) Mean number of trapped adults per m² by the proportion of basal area in ash ($y = 4.278 + 14.990x$; $P < 0.01$). Trapping schemes: green multifunnel trap (AF) and purple prism trap (AP) (USDA APHIS PPQ); light green prism trap (CL) and dark green prism trap (CD) (Natural Resources Canada, Canadian Forest Service); and purple-purple double-decker trap (PP) and green-purple double-decker trap (GP) (Michigan State University-USDA Forest Service).

and purple-purple double-decker trapping schemes (Michigan State University-USDA Forest Service) trapped at least one *A. planipennis* adult in 93.5% and 90.3% of the blocks, respectively, which were not significantly different from each other nor from the dark green panel traps (Natural Resources Canada-Canadian Forest Service), which captured an adult in 77.4% of the blocks. The dark green panel traps did not differ significantly from the light green panel traps (Natural Resources Canada-Canadian Forest Service) or the green multifunnel traps (USDA APHIS PPQ), which captured an adult in 74.2% and 64.5% of the blocks, respectively. Purple prism traps (USDA APHIS PPQ) trapped an adult in 48.4% of the blocks, which was significantly lower than all other trapping schemes.

Discussion

Use of an arbitrary minimum base temperature threshold of 10°C and accumulated degree-days from 1 January provided a stable threshold and biofix date across the study region (Fig. 3), which extended from $\sim 39.5^\circ\text{N}$ to $\sim 46.0^\circ\text{N}$. The study locations also represented a range of elevation, from ~ 90 to ~ 365 m above sea level, as well as differences in other features that can affect degree-day accumulation, such as the distance to bodies of water and urban areas. The estimated degree-days for 50% flight (587, Table 2) are very similar to a prior study from southern Michigan in which peak flight occurred at ~ 1060 -degree-days in 2006 when using $^\circ\text{F}$ as temperature units and 50°F as the base temperature threshold (McCullough et al. 2009b), which corresponds to ~ 580 degree-days when using 10°C as the base temperature threshold. Across all sites and years, the 10th, 50th, and 90th percentile of adult flight occurred at 428, 587, and 837 accumulated degree-days, respectively (minimum base

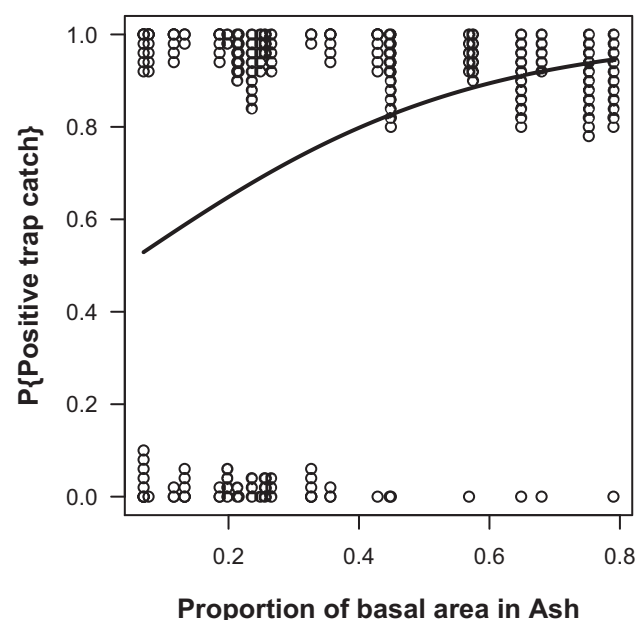


Fig. 6. The probability of a positive trap catch (e.g., at least one adult trapped) over the proportion of basal area comprised of ash per block when considering only low-density blocks (e.g., ≤ 100 *A. planipennis* adults captured across all trapping schemes in the block; $P\{\text{Positive trap catch}\} = \exp(-0.1499 + 3.8093 \times \text{proportion of basal area in ash}) / (1 + \exp(-0.1499 + 3.8093 \times \text{proportion of basal area in ash}))$; $P < 0.01$). Observations from blocks are represented as open circles in the form of a histogram; observations plotted at the top are instances of positive trap catch, while observations plotted at the bottom are instances of no trap catch. The black line represents the predictions from logistic regression.

temperature threshold = 10°C). This study further extends previous work on phenological modeling of *A. planipennis* adult flight by examining differences between adult males and females and parameterizing a nonlinear model to observed data (Eq. 1, Fig. 3).

All trapping schemes captured a statistically similar number of beetles across all sites irrespective of background *A. planipennis* abundance with the exception of the purple prism trapping scheme (USDA APHIS PPQ), which consistently captured fewer adults. This pattern was observed across all study sites (Fig. 4A), and when considering only low-density *A. planipennis* blocks (Fig. 5A). Across all sites, trapping schemes, except for the purple prism scheme, trapped more adults in areas with more ash (Fig. 4B), while all trapping schemes in low density blocks trapped more adults in areas with more ash (Fig. 5B). When considering trap catch as a binary response from low-density blocks, the predicted probability of a positive detection also increased with the proportion of basal area comprised of ash, with a predicted probability of ≥ 0.8 in areas where ash comprised at least 40% of the basal area (Fig. 6). Low density blocks could reflect either a low abundance of *A. planipennis* in the local area, trap placement in shaded locations, or trapping schemes that failed to attract many *A. planipennis* adults. Although we did not detect a significant effect of canopy coverage, as proxied by basal area, in *A. planipennis* adult trap catch in either all sites or low-density sites, prior studies have consistently shown a strong attraction of *A. planipennis* adults to light (Yu 1992; McCullough et al. 2009a,b; Wang et al. 2010; McCullough 2019).

Collectively, trap performance under varying landscape conditions provides insights that could be applicable to *A. planipennis* detection programs. In detection programs, for example, it might seem intuitive to place traps in forested areas where ash trees are abundant. However, detection efforts might also be focused on municipal and or residential settings where ash basal area is low, but where open-grown trees are more likely to be initially colonized by *A. planipennis* (Yu 1992, McCullough et al. 2009a, McCullough 2019). The differences we observed in *A. planipennis* trap catch across the range of ash basal area provide sampling guidance for managers of such areas. For instance, the purple-purple and green-purple double-decker trapping schemes (Michigan State University and the USDA Forest Service) tended to be less affected by ash basal area, yet trapped statistically similar numbers of adults as trapping schemes that were more influenced by ash basal area (Fig. 4). While many studies, including ours, focus on total adult beetle trap catch as a means to assess trapping schemes, detection rates can be particularly important. Specifically, even capturing a single *A. planipennis* in an area previously thought to be uninfested typically initiates regulatory action as well as management and outreach activities.

The trapping schemes tested in this study have different advantages and disadvantages, in addition to any differences in *A. planipennis* trap catch. Multifunnel traps (Fig. 2a) can be re-used from year-to-year and do not require Tangle-Trap Sticky Coating, although a preservative such as propylene glycol must be used and ideally replaced periodically during the summer. However, the initial cost of multifunnel traps is high relative to other trap designs, and they are bulky to transport and store. Multifunnel traps must also be hung at approximately mid-canopy in an ash tree, which limits deployment options, and they must be lowered to check for *A. planipennis*, which sometimes results in traps becoming tangled with branches and foliage. Prism traps deployed in the canopy (Fig. 2b–d) have few parts to assemble, are relatively light weight to carry to the field, and are the least expensive of all the trapping schemes tested. However, like multifunnel traps, they must be hung at approximately mid-canopy in an ash tree, which limits deployment

options. They also must be lowered to check for *A. planipennis*, which can result in traps becoming tangled or obscured by leaves sticking to the surfaces of the prism. The double-decker traps (Fig. 2e and f) are not hung in tree canopies and thus can be deployed in optimal locations and checked at ground level. However, they require additional components, such as PVC pipe and T-posts, that must be transported to sites and stored when not in use. Lastly, all trapping schemes that use prisms require Tangle-Trap Sticky Coating on the prism surfaces, which can be messy. Prisms can also only be used once, and result in some captures of non-target species.

This study provides a broad perspective of the effectiveness of different *A. planipennis* trapping schemes. The study locations were geographically diverse, which is a strength of the study given that *A. planipennis* continues to invade new areas of North America that are ecologically and climatically different than the Great Lakes region where the majority of research has been conducted (Herms and McCullough 2014 and references within). The opportunity to independently assess different trapping schemes from different research groups in a replicated block design was also a strength of the study. Also, variation in site characteristics and experience of personnel involved in setting up experiments could represent realistic operational conditions for conducting survey and detection programs. Given the importance of monitoring and sampling for invasive species management, this research should inform regulatory and management programs for *A. planipennis* as it continues to expand its distribution in North America.

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