Optimization of Trap Color for Emerald Ash Borer (Coleoptera: Buprestidae)

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ABSTRACT Field assays were performed to determine the optimal color for *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae) traps. Previous studies have found that more *A. planipennis* are caught on purple or green traps than traps of other colors. In three studies, we evaluated various shades of purple, wavelengths of green (500–570 nm), and greens of different reflectance (from 9 to 66%). In all tests, traps of corrugated plastic in standard, commercially available purple (currently used to survey *A. planipennis*) and a customized green color were used as bases for comparison. Among purple traps, a paint color previously shown to be generally attractive to buprestids caught significantly more *A. planipennis* adults than traps coated with paints containing more blue or red, or traps constructed of the standard purple plastic. Among traps with maximum reflectance at varying green wavelengths, those ranging in wavelength from 525 to 540 nm caught significantly more adult *A. planipennis* than traps of other wavelengths. In the 530–540 nm range of the electromagnetic spectrum, there was no significant difference among traps in the 23–66% reflectance range, but traps painted with a peak reflectance of 49% caught more beetles than purple or the custom green plastic traps. Male to female ratio was highest on green traps.

KEY WORDS emerald ash borer, prism trap, visual cues, trap height

The emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae), is an introduced Asian pest of ash (*Fraxinus* spp. L.; Oleaceae). Since its discovery in 2002 near Detroit, MI, and Windsor, ON, Canada (Haack et al. 2002), *A. planipennis* has subsequently been found in 12 additional U.S. states and one Canadian province (Bean 2004, Rauscher and Mastro 2004, Waltz 2006, IDOA 2007, PA DCNR 2007, Emerald Ash Borer Info 2009). By 2006, it was estimated that *A. planipennis* had killed at least 15 million ash trees in forested and urban areas in southeastern Michigan (Poland and McCullough 2006).

As *A. planipennis* spreads throughout the range of ash in North America, a survey tool that exploits cues that the beetles use to locate host trees or other *A. planipennis* could enhance efforts to contain and control populations of the pest. Emerald ash borer survey programs currently use a prism-shaped trap described by Francese et al. (2008). Prism traps are constructed of purple corrugated plastic (a standard color from the manufacturer Coroplast Inc., Dallas, TX) and coated externally with a sticky substance (Tangletrap Insect Trap Coating, The Tanglefoot Company, Grand Rapids, MI). In 2008 and 2009, the USDA–APHIS–PPQ Emerald Ash Borer Cooperative Program conducted a nationwide survey for *A. planipennis* by using prism traps in conjunction with semiochemical (kairomone) lures. The traps detected previously undiscovered populations in 10 new counties and one new state (Missouri).

Previous trapping studies by Oliver et al. (2002) found that purple was more attractive to at least 31 species of buprestids (including several *Agrilus* spp.) than other colors. In later studies, *A. planipennis* demonstrated attraction to purple plastic traps (peak wavelengths of 430, 600, and 670 nm) (Francese et al. 2005), especially those hung in the canopy of ash trees (Crook et al. 2008, Francese et al. 2008).

Electroretinogram assays have demonstrated that male and female *A. planipennis* are sensitive to light in the UV and violet (420–430 and 460 nm, respectively) range of the visible spectrum, whereas mated females are also sensitive to light in the red (640–650 and 670 nm, respectively) range (Crook et al. 2009). Peaks in the violet and red ranges combine to produce the color perceived as purple. The overall sex ratio of *A. planipennis* is skewed toward females on purple (Francese et al. 2008, Crook et al. 2009) and red (650 nm) traps (Crook et al. 2009). On traps placed at 1–1.5 m above the ground, captures on purple and red traps were not significantly different from one another, whereas dark blue traps (430 nm) caught significantly less *A. planipennis* than either of the other colors (Crook et al. 2009). The authors hypothesized that the red reflectance in both traps may have been attractive

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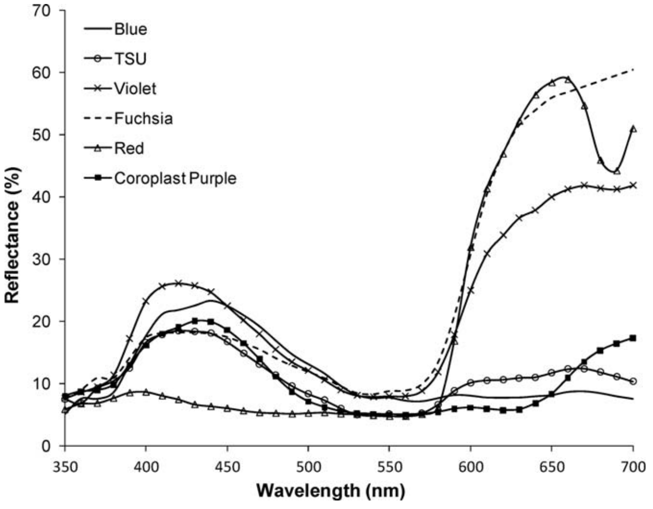

Fig. 1. Reflectance spectra of purple painted and plastic traps.

to *A. planipennis* adults, especially females, due to their increased sensitivity in this range of the visible spectrum (Crook et al. 2009).

A. planipennis is also sensitive to green light (540–560 nm) (Crook et al. 2009). In trapping assays, both dark green- (≈24% reflectance) and light green-painted prism traps (≈64% reflectance), with a peak reflectance at 540 nm, caught 2–3 times as many beetles as the standard purple plastic traps or purple-painted traps when placed in the mid-canopy. The sex ratio on these traps was heavily skewed toward males rather than females on both shades of green (Crook et al. 2009).

The objective of this study was to determine 1) the reflectance of the red peak (610–670 nm) in purple traps that produces the highest trap catch, 2) the optimal wavelength of green (500–570 nm) paints and plastics for attracting *A. planipennis* to traps, and 3) the optimal reflectance of green traps (9–66%) in the 530–540-nm range of the visible spectrum for attracting *A. planipennis.*

Materials and Methods

Color Selection. Paint chips from several manufacturers were scanned using a FieldSpec Pro (Analytical Spectral Devices Inc., Boulder, CO) contact probe spectrophotometer set to full range (350–2,500 nm) scan mode to measure reflectance curves (methods described by Crook et al. 2009). Wavelength and reflectance were recorded, and paints were selected based on the criteria listed below for each field assay.

Before painting, several translucent 0.30-cm-thick (30.0- by 30.0-cm) plastic (Coroplast Inc.) boards were coated with a gray-tinted plastic-bonding primer (P5 Primer Tint in Preprite B51W50, Sherwin Williams Ltd., Richardson, TX) and allowed to cure before small samples of the paints to be tested were applied. The corrugated plastic was the same material used to construct prism traps in the field assays. Samples of primed and painted plastic were scanned with the spectrophotometer to confirm a match to the originally scanned paint chips.

Purple Comparison. Five paint colors were tested, with the following reference names: blue, TSU purple, violet, fuchsia, and red (Fig. 1). Fuchsia (2078–30 Royal Fuchsia; 430 nm, 18.2% reflectance and 670 nm, 58.9% reflectance) and blue (1421 Bistro Blue; 440 nm, 23.3% and 660 nm, 8.7%) were stock colors produced by Benjamin Moore & Co. (Montvale, NJ), and violet (SW6979 Verve Violet; 420 nm, 25.9% and 670 nm, 41.9%) was produced by Sherwin Williams Ltd. The red color (ACE Ltd. 9963828 Ruby Red; Ace Hardware, Oak Brook, IL; 420 nm, 7.4% and 660 nm, 58.9%) tested was originally tested in studies by Crook et al. (2009) as "red," whereas "TSU purple" (425 nm, 18.6% and 670 nm, 12.5%) was found by Oliver et al. (2002) to be an attractant color for many buprestid species. All paints, including color-matched Benjamin Moore & Co. and Ace Hardware colors, were mixed at Sherwin Williams Paint and Stain Wallpaper (E. Falmouth, MA) with the exception of fuchsia, which was mixed at Botello Lumber (Mashpee, MA).

Green Wavelength Comparison. Paints were selected based on their peak reflectance in the green range of the visible portion of the electromagnetic spectrum (500–570 nm). Five paint colors were selected with a similar reflectance (≈56–66%) at peak wavelength. The colors tested will be referred to herein by their peak reflectance wavelength numbers: 500, 525, 540, 560, and 570 nm (Fig. 2). Three of the paints tested were stock colors from Benjamin Moore & Co., including 500 nm (2044-40 Amelia Island Blue; 500 nm, 64.1% reflectance), 525 nm (2033–40 Lime Tart; 525 nm, 64.1%), and 570 nm (2150–40 Spring Dust; 570 nm, 56.0%). The other colors, 540 nm (SW6920 Center Stage; 540 nm, 66.1%) and 560 nm (SW6918 Humorous Green; 560 nm, 60.1%), were stock colors from Sherwin Williams Ltd. The color representing 540 nm had been tested as "light green"

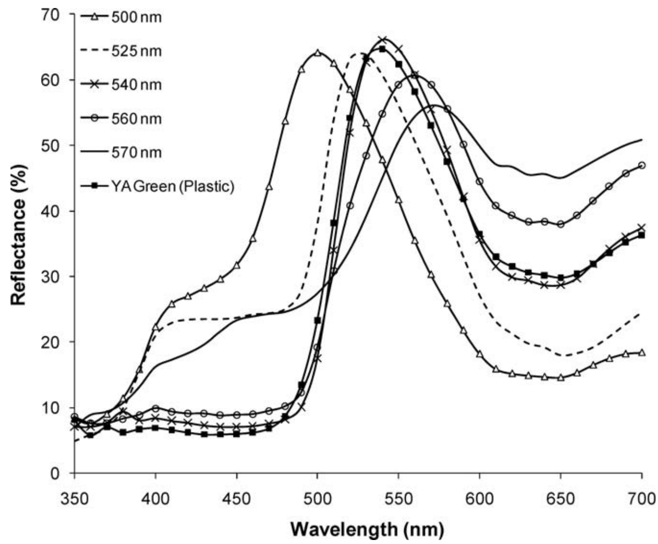

Fig. 2. Reflectance spectra of green painted and plastic traps used in a wavelength comparison study.

in previous studies (Crook et al. 2009). With the exception of 525 nm, which was mixed at Botello Lumber, all paints, including color-matched Benjamin Moore & Co. colors, were mixed at Sherwin Williams Paint and Stain Wallpaper.

Green Reflectance Comparison. Paints were selected based on their percentage of peak reflectance within the 530–540-nm portion of the electromagnetic spectrum. Four paint colors were picked and are referred herein by their peak reflectance percentages: 9, 23, 49, and 66% (Fig. 3). Two of the paints tested were produced as stock colors by Sherwin Williams Ltd.: 49% (SW6931 Jolly Green; 530 nm, 48.9% reflectance) and 66% (SW6920 Center Stage; 540 nm, 66.1%), whereas two were produced by Benjamin Moore & Co.: 9% (EXT RM Chrome Green; 530 nm, 8.7%) and 23% (2036–20 Irish Moss; 540 nm, 22.7%). Two of the paints used in this study were tested by Crook et al. (2009) under the designations of "light green" (66%, also tested in the green wavelength comparison as 540 nm) and "dark green" (23%).

Trapping Studies. Two coats of primer were applied to translucent three-panel prism traps (35.0 by 58.75 cm each; described by Francese et al. 2008) and allowed to cure for at least 1 d. Three to five coats of a single paint were then applied to a primed trap until the primer was no longer visible. Besides the painted traps, both field assays included two plastic color treatments as standards for trap catch comparisons: purple (stock color manufactured by Coroplast Inc.: 430 nm, 20.0%; 600 nm, 6.0%; and 670 nm 13.5%) (Fig. 1) found to be attractive to *A. planipennis* in previous studies (Francese et al. 2005, 2008, Crook et al. 2009); and a green plastic ("young ash [YA] green"; 540 nm, 64.7%

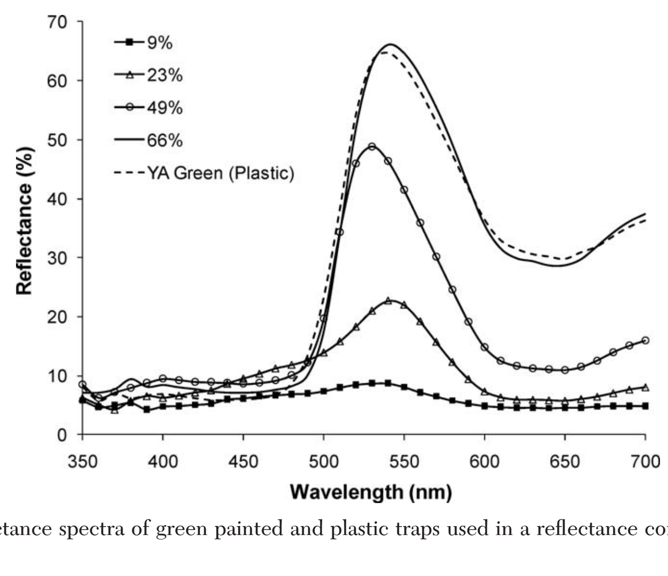

Fig. 3. Reflectance spectra of green painted and plastic traps used in a reflectance comparison study.

reflectance) custom-created to match the light green (540 nm; 66.1%) color found to be attractive in other field assays (Crook et al. 2009) (Fig. 2). Tanglefoot insect trapping glue (The Tanglefoot Company) was applied to the outer surface of all traps. Glue increased trap reflectance by 2% (Crook et al. 2009).

For the green wavelength and purple comparisons (see Results), 10 trap lines (treated as replicates) of each assay were placed along the edge of ash woodlots at four sites in LeRoy Township (both $n = 3$) and White Oak (both $n = 2$), Ingham County, MI. Traps in each line were hung at two heights, mid-canopy ($\approx$13 m) and near the ground (1.5 m), by using methods described by Francese et al. (2008). Trap colors were randomized at each height within each line. Traps were placed in the field by 20 May 2008 and removed from the field on 18 July 2008.

For the green reflectance study, 10 lines were placed at two sites in White Oak ($n = 3$, $n = 4$), and one site in Perry Township ($n = 3$), Shiawassee County, MI. Traps were hung using the methods described above; they were placed in the field by 29 May 2009 and removed on 29 July 2009.

Statistical Analyses. In all studies, trap catch was recorded weekly, and beetles were sexed and summed for each trap over the entire field season. Summed catch on each trap was log-transformed ($n + 0.5$) before statistical analysis. Separate analyses of variance (ANOVAs) using the general linear model were performed for each study (SYSTAT 12, Systat Software, Inc., San Jose, CA). Each analysis was performed with main effects for color, line, and height as well as an interaction effect between height and color. Tukey's honestly significant difference (HSD) (α = 0.05) test was used to compare differences in catch between treatments.

Chi-square analyses also were performed to determine whether there were differences in the overall sex ratio of males to females caught on traps in both studies ($\alpha = 0.05$). Additional pairwise comparisons of colors in each study were made using chi-square analysis on sex in each study with an adjusted α value (0.0024 for the purple and green wavelength comparisons; 0.0033 for the green reflectance comparison) by means of Bonferroni's correction.

Results

Purple Comparison. In this study, both trap color and trap height influenced capture of *A. planipennis.* The color × height interaction ($F = 0.87$; df = 6, 117; $P = 0.522$) did not significantly influence trap catch in the purple comparison study, so the ANOVA was rerun with the interaction term in the model error. Significantly more *A. planipennis* were caught on traps placed in the mid-canopy than on traps at 1.5 m (F = 15.86; df = 1, 123; $P < 0.001$). Catches of *A. planipennis* were higher on TSU purple traps than on blue, red or Coroplast purple traps, whereas YA green and fuchsia traps caught significantly more than red traps (F = 5.51; df = 6, 123; $P < 0.001$) (Table 1). There were no other differences among any of the paints tested. The effect of trap line did play a significant role in trap catch ($F = 2.05$; df = 9, 117; $P = 0.039$).

Table 1. Number of *A. planipennis* caught on prism traps in a study comparing catch between purple paints ($n = 20$)

Trap color	Mean catch ± SE[a]	Ratio M:F[b]
Blue	8.2 ± 2.1bc	0.70b
TSU purple	26.3 ± 5.3a	0.75b
Violet	16.6 ± 3.5abc	0.84ab
Fuchsia	16.9 ± 2.7ab	0.63b
Red	7.2 ± 1.7c	0.66b
YA green	26.8 ± 9.3ab	1.17a
Coroplast purple	11.1 ± 3.3bc	0.58b

[a] Letters denote significant differences between treatments (α = 0.05; Tukey's HSD).

[b] Pairwise chi-square analyses performed using a Bonferroni-adjusted α value (0.0024). Letters represent significant differences between color treatments.

The overall sex ratio of males to females (1,001: 1,258 = 0.80:1) was significantly skewed toward female catch in this study ($\chi^2 = 32.6$, df = 6, $P < 0.001$). However, more males than females were caught on YA green traps than on all other treatments, except for violet-painted traps (Table 1). There were no other differences in sex ratio among any of the other treatments.

Green Wavelength Comparison. As in the purple color test, both trap color and trap height influenced capture. In an initial analysis, main effects of trap color ($F = 7.48$; df = 6, 117; $P < 0.001$) and height ($F = 81.87$; df = 1, 117; $P < 0.001$) were significant, but in this case the interaction between them also was significant (F = 2.65; df = 6, 117; $P = 0.019$). Thus, separate analyses were performed within each height. In the mid-canopy, trap color ($F = 8.54$; df = 6, 54; $P < 0.001$) was significant, with more *A. planipennis* caught on YA green traps than on all other colors, with the exception of the 525- and 540-nm paints (Table 2). At ground level (1.5 m), there was no significant color effect on overall numbers of beetles captured ($F = 1.40$; df = 6, 54; $P = 0.231$) (Table 2).

Green wavelength affected the sex ratio of *A. planipennis* caught at both heights. In the mid-canopy (13 m), the overall ratio of males to females (2,745:1,903 = 1.44:1) was male-skewed among all treatments (χ^2 = 173.6, df = 6, $P < 0.001$). On traps painted with the 520-nm paint, the ratio was significantly higher than on all other treatments (Table 1). Coroplast purple caught a significantly lower ratio of males to females than all other colors except 570-nm paint. The 570 nm was not significantly different from 560 nm but caught a lower ratio of males to females than all other treatments. There were no significant sex ratio differences among any of the other treatments. Near the ground (1.5 m), the overall ratio of male to female catch (359:326 = 1.10:1) was significantly skewed toward males ($\chi^2 = 39.1$, df = 6, $P < 0.001$). The ratio of males to females caught on 520-nm painted traps was higher than on all other traps except for traps painted with the 500-nm paint (Table 1). There were no significant differences in sex ratios of *A. planipennis* caught on any other traps near the ground.

Table 2. Number of *A. planipennis* caught on prism traps at two heights (13 and 1.5 m) in a study comparing catch between green paints of varying wavelengths (*n* = 10)

Trap color	Mid-canopy (13 m)		Ground (1.5 m)	
	Mean catch ± SE[a]	Ratio M:F[b]	Mean catch ± SE[a]	Ratio M:F[b]
500 nm	23.2 ± 6.9cd	1.47b	4.4 ± 2.3a	1.44ab
525 nm	91.1 ± 27.9abc	2.81a	11.8 ± 6.8a	2.93a
540 nm	115.4 ± 39.4ab	1.21b	20.9 ± 5.4a	1.06b
560 nm	34.0 ± 9.5bcd	1.13bc	6.9 ± 3.4a	0.60b
570 nm	12.4 ± 3.5cd	0.67cd	6.8 ± 2.2a	0.89b
YA Green	170.9 ± 39.1a	1.48b	9.6 ± 2.7a	1.09b
Coroplast purple	17.9 ± 4.4cd	0.44d	8.2 ± 2.1a	0.58b

[a] Letters denote significant differences between treatments within each ht ($\alpha = 0.05$; Tukey's HSD).
[b] Pairwise chi-square analyses performed using a Bonferroni-adjusted α value (0.0024). Letters represent significant differences treatments within each height.

Green Reflectance Comparison. Green reflectance played a role in the number of *A. planipennis* caught on prism traps. The color × height interaction ($F = 1.18$; df = 5, 99; $P = 0.323$) did not significantly influence trap catch in the green reflectance comparison study, so the ANOVA was rerun with the interaction term in the model error. Trap color ($F = 17.36$; df = 5, 104; $P < 0.001$) and trap line ($F = 4.18$; df = 9, 104; $P < 0.001$) significantly affected catch. Traps painted with the 23, 49, and 66% reflectance paints and the YA green plastic caught significantly more *A. planipennis* adults than the 9% paint and purple plastic, and the 49% paint also caught more than the green plastic (Table 3). There were no other significant differences in catch among any of the paint colors or plastics. More *A. planipennis* also were caught on traps placed in the mid-canopy (215.3 ± 44.2) than on traps placed near the ground (17.8 ± 6.3) ($F = 232.09$; df = 1, 104; $P < 0.001$).

The overall ratio of males to females (8,393:5,621 = 1.49:1) caught was significantly skewed toward males among all treatments ($\chi^2 = 464.4$, df = 5, $P < 0.001$). The ratio of males to females caught on traps was highest on the 23% paint and was lowest on the purple plastic (Table 3). Although the sex ratios among the 9 and 66% paints and the green plastic were not significantly different, all three color treatments caught significantly lower ratios of males to females than the 49% paint.

Table 3. Number of *A. planipennis* caught on prism traps in a study comparing catch between green paints (530–540 nm) of varying peak reflectance (*n* = 20)

Trap color	Mean catch ± SE[a]	Ratio M:F[b]
9%	28.1 ± 7.6c	1.03c
23%	142.9 ± 39.3ab	2.63a
49%	255.3 ± 56.4a	1.68b
66%	138.5 ± 33.1ab	1.09c
YA green	114.5 ± 37.3b	1.21c
Coroplast purple	20.5 ± 4.9c	0.45d

[a] Letters denote significant differences between treatments ($\alpha = 0.05$; Tukey's HSD).
[b] Pairwise chi-square analyses performed using a Bonferroni-adjusted α value (0.0033). Letters represent significant differences treatments within each height.

Discussion

Early studies testing trap colors revealed some attraction to red traps by several species of wood-boring insects (Entwistle 1963; Timmons and Potter 1981). Entwistle (1963) speculated that some species of scolytine and platypodid beetles were attracted to red-painted traps due to their resemblance to host bark. Later field observations found more female than male *A. planipennis* on the trunks of host trees during peak daytime activity (Lelito et al. 2008). Subsequently, more *A. planipennis* females were found to be attracted to purple and red traps than males (Francese et al. 2008; Crook et al. 2009). In this study, among blue, red, and purple paint and plastics, there were a higher proportion of females than males caught, regardless of the amount of the red reflectance peak. The greater preference by females for colors found in bark may be explained by their need to locate oviposition sites on the trunks of host ash trees.

Although overall *A. planipennis* catch in the purple comparison study was relatively low, both the blue and the red reflectance peak seem to play a role in trap catch. Although the blue paint had a reflectance peak in the blue range (430 nm) similar to that of TSU purple (425 nm), the TSU purple outperformed the blue by a margin of over 3:1. We hypothesize that this was due to the second wavelength peak from 650 to 670 nm in the TSU purple that was absent in the blue paint.

Traps painted with the TSU purple were more effective at capturing *A. planipennis* than the current purple plastic used in the survey program. Within the purple study TSU purple traps were not significantly different from the green plastic tested. The TSU purple's relatively low yield in comparison with some of the green wavelengths tested in other studies may preclude it from being incorporated into a new *A. planipennis* purple prism trap. However, as new tools (and possibly new traps) are developed for the emerald ash borer, this color may serve a purpose in later research and survey programs.

Based on the results presented, the optimal trap color wavelength for *A. planipennis* would appear to be in the 525–540-nm (green) range. Traps painted with colors in this range made up only 42.9% of those used in the green wavelength study, but they were responsible for 72.9% of the total number of *A. planipennis* caught. This confirms earlier electrophysiological and behavioral findings that greens, specifically in the 540 nm range were most attractive to *A. planipennis* (Crook et al. 2009).

Within the 530–540-nm range, traps painted in the 23 to 66% reflectance range were optimal, catching 93.1% of all *A. planipennis* in the reflectance study. These colors most closely mimic ash foliage during the time of year when *A. planipennis* is in its active flight period (66% representing early leaf color and 23% representing mature leaf color in late flight season; Crook et al. 2009). The new green paint, tested at 49% reflectance, represents an intermediate between the 23 and 66% colors. Although only representing 25% of the traps painted in the 23–66% reflectance range, the traps painted with the 49% reflectance caught 39.3% of all *A. planipennis* in the study. These traps are most effective when placed in the canopy among ash foliage. Reflectance plays a role in the detection of foliage within the canopy for the tephritid *Rhagoletis pomonella* (Walsh) (Prokopy and Owens 1983) and could be an important factor in the attraction of adult *A. planipennis* males to traps. Alternatively, green-colored traps in the middle reflectance range (23–66%) may seem camouflaged to *A. planipennis* when presented against a foliar background, reducing avoidance behaviors and resulting in higher collections. The darkest trap in the green reflectance study (9%), selected to emulate the elytra of an adult emerald ash borer, caught 4 times less than other colors.

More males in general were caught on green traps in the canopy throughout all three studies, which is not surprising as most male activity is known to occur in and above the ash canopy where the beetles feed and search for mates (Lance et al. 2007, Rodriguez-Saona et al. 2007, Lelito et al. 2008). A male-to-female ratio of almost 3:1 was found for *A. planipennis* during field observations of *A. planipennis* behavior by Rodriguez-Saona et al. (2007). Similarly, traps painted with the 525 nm, 63% (2.8:1) and 540 nm, 23% (2.6:1) paints caught the highest male-to-female ratios in their respective studies. The latter color had exhibited the highest male to female ratio in previous studies (Crook et al. 2009). In the green wavelength comparison, trap catch dropped precipitously between the canopy and ground level; however, sex ratios seemed to remain relatively consistent between the heights with the exception of beetles caught on the 570-nm paint. However, catch on 570-nm traps was relatively low at both heights, so this change in sex ratio is probably irrelevant.

The new green plastic traps caught significantly more *A. planipennis* than most of the paints or the survey-standard purple plastic in the purple and green wavelength comparisons. However, in 2009, they were outperformed by the 49% paint. Changing the formulation of the green plastic to more closely match the better paint could potentially improve the green plastic prism trap. For these traps to be optimally effective, the green traps need to be placed in the mid-canopy of ash trees. In a large-scale survey this may not be an option as the equipment needed (i.e., bucket trucks, line-throwing devices, and ladders) can be prohibitive. However, our study indicates the best trap for an *A. planipennis* survey program will be a green trap with 540-nm wavelength and 49% reflectance placed in the mid-canopy where possible.

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