Comparison of Trap Types, Placement, and Colors for Monitoring *Anthonomus musculus* (Coleoptera: Curculionidae) Adults in Highbush Blueberries

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Received 14 September 2017; Editorial decision 12 January 2018

Abstract

The cranberry weevil, *Anthonomus musculus* Say (Coleoptera: Curculionidae), is a key (univoltine) pest of highbush blueberries in the northeast United States. To date, however, no trapping system has been developed to successfully monitor this pest. In 2012–2014, studies were conducted in commercial highbush blueberry farms in New Jersey to 1) evaluate the efficacy of various commercially available traps, designed for other weevil species (e.g., pepper weevil, plum curculio, boll weevil, red palm weevil, and black vine weevil), in capturing *A. musculus* adults; 2) test whether the relative location of traps within the blueberry canopy affects adult captures and 3) determine the effects of different colored (yellow, white, green, red, blue, brown, and black) sticky traps on weevil captures. For a comparison with existing techniques, we also monitored the number of overwintered adult weevils on blueberry bushes using beat sheet sampling. Of all traps and colors tested, the most *A. musculus* adults were caught on yellow sticky traps and more adults were captured when these traps were placed at the bottom half of the blueberry canopy, i.e., 0.5–1.0 m above ground. Most weevils were caught on colored traps late in the season (i.e., during bloom), which corresponds mostly to the second (summer) adult generation. Thus, number of overwintered adults caught on traps did not correlate with those on bushes. Although our study identified traps that can be used to capture *A. musculus* adults, these traps alone (i.e., without semiochemicals) have so far limited applicability for monitoring overwintered adult weevils in highbush blueberries.

Key words: cranberry weevil, attraction, color, height, trap design

The cranberry weevil, *Anthonomus musculus* Say (Coleoptera: Curculionidae), also known as blueberry blossom weevil, causes economic losses to commercial blueberry and cranberry growers (Marucci 1966, Averill and Sylvia 1998, Long and Averill 2003). *A. musculus* is native to North America and its distribution in the United States ranges from Massachusetts to New Jersey in the east coast, and Wisconsin and Michigan in the north central region (Szendrei and Rodriguez-Saona 2009). Although some aspects of the *A. musculus* life cycle remain unknown, it is known that this weevil can complete a single generation in blueberry fields in New Jersey. Overwintered adults move into blueberry fields from surrounding wooded areas early spring (late March through April), where they feed on the developing flower buds (Doehlert and Tomlinson 1947, Mechaber 1992). While it is unknown whether *A. musculus* adults disperse through flying or a combination of flying and walking, once they reach the blueberry fields, overwintered females deposit their eggs into flower buds where the larvae develop (Szendrei and Rodriguez-Saona 2009). Infested flower buds turn purple, fail to open, and eventually fall to the ground. In mid-May through June, next-generation (summer) adults feed on blueberry leaves and then move out of the blueberry fields to nearby wooded areas where they may attack other hosts and/or overwinter (Szendrei and Rodriguez-Saona 2009).

In blueberries, current methods for monitoring the overwintered *A. musculus* adults focus on beat sheet sampling along the edges of fields facing wooded areas, starting at the end of March (bud break) until early May (beginning of bloom) (Szendrei and Rodriguez-Saona 2009). Overwintered adults are the target of insecticide applications to prevent oviposition on flower buds and subsequent injury by larval feeding/developing within buds, which is the main cause of economic damage. An economic threshold based on beat sheet sampling is set at five *A. musculus* adults per bush; however, this sampling
method is labor-intensive and often unreliable because adult weevils have cryptic behaviors and tend to be active mostly on sunny days (Szendrei and Rodriguez-Saona 2009). Therefore, a cost-effective and reliable method for monitoring overwintered A. musculus adults is needed to more accurately time insecticide applications. Insect traps are commonly used for monitoring pest populations in agricultural crops (Pedigo and Rice 2014) and may help improve the timing of insecticide applications used for A. musculus. However, the potential of using a trapping system for monitoring A. musculus has yet to be investigated.

Several different trap designs, including trap types and colors, have been developed to monitor weevil species of agricultural importance (Mizell and Tedders 1999, Cross et al. 2006, McQuate et al. 2014, Tewari et al. 2014, Avalos and Soto 2015). A number of weevils, such as the pepper weevil, Anthonomus eugeni Cano (Coleoptera: Curculionidae), are attracted to simple trap designs like colored sticky cards (Riley and Schuster 1994), while more sophisticated trap designs that incorporate a capturing devise are used for other species such as the plum curculio, Conotrachelus nematicus (Herbst) (Coleoptera: Curculionidae), and the boll weevil, Anthonomus grandis grandis Boheman (Coleoptera: Curculionidae) (Hardee et al. 1996). Trap captures can be influenced also by their placement within the field such as the location of traps within the crop canopy (Mulder et al. 1997, Prokopy et al. 2000, Prokopy et al. 2001, Cross et al. 2006). For example, A. eugeni adults were more likely to be captured on yellow sticky cards placed 10–60 cm above ground than at other heights (Riley and Schuster 1994). Fountain et al. (2017) reported that the strawberry blossom weevil, Anthonomus rubi Herbst (Coleoptera: Curculionidae), was more likely to be trapped at 0 m than at 0.5 or 1.5 m above the soil surface. Color often plays an important role in weevil attraction to traps.

Mizell and Tedders (1999) showed that the root weevils Hylobius pales (Herbst) (Coleoptera: Curculionidae) and Pachylophobius picivorus (Germar) (Coleoptera: Curculionidae) are more attracted to black or brown pyramid-shaped Tedder’s traps than to yellow or white traps. Similarly, the red palm weevil, Rhynchophorus ferrugineus (Olive) (Coleoptera: Curculionidae), is attracted to black traps (Abuagla and Al-Deeb 2012, Al-Saoud 2013). In contrast, A. eugeni is attracted to yellow traps (Riley and Schuster 1994). A study by Szendrei et al. (2011) employed yellow sticky traps to capture A. musculus adults. Whether other trap designs and colors are, however, effective at capturing A. musculus in the field has not been investigated.

Here, we present results of a three year (2012–2014) study done in commercial highbush blueberry, Vaccinium corymbosum L., fields to determine the effects of trap design, location, and color on captures of A. musculus adults in the absence of semiochemical attractants. Experiments were conducted to address the following specific questions: 1) Which of various commercially available traps designed for other curculionid beetles is most effective at capturing A. musculus adults? 2) Are A. musculus adult captures affected by trap placement within the blueberry canopy? 3) Do A. musculus adults respond to different colored traps? and 4) At what period during the blueberry growing season are weevils most responsive to these traps? These studies intended to identify a monitoring tool for A. musculus adults that could be combined in the future with semiochemicals and to learn about the visual cues that trigger its foraging behaviors.

Materials and Methods

Trap Type

A 2yr study (2012–2013) was conducted to evaluate the efficacy of various commercially available trap types, used for monitoring other weevil species, on A. musculus adult captures in commercial blueberry farms. All farmers followed standard crop management procedures (i.e., pesticide use; according to Oudemans et al. 2017), and insecticides (usually a pyrethroid) were used only once if the number of overwintered weevils exceeded the economic threshold of an average of five weevils per bush (Szendrei and Rodriguez-Saona 2009).

2012 Experiment. This experiment was carried out at four commercial blueberry farms located in Burlington and Atlantic Counties in southern New Jersey (farm A: Latitude 39°35’29.3” N, Longitude 74°46’09.8” W, Hammonton township; farm B: Latitude 39°42’18.8” N, Longitude 74°45’01.8” W, Hammonton township; farm C: Latitude 39°55’49.0” N, Longitude 74°36’46.1” W, Pemberton township; farm D: Latitude 39°38’43.3” N, Longitude 74°32’31.2” W, Hammonton township). Farm selection was based on previous history of A. musculus infestation and farms were separated at least 8 km from each other. Five different trap types were tested: 1) yellow sticky traps (23 × 28 cm; Pherocon AM no-bait trap, Trécé, Adair, OK; Fig. 1a); 2) Whalon modified Tedder’s traps, with a collection top, used for monitoring plum curculio (C. nematicus) and pecan weevil (Curculio caryae (Horn)) (Coleoptera: Curculionidae) (Great Lakes IPM, Vestaburg, MI; Fig. 1b); 3) boll weevil traps, with a collection top, used in boll weevil (A. grandis) eradication programs (Great Lakes IPM) (Fig. 1c); 4) ISCA pitfall traps, used for monitoring red palm weevil (R. ferrugineus) and South American palm weevil (Rhynchophorus palmarum (L.)) (Coleoptera: Curculionidae) (ISCA Technologies, Riverside, CA; Fig. 1d); and 5) ChemTica pitfall traps, used for monitoring black vine weevil (Otiorhynchus sulcatus (E.)) (Coleoptera: Curculionidae) (ChemTica International S.A., Heredia, Costa Rica; Fig. 1e). Two of these traps (sticky trap and boll weevil trap) are designed to intercept flying weevils, whereas the other three traps are designed to capture walking insects. Yellow sticky traps were used as our standard trap based from a previous study (Szendrei et al. 2011) and were placed vertically (i.e., with the narrow edge perpendicular to the ground and the long trap dimension horizontal) at mid-canopy (1–1.5 m above the ground) using 2.5–m metal poles. The Whalon modified Tedder’s trap is a 1.2-m tall pyramid trap that is placed on the ground and has a capturing device at the top of the trap (Fig. 1b); the insect flies near the trap, which it reaches by walking, and then accesses the trap device by walking upward on one of the trap panes. Boll weevil traps were hung at mid-canopy (1–1.5 m above the ground) using bamboo stakes; the insects attracted to this yellow-green color trap land on the outside of the body, crawl to the inside of the cone, and enter the collection chamber through an opening at the top of the cone (Fig. 1c). The ISCA and ChemTica pitfall traps were placed at ground level (i.e., 0 m); a major difference between these traps besides size is that the ISCA trap has the opening (entrance) at the top (Fig. 1d), while the opening in the ChemTica trap is at the bottom (Fig. 1e), of the trap. For plum curculio and boll weevil traps, a killing strip (Hercon Vaportape II insecticidal strip; Gempler’s, Janesville, WI) was placed inside the collection top to prevent weevils from exiting. Ethylene glycol (antifreeze) and a sticky card, placed at the bottom of trap interiors, were used in ISCA and ChemTica traps, respectively, to kill weevils. Killing strips were replaced every three weeks, while the antifreeze and sticky cards were replaced weekly.

Treatments were arranged as a randomized block design. Each block consisted of a set of five different trap types, one of each type, and there were three blocks at each site (i.e., farm) (N = 12 replicates per trap type). Traps were placed in a straight line inside blueberry fields parallel to the field’s edge, 5 m from the edge of the field, and at least 10 m apart from each other within each block. Because A. musculus disperses into blueberry fields from adjacent wooded...
areas (Szendrei and Rodriguez-Saona 2009), all traps were placed near the field’s edge and facing the forest. Distance between blocks was at least 20 m. Traps were placed at the end of March and were rotated (e.g. sequentially moved down a space) weekly. The number of weevils per trap was counted weekly for 12 wk between 20 March and 11 June 2012; this period corresponded from bud break until fruit set/maturation, when *A. musculus* adults are active in commercial blueberry fields in New Jersey.

**2013 Experiment.** This experiment was conducted in four commercial blueberry farms located in southern New Jersey at farms A, B, and C, as mentioned above, and Farm E (Latitude 39°55’43.1”N, Longitude 74°30’06.7”W, Pemberton township). Three of the same traps used in 2012 were tested in 2013: 1) yellow sticky traps; 2) Whalon modified Tedder’s traps; and 3) boll weevil traps. ISCA and ChemTica pitfall traps were not included because they were inefficient at capturing *A. musculus* adults (see Results). In addition, we added white sticky traps used for tarnished plant bugs, *Lygus lineolaris* (Palisot de Beauvois) (Hemiptera: Miridae) (23 × 28 cm; Great Lakes IPM; Fig. 1f), to test for color preference. White sticky traps had the same size, shape, and placement as the yellow sticky traps. Treatments were arranged as a randomized block design with six replicates at each site (i.e., farm) \((N = 24\) replicates per trap design; see above). Distance between traps within sites and their placement were the same as described above for the 2012 experiment. Traps were placed in early April and rotated weekly. The number of weevils per trap was recorded weekly for 9 wk between 8 April and 3 June 2013.

**Trap Height**

An experiment was conducted to determine the effect of trap height within the canopy for capturing *A. musculus* adults. The experiment was conducted in four commercial blueberry farms located in southern New Jersey (farm A, farm B, farm C, and farm D) in 2013. We used yellow sticky traps in this experiment because they were effective at capturing *A. musculus* adults based on previous experiments (see Results). We tested four different trap heights: 1) ground level (i.e., 0 m); 2) bottom of the bush canopy (i.e., 0.5–1.0 m above ground); 3) middle of the canopy (i.e., 1.0–1.5 m above ground); and 4) top of the canopy (i.e., 1.5–2.0 m above ground). This 0.5 m variation within canopy sections accommodated for variation in canopy height among bushes. Within the canopy, the middle part of the trap was adjusted to each of the heights such that the trap was located at the center of each canopy height. Traps were randomly placed at one of the four heights in each bush, all trap heights were tested concurrently in different bushes, and trap height within bushes was changed weekly by a systematic height rotation schedule, as described above. Traps were attached to 2.5-m vertical poles, and trap height was adjusted along the pole. Each trap height was replicated four times (blocks) at each of the four farms in a randomized block design \((N = 16\) replicates per trap height). Distance between traps within farms and placement within fields were the same as described above. Traps were monitored weekly for 9 wk between 8 April (bud break) and 5 June (fruit set per maturation). Farmers followed standard pest management procedures.
Trap Color
A study was conducted to test A. musculus adult preference for different color traps. The experiment was done in three
commercial blueberry farms in New Jersey (farms A, B, and C) in 2014. Seven color traps were tested: yellow (used as our standard; Szendrei et al. 2011), white, green, blue, red, brown, and black. All traps were 22.8 x 14.0 cm made of (3.12-mm thick) colored acrylic sheets (Laird Plastics, Bristol, PA; catalog nos. = 103617, 103416, 207486, 102249, 103220, 102318, and 102091 for yellow, white, green, blue, red, brown, and black, respectively), and were coated on both sides with Tangle-Trap Insect Trap coating (The Tanglefoot Co., Grand Rapids, MI). Treatments were arranged as a randomized block design with three replicates (blocks) at each site (farm), as described above for trap design and placement (N = 9 replicates per colored trap). Traps were placed at mid-canopy height (1.0–1.5 m above ground) and attached vertically to metal poles. Traps within each site were placed at least 10 m apart from each other and rotated weekly, as described above. Distance between blocks was at least 20 m. The number of weevils per trap was recorded weekly for three consecutive months (from 8 April until 3 July).
In addition, numbers of overwintered A. musculus adults on bushes were monitored weekly at each of the sites from 8 April until 6 May using beat sheet sampling. Beat sheet samples were stopped from the beginning of bloom following grower recommendations (Szendrei and Rodriguez-Saona 2009) and to avoid damage to the crop. Ten randomly selected bushes near the colored sticky traps were sampled for adult weevils with a 71 x 71-cm beat sheet (BioQuip Products Inc.). These bushes were located either within the same row as the traps or the row adjacent to the traps closest to the forest and were at least 3 m from the nearest trap. For each bush, two random (mid-canopy) branches were beaten on the sheet, which corresponds to about 1/5 of the bush, and the number of weevils on the sheet was counted. We then calculated the average number of weevils per bush for the 10 bushes per site (block; N = 30 bushes per farm) and each sampling date. All beat sheet samples were taken on the same day as the trap counts. Farmers used standard pest management procedures.
Color Attributes
To better understand the perception of various colors by A. musculus adults, the color reflectivity of the seven different colored traps tested here (yellow, white, red, blue, green, black, and brown) was obtained by reflectance measurements. For this, we used a Varian Cary 500 Scan UV-VIS-NIR spectrophotometer (Varian Inc., Palo Alto, CA), in the spectral wavelength range from 400 to 700 nm (visible light), and equipped with a diffuse reflectance model Varian DRA110 mm. Varian UV Scan application software version 3.00 (399) was used for reflectance data acquisition. Three independent reflectance measurements were conducted for each colored trap; the average percent reflectance from these three measurements is reported here. All measurements were done without an adhesive because a previous study using similar colored traps found very little difference in the wavelength reflectance due to the adhesive (Rodriguez-Saona et al. 2012).
Statistical Analyses
Data on weekly numbers of A. musculus adult captures per trap were checked for normality using the Shapiro–Wilk test (Shapiro and Wilk 1965) and for homoscedasticity using the Levene’s test (‘car’ package in R; R version 3.3.1; R Development Core Team 2016). To test for the effects of trap type, trap height, and trap color on weevil captures, we performed analysis of variance (ANOVA) using linear mixed-effects analysis of covariance models lm() using the ‘nlme’ package in R. The models included treatment (trap type or height or color; fixed factor), week, and block (sites within farms) as main effects, and all possible two-way interactions among them. Blocks were nested with farm, with farm as a random factor. Three-way interactions were not included in the models because the degrees of freedom were too limited. A significant ANOVA was followed by Tukey’s HSD test (α = 0.05; ‘agricole’ package in R). If needed, data were transformed prior to ANOVA using Log, to meet assumptions of normality. Untransformed data are presented in figures. In addition, the number of weevils on colored traps was correlated with the number of weevils on bushes using Pearson correlation (Minitab version 16; Minitab 2010).
Results
Trap Type
2012 Experiment. In 2012, trap type had a significant effect on A. musculus adult captures (Table 1). On average, the yellow sticky trap caught 45 and 4.5 times more A. musculus adults than the Whalon modified Tedder’s trap and the boll weevil trap, respectively; whereas the ISCA and ChemTica pitfall traps did not catch any weevils (Fig. 2a). There was also a significant effect of week and a significant interaction between trap type and week, indicating that the effect of trap type on weevil captures was influenced by the week of sampling. Trap Type-by-Block(Farm) and Week-by-Block(Farm) interactions were also significant, indicating that the effect of trap type and week of sampling on weevil captures varied among geographic locations (Table 1).

| Year     | Variables          | F     | df  | P      |
|----------|--------------------|-------|-----|--------|
| 2012     | Trap type          | 8.80  | 4, 481 | <0.001 |
|          | Week               | 4.04  | 11, 481 | <0.001 |
|          | Block(Farm)        | 1.15  | 9, 481  | 0.31   |
|          | Trap type × Week   | 2.83  | 44, 481 | <0.001 |
|          | Trap type × Block(Farm) | 3.05 | 36, 481 | <0.001 |
|          | Week × Block(Farm) | 1.53  | 99, 481 | 0.01   |
| 2013     | Trap type          | 3.66  | 3, 480  | 0.01   |
|          | Week               | 2.06  | 7, 480   | 0.04   |
|          | Block(Farm)        | 1.24  | 18, 480  | 0.22   |
|          | Trap type × Week   | 1.09  | 21, 480  | 0.34   |
|          | Trap type × Block(Farm) | 1.69 | 54, 480 | <0.002 |
|          | Week × Block(Farm) | 1.27  | 126, 480 | 0.03   |

Results
2013 Experiment. In 2013, trap type and week had a significant effect on A. musculus adult captures (Table 1). The yellow sticky trap captured significantly more A. musculus adults than the boll weevil trap (Fig. 2b) but was not different from the white sticky trap and the Whalon modified Tedder’s trap (Fig. 2b). There were also significant Trap Type-by-Block(Farm) and Week-by-Block(Farm) interactions, indicating that the effect of trap type and week of sampling on weevil captures varied among geographic locations (Table 1).

| Year     | Variables          | F     | df  | P      |
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|          | Trap type × Week   | 1.09  | 21, 480  | 0.34   |
|          | Trap type × Block(Farm) | 1.69 | 54, 480 | <0.002 |
|          | Week × Block(Farm) | 1.27  | 126, 480 | 0.03   |

Trap Height
Trap height had a significant effect on captures of A. musculus adults (Table 2). Traps placed at the bottom of the bush canopy captured twice as many A. musculus adults as traps placed at the top of the canopy (Fig. 3), but numbers of weevils at the bottom of the canopy
were not significantly different than those from traps placed in the middle of the canopy or at ground level (Fig. 3). There were no interaction effects between trap height and week of sampling or between trap height and block (farm) on weevil captures (no two-way interactions, Table 2), indicating that the effect of trap height on weevil captures was not influenced by week of sampling or geographic location.

**Trap Color**

Color significantly affected attraction of *A. musculus* adults (Table 3). Yellow was the most attractive color, followed by white (Fig. 4). In contrast, blue, brown, and black were the least attractive colors whereas attraction to green and red was intermediate (Fig. 4). Numbers of *A. musculus* captured were also significantly influenced by the week of sampling (Table 3), but there was no significant Trap Color × Week interaction (Table 3), indicating that weevils responded similarly to all colored traps throughout the sampling period. The number of *A. musculus* adults on colored traps increased from 6 May until 30 May (summer adults), which coincided with bloom, with a peak in numbers by mid-to end of bloom (Fig 5a). There were significant Trap Color × Block (Farm) and Week × Block (Farm) interactions, indicating that the effect of color and time of season (week) on number of weevils captured on traps varied based on geographic location (Table 3).

We found no correlation between the number of *A. musculus* adults on beat sheet samples from the blueberry brushes versus those trapped on yellow sticky cards (Pearson correlation = -0.077; \(P = 0.784\)) or on any of the other colored traps (all \(P > 0.05\)). In April, we found high numbers of overwintered *A. musculus* adults on bushes, which exceeded the economic threshold on 14 April and 22 April (Fig. 5b), but the number of weevils remained very low on traps during this period (Fig. 5a).

**Table 2.** Effects of trap height, week, and block nested within farm, and their interactions, on the number of cranberry weevil, *A. musculus*, adults (2013)

| Variables                  | \(F\)  | df  | \(P\)    |
|----------------------------|-------|-----|----------|
| Trap height                | 3.10  | 3, 357 | 0.02    |
| Week                       | 3.91  | 8, 357 | <0.001  |
| Block(Farm)                | 1.48  | 12, 357 | 0.12    |
| Trap height × Week         | 1.10  | 24, 357 | 0.33    |
| Trap height × Block(Farm)  | 1.26  | 36, 357 | 0.14    |
| Week × Block(Farm)         | 1.90  | 96, 357 | <0.001  |

**Table 3.** Effects of trap color, week, and block nested within farm, and their interactions, on the number of cranberry weevil, *A. musculus*, adults (2014)

| Variables                  | \(F\)  | df  | \(P\)    |
|----------------------------|-------|-----|----------|
| Trap color                 | 7.33  | 6, 574 | <0.001  |
| Week                       | 6.51  | 12, 574 | <0.001  |
| Block(Farm)                | 1.46  | 6, 574 | 0.18    |
| Trap color × Week          | 1.82  | 72, 574 | 0.36    |
| Trap color × Block(Farm)   | 1.75  | 36, 574 | 0.004   |
| Week × Block(Farm)         | 1.76  | 72, 574 | <0.001  |
Trap Attributes
The colored traps used in our study had differences in reflectance along the visible spectrum (400–700 nm) (Fig. 6). White traps had high reflectance (> 80%) at wavelengths above 420 nm. In contrast, black and brown had zero or close to zero reflectance at all wavelengths measured. Yellow traps also had high reflectance (> 60%) from 530 to 700 nm. The reflectance of blue traps was between 10 and 30% from 400 to 500 nm, with a peak around 450 nm, while green traps had spectral reflectance ranging from 450 to 560 nm, with a peak at 530 nm. Red traps had high reflectance (~90%) at wavelengths ≥650 nm (Fig 6).

Discussion
This study provides the first insights into the visual ecology and foraging behavior of the cranberry weevil, *A. musculus*, which is necessary for the development of a trapping system. We demonstrated that 1) yellow sticky traps captured the highest numbers of *A. musculus* adults; 2) more *A. musculus* adults were caught on yellow sticky traps when placed in the lower half of blueberry bushes; and 3) yellow traps attracted more *A. musculus* adults than other colored traps, which correspond to a reflectance specific for yellow of 550–650 nm. The number of overwintered *A. musculus* adults caught on yellow sticky traps did not, however, correlate with the estimated number of weevils on bushes. In fact, the relatively lower catch of the overwintered generation on yellow sticky traps indicates that, in the absence of other cues (e.g., chemical), these traps have limited practicability for monitoring the most damaging (overwintered) generation of *A. musculus* adults in highbush blueberries.

Among all trap types tested in this study, colored sticky traps (yellow) were most effective at capturing *A. musculus* adults. Yellow sticky traps have been used to monitor other weevils including the pepper weevil, *A. eugenii* (Riley and Schuster 1994) and the pea leaf weevil, *Sitona lineatus* (L.) (Coleoptera: Curculionidae) (Fisher and O’Keeffe 1979). Two of the trap types we tested (colored sticky traps and boll weevil traps) were placed at canopy level, while the other traps (Whalon modified Tedder’s and ISCA and ChemTica pitfall traps) were placed at ground level. The Whalon modified Tedder’s and ISCA and ChemTica pitfall traps are designed for walking insects, while colored sticky and boll weevil traps are designed to intercept flying insects. It is worth noting, however, that although the Whalon modified Tedder’s traps, used to monitor plum curculio (*C. nenuphar*) populations, were designed to intercept walking rather than flying individuals (Blanchett 1987, Duan et al. 1996, Prokopy et al. 1999), the collection vial in these traps is located 1.2 m above ground, which matches the height of the bottom half of the blueberry canopy. In our study, *A. musculus* adults were recovered only from colored sticky, boll weevil, and Whalon modified Tedder’s traps; whereas no weevils were found in ISCA and ChemTica pitfall traps. These results suggest that *A. musculus* adults are unlikely to locate blueberry bushes by walking but instead they likely flew to find their host plant; thus, traps located at canopy level to intercept flying weevils will be best at capturing this weevil pest in highbush blueberry fields. However, the location of traps within the blueberry canopy affected *A. musculus* adult captures, i.e., yellow sticky traps placed in the bottom half of the canopy captured more weevils than those placed in the upper half or on the ground. Altogether our results from the trapping design and placement experiments suggest that *A. musculus* do not walk to locate
A blueberry host plant but rather fly at heights between 0.5 and 1.5 m above ground. The role of wind on *A. musculus* dispersal and within-canopy pattern of capture needs further investigation.

*A. musculus* adults were more attracted to yellow than to red, blue, black, and brown. These findings agree with the visual response of the boll weevil (*A. grandis*), the pepper weevil (*A. eugenii*), and the root weevil (*Sitona lepidus* Gyllenhall), which are also attracted to yellow (Cross et al. 1976, Riley and Schuster 1994, Hardwick and Harens 2007). On the other hand, two root weevils, *H. pales* and *P. picivorus*, respond better to black and brown than to other colors (Mizell and Tedders 1999). Therefore, different weevil species respond differently to colors probably depending on their specific resource and environmental needs. In fact, attraction to colors in *A. musculus* was related to the crop phenology as overwintered adults were not responsive to any colors, while yellow attracted mostly the summer generation adults. In blueberries, summer generation *A. musculus* adults become active in May–June, when plants are producing new vegetation and flowering (peak bloom). It is likely that these weevils utilize the color of blueberry foliage as one cue to locate their host plant. In fact, yellow is a known foliage-type stimulus for many insects (Prokopy and Owens 1983, Lasa et al. 2014, Do Bae et al. 2015, Devi and Roy 2017). Interestingly, boll weevil traps also mimic the color of foliage (yellow-green) but were much less attractive to *A. musculus* adults than sticky traps of similar color, indicating that trap design, and not simply color, is important for capturing this weevil. In addition to color, Szendrei et al. (2009) reported that volatiles from blueberry flowers are attractive to *A. musculus* adults, which suggests that multiple cues might be employed during host location. More research is needed to understand the different cues used by overwintered adults during their movement into blueberry fields. Attraction of insects to colors is based on their sensitivity to different wavelengths of light (Li et al. 2017). Yellow, the most attractive to *A. musculus* adults of those tested here, reflects light at wavelengths between 550 and 600 nm (this study, Mensah et al. 1996, Rodriguez-Saona et al. 2012). Previous studies have also shown that similar wavelength ranges (500–600 nm) are most suitable for trapping other weevil species such as *A. grandis* and *Diaprepes abbreviatus* L. (Cross et al. 1976, Otalora-Luna and Dickens 2011). Our goal was to identify an effective trap that farmers could use to monitor *A. musculus* adults, regardless of their gender. Thus, weevils were not sexed due to the difficulties of sexing them in the field. In any case, a study by Szendrei et al. (2011) found no indication that males and females *A. musculus* differ in their response to yellow sticky traps.

This study aimed at understanding the visual ecology of *A. musculus* and, thus, semiochemicals were not used in traps. Semiochemicals, mainly aggregation pheromones, are commonly used to monitor weevil pests of agricultural crops (reviewed by Tewari et al. 2014). Szendrei et al. (2011) identified (Z)-2-(3,3-dimethyl-cyclohexylidene) ethanol ([Z] grandlure II), (Z)-(3,3-dimethylcyclohexylidene) acetaldehyde ([Z] grandlure III), and (E)-(3,3-dimethylcyclohexylidene) acetaldehyde ([Z] grandlure IV) as components of the male-produced aggregation pheromone in *A. musculus*. A fourth component, (E)-3,7-dimethyl-2,6-octadien-1-ol (geraniol), was produced by both males and females. However, the *A. musculus* aggregation pheromone has performed inconsistently in field trials, pointing at the possibility of key components missing in the blend (C.R.-S. and H.T.A., unpublished data). Moreover, weevil pheromones usually synergize with host plant odors (Tewari et al. 2014), and there is also some evidence that *A. musculus* may utilize host-plant volatiles to locate blueberry plants (Szendrei et al. 2009, D.S., unpublished data). Further studies are needed to optimize an attractant for *A. musculus* and to test whether combining visual and chemical cues enhance the capture of overwintered adults on traps.

Understanding the behavior of insect pests is critical for the development of an effective trapping system (Foster and Harris 1997, Prokopy 1997). From our studies, we learned that *A. musculus* adults likely fly (rather than walk) to locate highbush blueberry plants and that this flight takes place at heights between 0.5 and 1.5 m above ground. We also learned that these weevils seek colors with high reflectance like yellow during foraging. Additionally, we identified and optimized placement within the canopy of a trap that could be used to monitor *A. musculus* adults in highbush blueberry fields. Yellow sticky traps capture more *A. musculus* adults than traps designed for other weevil species and colors; and, they need to be placed at the bottom half of blueberry bushes. These traps can reduce...
Acknowledgments

Thanks to Sunil Tewari, Kris Dahl, Manuel Chacón-Fuentes, Sarah Ongaro, and Gabrielle Pintauro for assistance in the field, and to the New Jersey blueberry farmers (Macrie Brothers Blueberry Farm, Merlino Brothers Farm, Reeves Berries Farm, and North Branch Blueberry & Co.) who kindly allowed us to use their properties as field sites for the experiments. We are also thankful to Dr. Jenny Lockard, Dr. Pavel Kucheryavy, and Robert Holdcraft for their assistance with statistical advice, and to Dr. George Hamilton and three anonymous reviewers for helpful comments on an early version of the manuscript. This research was financially supported by the USDA Pest Management Alternatives Program (PMAP) and the New Jersey blueberry orchard owners from a woodlot to an orchard in southwestern Quebec. B.Sc. dissertation, University of Massachusetts, Amherst, MA. 112 pp.

References Cited

Abuagla, M. A., and M. A. Al-Deeb. 2012. Effect of bait quantity and trap color on the trapping efficacy of the pheromone trap for the red palm weevil, Rhynchophorus ferrugineus. J. Insect Sci. 12: 120.

Al-Saoud, A. H. 2013. Effect of ethyl acetate and trap color on weevil captures in red palm weevil Rhynchophorus ferrugineus (Coleoptera: Curculionidae) pheromone traps. Int. J. Trop. Insect Sci. 33: 202–206.

Ávulos, J. A., and A. Soto. 2015. Study of chromatic attraction of the red palm weevil, Rhynchophorus ferrugineus using bucket traps. Bull. Insectol. 68: 83–90.

Averill, A. L., and M. M. Sylvia. 1998. Cranberry insects of the northeast: a guide to identification, biology, and management. Cranberry Exp. Station Publication. University of Massachusetts, Amherst, MA. 112 pp.

Blanchett, R. 1987. Movement of plum curculio (Conotrachelus nenuphar) from a woodlot to an orchard in southwestern Quebec. B.Sc. dissertation, Department of Entomology, McGill University, Montreal, Quebec, Canada.

Cross, W. H., H. C. Mitchell, and D. D. Hardee. 1976. Boll weevils: Response to light sources and colors on traps. Environ. Entomol. 5: 565–571.

Cross, J. V., H. Hesketh, C. N. Jay, D. R. Hall, P. J. Innocenzi, D. I. Farman, and C. M. Burgess. 2006. Exploiting the aggregation pheromone of strawberry blossom weevil Anthrenomus rubi Herbst (Coleoptera: Curculionidae): Part I. Development of lure and trap. Crop Prot. 25: 144–154.

Devi, M. S., and K. Roy. 2017. Counter study on different coloured sticky traps for attracting Rhynchophorus ferrugineus (Rhynchophorus ferrugineus). J. Entomol. 33: 202–206.

Foster, S. P., and M. O. Harris. 1997. Behavioral manipulation methods for insect pest-management. Annu. Rev. Entomol. 42: 123–146.

Fountain, M. T., C. Baroffio, A. K. Borg-Karlson, P. Brain, J. V. Cross, D. I. Farman, and L. Sigsgaard. 2017. Design and deployment of semi-chemical traps for capturing Antthonomus rubi Herbst (Coleoptera: Curculionidae) and Lygus rugulipennis Pappus (Heteroptera: Miridae) in soft fruit crops. Crop Prot. 99: 1–9.

Hardee, D. D., A. A. Weathersbee III, J. M. Gillespie, G. L. Snodgrass, and A. R. Quisumbing. 1996. Performance of trap designs, lures, and kill strips for the boll weevil (Coleoptera: Curculionidae). J. Econ. Entom. 89: 170–174.

Hardwick, S., and B. Harens. 2007. Influence of trap colour, design and height on catch of flying clover root weevil adults. N. Z. Plant Prot. 60: 217–222.

Lasa, R., O. E. Velázquez, R. Ortega, and E. Acosta. 2014. Efficacy of commercial traps and food odor attractants for mass trapping of Anastrepha ludens (Diptera: Tephritidae). J. Econ. Entomol. 107: 198–205.

Li, L., H. Ma, L. Niu, D. Han, F. Zhang, J. Chen, and Y. Fu. 2017. Evaluation of chromatic cues for trapping Bactrocera tau. Pest Manag. Sci. 73: 217–222.

Long, B. B. and A. L. Averill. 2003. Compensatory response of cranberry to simulated damage by cranberry weevil (Anthrenomus musculus Say) (Coleoptera: Curculionidae). J. Econ. Entomol. 96: 407–412.

Marucci, P. E. 1966. Insects and their control, pp. 199–235. In P. Eck and N. F. Childers (eds.), Blueberry culture. Rutgers University Press, New Brunswick, NJ.

McQuate, G. T., and C. D. Silva. 2014. Trapping sweetpotato weevil, Cylas formicarius (Coleoptera: Brentidae), with high doses of sex pheromone: Catch enhancement and weathering rate in Hawaii. Proc. Hawaii. Entomol. Soc. 46: 59–69.

Mechaber, W. L. 1992. Ecology of Anthrenomus musculus: Hostplant finding and oviposition by cranberry weevil. Ph.D. dissertation. Tufts University, Medford, MA.

Mensah, R. K. 1996. Evaluation of coloured sticky traps for monitoring populations of Aasstroa casiraghesia (Paoli) (Hemiptera: Cicadellidae) on cotton farms. Austral. Entomol. 35: 349–353.

Mintah. 2010. Minitab Computer Software. Minitab, Inc., State College, PA.

Mizell, R. F., III, and W. L. Tedders. 1999. Evaluation of trap type and color for monitoring Hylobius pales and Pachylobius piscivorus in Florida. Fl. Entomol. 82: 615–624.

Mulder, P. G., B. D. McCraw, W. Reid, and R. A. Grantham. 1997. Monitoring adult weevil populations in pecan and fruit trees in Oklahoma. Ext. Facts F-7190. Oklahoma State University, Stillwater, OK. 1–8.

Oudemans, P., D. Ward, B. Majek, D. Polk, and C. Rodriguez-Saona. 2017. Commercial blueberry pest control recommendations for New Jersey. Cooperative Ext. Bull. E265, Rutgers New Jersey Agricultural Experimental Station, New Brunswick, NJ.

Olóra-Luna, E., and J. C. Dickens. 2011. Multimodal stimulation of Colorado potato beetle reveals modulation of pheromone response by yellow light. PLoS One. 6: e20990.

Peplos, L. P., and M. E. Rice. 2014. Entomology and pest management. Waveland Press, Long Grove, IL.

Prokopy, R. J. 1997. Principles of monitoring tephritid fruit flies. pp. 155–161. In G. Bourgeois and M. Guibord (eds.), Agricultural pest forecasting and monitoring. Rezese d’Avertissements Phytsosanitaires du Quebec, Sainte Foy, Quebec, Canada.

Prokopy, R. J., and E. D. Owens. 1983. Visual detection of plants by herbivorous insects. Annu. Rev. Entomol. 28: 337–364.

Prokopy, R. J., C. B. Wirth, and T. C. Leskey. 1999. Movement of plum curculio adults toward host trees and traps: flight versus walking. Entomol. Exp. Appl. 91: 383–392.

Prokopy, R. J., B. Chandler, T. C. Leskey, and S. Wright. 2000. Comparison of traps for monitoring plum curculio adults (Coleoptera: Curculionidae) in apple orchards. J. Entomol. Sci. 35: 411–420.

Prokopy, R. J., P. L. Phelan, S. E. Wright, A. Minalga, J. R. Barger, and T. C. Leskey. 2001. Compounds from host odor attractive to plum curculio adults (Coleoptera: Curculionidae). J. Econ. Entomol. 36: 123–134.

R Development Core Team. 2016. R, A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
Riley, D. G., and D. J. Schuster. 1994. Pepper weevil adult response to colored sticky traps in pepper fields. Southwest. Entomol. 19: 93–107.

Rodriguez-Saona, C. R., J. A. Byers, and D. Schiffhauer. 2012. Effect of trap color and height on captures of blunt-nosed and sharp-nosed leafhoppers (Hemiptera: Cicadellidae) and non-target arthropods in cranberry bogs. Crop Prot. 40: 132–144.

Shapiro, S. S., and M. B. Wilk. 1965. An Analysis of variance test for normality (complete samples). Biometrika. 52: 591–611.

Szendrei, Z., and C. Rodriguez-Saona. 2009. Cranberry weevil in blueberries. New Jersey Experimental Station, Rutgers University, New Brunswick, NJ. Fact Sheet FS1087. 2pp.

Szendrei, Z., E. Malo, L. Stelinski, and C. Rodriguez-Saona. 2009. Response of cranberry weevil (Coleoptera: Curculionidae) to host plant volatiles. Environ. Entomol. 38: 861–869.

Szendrei, Z., A. Averill, H. Alborn, and C. Rodriguez-Saona. 2011. Identification and field evaluation of attractants for the cranberry weevil, Anthonomus musculus Say. J. Chem. Ecol. 37: 387–397.

Tewari, S., T. C. Leskey, A. L. Nielsen, J. C. Piñero, and C. Rodriguez-Saona. 2014. Use of pheromones in insect pest management, with special attention to weevil pheromones, pp. 141–168. In D. P. Abrol, (ed.), Integrated pest management: current concepts and ecological perspective. Elsevier Inc., San Diego, CA.