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Effect of trap color and height on captures of blunt-nosed and sharp-nosed leafhoppers (Hemiptera: Cicadellidae) and non-target arthropods in cranberry bogs

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A B S T R A C T

A series of field experiments was conducted in cranberry bogs in 2006–2010 to determine adult attraction of the two most economically important leafhopper pests of cultivated *Vaccinium* spp. in the northeast USA, the blunt-nosed leafhopper, *Limotettix vaccinii* (Van Duzee), and the sharp-nosed leafhopper, *Scaphytopius magdalensis* (Provancher), to colored (yellow, green, red, blue, white, and clear) sticky traps. We also determined the effects of trap height on insect captures, evaluated trap color characteristics (i.e., reflectance spectra, and red, green, and blue RGB values) for maximizing leafhopper capture while minimizing beneficial arthropod capture, and correlated within-season adult leafhopper captures from traps with nymphal captures from sweep nets. Leafhopper species exhibited distinct preferences to particular colors differing in intensities along a spectrum of wavelengths and RGB values: green was the most attractive color to blunt-nosed leafhoppers, followed by red and yellow; while yellow was most attractive to sharp-nosed leafhoppers, followed by green and red. Attraction of leafhoppers to other colors was similar to clear. Most insect predators (e.g. lady beetles, hoverflies, and minute pirate bugs), parasitic wasps, and honey bees also exhibited preferences to particular trap color characteristics, whereas green lacewings and spiders did not. An effective attraction radius was calculated for each color of trap and species. Additionally, we measured mean ± SD of flight heights of several species and showed that more leafhoppers and hoverflies were captured on red and yellow traps placed 0.1 m above the canopy; while captures of lady beetles were highest on traps placed 0.5 m above the canopy. Numbers of adult leafhoppers on traps were largely uncorrelated with numbers of nymphs in sweep net samples, except for blunt-nosed leafhoppers captured on red traps which were positively correlated with sweep net counts. We discuss the potential of using colored sticky traps to monitor leafhopper populations in the context of their non-target species effects in cranberries.

1. Introduction

Two leafhoppers (Hemiptera: Cicadellidae), the blunt-nosed leafhopper, *Limotettix* (=*Scleroracus*) *vaccinii* (Van Duzee), and the sharp-nosed leafhopper, *Scaphytopius magdalensis* (Provancher), are commonly found in cranberries, *Vaccinium macrocarpon* Ait., in the northeast USA (Beckwith and Hutton, 1929a,b; Averill and Sylvia, 1998). These leafhoppers feed on cranberry stems and leaves, which can cause loss of sap material; but this injury is rarely noticeable and its economic impact has yet to be determined (Beckwith and Hutton, 1929b). Besides damage caused by direct feeding and perhaps more importantly, these leafhoppers are vectors of diseases of wild and cultivated *Vaccinium* spp. (Chen, 1971). The blunt-nosed leafhopper is of particular economic importance to cranberry growers because it vectors a phytoplasma that causes false blossom disease (Beckwith and Hutton, 1929b; Dobroscky, 1931; Wilcox and Beckwith, 1935; Chen, 1971). This disease almost destroyed the cranberry industry in New Jersey (USA) in the 1920s (Averill and Sylvia, 1998). Conversely, the sharp-nosed leafhopper does not transmit false blossom (Dobroscky, 1931), but transmits a similar phytoplasma that causes stunt disease in blueberries, *Vaccinium corymbosum* L. (Tomlinson et al., 1950; Hutchinson, 1955; Chen, 1971). However, blueberry stunt disease is of no economic importance in cranberries (Averill and Sylvia, 1998).

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In New Jersey, the blunt-nosed leafhopper can complete one generation a year in cranberries, while the sharp-nosed leafhopper can complete two generations a year. Both species overwinter as eggs. The overwintered eggs hatch in May, and nymphs go through five instars (Beckwith and Hutton, 1929a; Dobroscky, 1931; Averill and Sylvia, 1998). Blunt-nosed leafhopper adults appear in early July and remain active until early August; eggs are laid mostly at the end of July and in August. First- and second-generation sharp-nosed leafhopper adults appear from mid-June into July and from mid-August into September, respectively.

Leafhoppers are difficult insects to monitor in cranberry bogs. Historically, monitoring for leafhoppers in cranberries has relied on sweep net sampling (Beckwith and Hutton, 1929a,b; Franklin, 1935). However, monitoring leafhoppers using sweep nets is challenging for cranberry growers because samples are typically taken only prior to bloom of cranberry (i.e., month of May in New Jersey), and then discontinued due to potential damage to flowers and fruit (Averill and Sylvia, 1998). Prior to bloom, only leafhopper nymphs are present in cranberry bogs, and using sweep nets to monitor immature leafhoppers is problematic because of their small size, which often requires bringing the samples to a laboratory for processing under a microscope. Although adult leafhoppers are more easily recognized from sweep net samples, they are mostly active after bloom (i.e., July–August in New Jersey) when sweep net samples have been discontinued. Furthermore, blunt-nosed leafhopper adults are the most mobile stage and more likely than nymphs to spread false blossom disease among cranberry bogs; it also remains poorly known to what extent immatures can transmit the disease. Thus, developing an alternative sampling technique that can be used to monitor adult leafhoppers, as opposed to nymphs, and that can be easily adopted by growers will improve current IPM practices in cranberries.

Colored sticky traps may be a sampling technique acceptable to cranberry growers for monitoring adult leafhoppers. These traps have been commonly used to monitor insect pests in agricultural fields (Prokopy, 1975; Cross et al., 1976; Prokopy and Owens, 1983; Meyerdirk and Moreno, 1984; Knight and Miliczky, 2003; Atakan and Canhilal, 2004), including leafhoppers (Alverson et al., 1977; Meyerdirk and Oldfield, 1985; Todd et al., 1990a,b; DeGooyer et al., 1998; Lessio and Alma, 2004). Most critical, these traps are very useful when pheromone traps are unavailable or when use of other sampling methods can damage the crop; which is the case for leafhoppers in cranberries. Yellow, in particular, is effective for capturing leafhoppers (Ball, 1979; Van Steenwyk et al., 1990; Mensah, 1996; DeGooyer et al., 1998; Demirel and Yildirim, 2008). In fact, yellow sticky traps are regularly used to monitor populations of the sharp-nosed leafhopper in blueberries (Tomlinson et al., 1950; Hopkins and Johnson, 1984; Meyer and Colvin, 1985). However, the potential of using colored sticky traps for monitoring blunt-nosed and sharp-nosed leafhoppers in cranberries has yet to be explored. In addition, trap height can affect the number of leafhoppers captured (Meyer and Colvin, 1985; Van Steenwyk et al., 1990; DeGooyer et al., 1998; Atakan and Canhilal, 2004; Pilkington et al., 2004); thus, height is an important factor that needs to be considered when monitoring with these traps. Because color can also influence the foraging behavior of natural enemies of pests (Maredia et al., 1992; Blackmer et al., 2008; Roubos and Liburd, 2008) and pollinators (Clare et al., 2000; Knight and Miliczky, 2003; Roubos and Liburd, 2008), attraction of these beneficials to colored traps needs to be addressed to minimize non-target effects.

The main objective of the present study was to develop a sticky trap sampling technique for leafhopper adults in cranberries. Specifically, we conducted field experiments in 2006–2010 in commercial cranberry bogs to: 1) examine the response of blunt-nosed and sharp-nosed leafhopper adults to colored sticky traps; 2) monitor the response of key natural enemies [e.g. lady beetles (Coleoptera: Coccinellidae), hoverflies (Diptera: Syrphidae), green lacewings (Neuroptera: Chrysopidae), minute pirate bugs (Hemiptera: Anthocoridae), spiders (Araneae), and parasitic wasps (Hymenoptera)] and honey bees, *Apis mellifera* L. (Hymenoptera: Apidae), to these traps in order to identify traps that are selective to leafhoppers, our target pest; 3) determine the effect of trap height on insect captures; and, 4) evaluate the effectiveness of commercially-available yellow sticky traps in capturing blunt-nosed and sharp-nosed leafhopper adults in relation to sweep net sampling.

2. Materials and methods

2.1. Colored sticky traps

Three field experiments were performed in separate years to examine the attraction of blunt-nosed and sharp-nosed leafhoppers to different color traps. All sites were cranberry bogs [a “bog” is a wetland with high water table and high acidic organic matter; because cranberries in New Jersey are grown in wet, marshy areas with acidic, sandy soils, these are called bogs (other terms include beds or marshes)] of at least 0.5 acres (0.202 ha), located in Burlington Co., New Jersey, selected based on prior history of leafhopper infestation. These sites had no broad-spectrum insecticides applied throughout the growing season.

2.1.1. Trap description

Colored sticky traps were made of 4 mm-thick flat Plexiglas (Laird Plastics; Bristol, PA, USA). Five or six colors were tested each year for attraction (see below). Traps were coated on both sides with sticky polymers (Tangle-Trap® Insect Trap Coating; The Tanglefoot Company, Grand Rapids, MI, USA), and attached horizontally with 2 screws to the top ends of 40-cm high metal poles. Poles were buried in fields such that trap bottoms were ∼10 cm above the ground, i.e., just above canopy height.

2.1.2. 2006 experiment

This experiment was conducted in two commercial cranberry farms (Chatsworth, New Jersey) (farm A: Latitude 39.74°N, Longitude −74.43°W; farm B: Latitude 39.68°N, Longitude −74.49°W) from 7 June to 26 July 2006, to coincide with peak adult leafhopper flight activity. Five colors representing a wide wavelength range were tested for attraction: red (a mimic for cranberry fruit or that of senescing foliage; Cat. no. 2157; Laird Plastics), blue (a blueberry fruit mimic; Cat. no. 2114), green (a mature leaf mimic; Cat. no. 2108), yellow [a young leaf mimic or a color associated with insect or pathogen infestation; yellow traps were made by painting colorless clear Plexiglas with bright yellow (Painter’s Touch multipurpose latex paint, Rust-oleum Corporation, Vemon Hills, IL, USA)], and white (a flower mimic; Cat. no. 3015). Traps were 20.5 cm (horizontal) × 30.5 cm (vertical) rectangles. Each set of five traps, one of each color, was replicated 7 times in a randomized complete block design, and blocked by site. Traps within each block were placed at least 10 m apart from each other, 20 cm away from the bog edge, following a straight-line arrangement, and rotated weekly to randomize their position relative to other traps, such that no trap of a particular color was placed in the same position twice during the experiment.

2.1.3. 2009–2010 Experiments

These experiments were conducted in two commercial cranberry farms from 26 June to 31 July (2009) and 28 June to 2 August (2010) [the farm used in the 2009 experiment was located in Chatsworth, New Jersey (farm A), while the farm in the 2010 experiment was located in Pemberton, New Jersey (farm C; 39.94°N, −74.48°W)] and at the Rutgers P.E. Marucci Research Center (Chatsworth; 39.72°N, −74.51°W; this last location was used in both years). In 2009 and 2010, instead of painting the traps yellow, we used a yellow Plexiglas (Cat. no. 2037; Laird Plastics) that was similar in color. Also, in addition to the five colors tested in 2006, we included a clear (colorless "control") trap. Traps were 14 cm (horizontal) × 23 cm (vertical) rectangles. Compared to 2006, smaller traps were used in 2009–2010 because these are more comparable in size to those commercially available (see below). A set of six traps was placed in each of four different cranberry bogs. Each year, one set of traps was placed in a cranberry bog at the Rutgers P.E. Marucci Research Center, while the others ($n = 3$ sets) were placed in different bogs at a commercial farm (1 set per bog). Thus, each trap color was replicated four times each year in a randomized complete block design, using bog (site) as block. Distance among traps within blocks and their arrangement was similar as described above (2006 experiment).

2.1.4. Visual preferences of leafhoppers and beneficial arthropods

Traps were checked 1–2 times a week in the laboratory for the presence of leafhoppers and other arthropods (i.e., beneficial insects and spiders). In all years, numbers of adult blunt-nosed and sharp-nosed leafhoppers were counted under a stereomicroscope. In 2009–2010, we also counted the numbers of predators, parasitic wasps, and honey bees. Insect predators were identified to family and, when possible, to species; principal predator families were: hoverflies, lady beetles, green lacewings, and minute pirate bugs. Other major groups of beneficial arthropods were also identified and counted, including spiders, parasitic wasps, and honey bees.

2.1.5. Statistical analysis

Data for leafhoppers and beneficial arthropods were analyzed separately as a group using repeated-measures MANOVA (Minitab 16; Minitab Inc., State College, PA, USA). MANOVA was initially performed on the data because densities of individual arthropod groups were not independent (Scheiner, 2001). The model included treatment (color), time of year (date), treatment × date, and block (site). Each year was analyzed separately. A significant MANOVA was followed by repeated-measures ANOVA for individual leafhoppers, insect predator families, spiders, parasitic wasps, and honey bees. After a significant ANOVA for treatment or treatment × date effects was found, means were separated by Tukey tests. When needed, data were $\ln(y)$ or $\ln(y + 0.5)$-transformed before analysis to meet assumptions of normality and homogeneity of variance.

2.1.6. The effective attraction radius

The Effective Attactive Radius (EAR) was calculated from the catch data according to previous methods (Byers et al., 1989; Byers, 2009, 2011) in order to determine the attractive effect of various colored sticky cards to target pests and non-target insects and spiders. The EAR is a spherical radius that would intercept the same number of insects as caught by an attractive trap (semiochemical or color or both). The EAR conveniently substitutes in simulation models for the complex spatial dimensions of attractive odor plumes dynamically interacting with orientation behavior of insects that are nearly impossible to characterize in the field. The EAR is calculated from a ratio of trap catches in the field; a catch on an attractive trap and a catch on a passive blank trap (Byers et al., 1989; Byers, 2008). In addition, the EAR equation needs the silhouette area of the trap as seen from the horizontal direction. Thus, if the trap is a cylinder of 30 cm diameter and 30 cm high then the area is $0.3 \times 0.3 = 0.09$ m^2. Flat traps, as used here, must be rotated for all possible interception directions to obtain an average, which is width × length × 0.637 (Byers et al., 1989). The EAR is converted to a circular EARc for use in two-dimensional models of monitoring, mass trapping, and mating disruption that use attractive traps or dispensers in pest management programs (Byers, 2007, 2008, 2009, 2011). In general, if the EAR of the treatment trap is larger than the clear control trap, this is indicative of attraction, but if the EAR is smaller, then the treatment may be repellent.

2.2. Trap height

The effect of trap height on catches of the two leafhopper species was examined in 2007 (20 June–23 August) using two different colored (yellow or red) Plexiglas traps (Laird Plastics) in cranberries. Yellow and red were used in these experiments because these colors differentially attracted blunt-nosed and sharp-nosed leafhoppers in cranberries (see Results section). These studies were conducted in three different bogs: one bog at the Rutgers P.E. Marucci Research Center and two bogs at a commercial farm (farm A). Traps were 14 × 23 cm rectangles placed horizontally on 1.5-m high metal poles, such that the traps were located at 0.1, 0.5, and 0.9 m above the top of the cranberry canopy. Two sets of three traps at different heights, one of each color, were placed in each of the three cranberry bogs. The design was a randomized complete block with six replicates (blocked by site). Traps were visually inspected weekly for leafhoppers, as well as for hoverflies and lady beetles, two of the most common predators. Poles within each bog were placed at least 10 m apart from each other.

2.2.1. Statistical analysis

The effects of height, color, site (block), and color × height were analyzed using ANOVA for each insect group. Season total numbers of insects were calculated, and $\ln(y)$- or $\ln(y + 0.5)$-transformed, if needed, prior to analysis. In addition, different trap heights were used to estimate a mean flight height and standard deviation (SD), as well as to fit a normal equation to the vertical flight distribution according to methods presented in Byers (2011). The strength of the fit of the normal equation to the observed data was determined by a squared product–moment correlation (Byers, 2011). The SD was used to calculate an effective flight layer (F_L) used in transforming the spherical EAR of attractive traps into a circular EARc for potential use in two-dimensional encounter rate models of monitoring and mass trapping (Byers, 2007, 2008, 2009, 2011) using colored traps.

2.3. Sweep net sampling vs sticky traps

Experiments were conducted in 2007 and 2008 to determine whether sweep net samples correlate with sticky trap captures of blunt-nosed and sharp-nosed leafhoppers. These studies were conducted in 10 different bogs, cv. 'Stevens' (>3 acres each), located across four commercial cranberry farms in Burlington Co. (New Jersey; farms A-C and farm D: Latitude 39.75°N, Longitude −74.54°W). Bogs were selected randomly within farms. In 2007 we tested the attraction of leafhoppers to 14 × 23 cm yellow or red sticky traps made of Plexiglas (similar to those described above); while in 2008 we used commercially-available yellow (14 × 23 cm; ISCA Technologies, Riverside, CA, USA) and red (14 × 23 cm; Great Lakes IPM Inc., Vestaburg, MI, USA) sticky traps. The yellow and red colors were selected because they showed differential attractiveness to the two target species of leafhoppers in cranberries. Two traps of each color were placed in each bog at least 10 m apart. Weekly sweep net samples began soon after winter flood water was taken off cranberry bogs (i.e., 1st week in May) until just prior to bloom (i.e., 1st week in June). These samples consisted of five sets of 25 consecutive sweeps each taken from across each of the bogs with a 38-cm sweep net (Great Lakes IPM Inc.), as described in

Averill and Sylvia (1998). Colored sticky traps were placed in bogs for a total of ∼3 months, from the beginning of bloom (second week in June) until fruit maturation (end of August), and checked weekly. Numbers of leafhoppers from sweep net samples and traps were counted weekly. In 2008 leafhoppers from both sampling methods were separated by species, but only trapping samples were separated by species in 2007. In addition, leafhoppers from sticky traps were sexed in 2008.

2.3.1. Statistical analysis

Because the timing of the sticky traps and sweep samples did not coincide, weekly numbers of leafhoppers obtained from sweep net samples and colored sticky traps were summed separately for each species and color combination to obtain season total counts. Leafhopper nymphal counts from the five sweep net sets were averaged to obtain the season-total number of leafhopper nymphs for each species/color/sweep set per bog. Similarly, counts from the two color traps in each bog were averaged to calculate the season-total number of leafhopper adults for each species/color/trap/bog. Samples for nymphal counts as well as for adult counts were averaged for each bog because these were not independent. These two numbers (i.e., season total counts of nymphs from sweep net samples and adults from traps) for the two different leafhopper species and for the two different color traps were then correlated across all 10 bogs using Pearson correlation (Minitab).

2.4. Color attributes

Reflected light and RGB (red, green, blue) values of the colored traps (with and without Tangle-Trap adhesive applied) used in the experiments were measured in the field between 1130 and 1230 h under sunny conditions (∼100,000 lux) on 29 January and 21 February 2008. We measured color attributes from three yellow traps: clear Plexiglas traps painted with yellow (used in 2006) (referred to as “yellow 1”, commercially-available yellow traps (ISCA Technologies) (“yellow 2”), and yellow Plexiglas traps (Laird Plastics) (“yellow 3”); two red traps: commercially-available red traps (Lakes IPM Inc.) (referred to as “red 1”), and red Plexiglas traps (Laird Plastics) (“red 2”); and from blue, green, and white Plexiglas traps (Laird Plastics). Reflectance spectra were measured by a USB2000 spectroradiometer using OOIBase32 version 2.0.2.2 software (Ocean Optics Inc., Dunedin, FL). A solarization-resistant, UV transparent, optical fiber (400 μm) probe with an adjustable collimating lens was held perpendicular to the trap surface to capture the spectral reflection. Reflectance intensity readings from the near UV through the visible wavelengths (300–850 nm) were automatically scanned using an integration time from 3 to 29 ms adjusted to keep recorded intensities under the maximum 4000 counts (Byers, 2006). Digital images of the colored sticky traps were taken with a Canon PowerShot A540 digital camera at 2816 by 2112 pixel resolution and 24-bit color. Computer software (Byers, 2006) was used to analyze the RGB attributes of pixels that ranged from 0 to 255 in value of each attribute ($N = 1600$ pixels for each sample color). RGB values of trap colors were converted to hue, saturation, and luminosity (HSL) values with internet software (www.chemical-ecology.net/java2/rgb.htm).

3. Results

3.1. Colored sticky traps

Trap color (MANOVA, *2006*: Wilks’ $\lambda = 0.46$, $F = 8.72$, ndf = 10, ddf = 182, $P < 0.001$; 2009: Wilks’ $\lambda = 0.55$, $F = 5.92$, ndf = 10, ddf = 172, $P < 0.001$; 2010: Wilks’ $\lambda = 0.56$, $F = 5.77$, ndf = 10, ddf = 172, $P < 0.001$), date (MANOVA, 2006: Wilks’ $\lambda = 0.09$, $F = 70.08$, ndf = 6, ddf = 182, $P < 0.001$; 2009: Wilks’ $\lambda = 0.06$, $F = 63.58$, ndf = 8, ddf = 172, $P < 0.001$; 2010: Wilks’ $\lambda = 0.37$, $F = 13.86$, ndf = 8, ddf = 172, $P < 0.001$), and block (MANOVA, 2006: Wilks’ $\lambda = 0.55$, $F = 8.03$, ndf = 8, ddf = 182, $P < 0.001$; 2009: Wilks’ $\lambda = 0.75$, $F = 4.28$, ndf = 6, ddf = 172, $P < 0.001$; 2010: Wilks’ $\lambda = 0.59$, $F = 8.79$, ndf = 6, ddf = 172, $P < 0.001$) had a significant effect on leafhopper attraction. Color-by-date interaction affected leafhopper attraction to traps in 2006 and 2009 (MANOVA, 2006: Wilks’ $\lambda = 0.62$, $F = 1.61$, ndf = 30, ddf = 182, $P = 0.031$; 2009: Wilks’ $\lambda = 0.54$, $F = 1.55$, ndf = 40, ddf = 172, $P = 0.03$), but not in 2010 (Wilks’ $\lambda = 0.67$, $F = 0.96$, ndf = 40, ddf = 172, $P = 0.54$).

When analyzed separately, color significantly affected attraction of adult sharp-nosed leafhoppers (Fig. 1; Table 1). In all 3 years, yellow was the most attractive trap to sharp-nosed leafhoppers, followed by red and green; whereas attraction to blue and white was not significantly different from clear (Fig. 1a–c; Table 2). Time of year did not affect the response of sharp-nosed leafhoppers to color (Table 1). Color also had a strong effect on attraction of adult blunt-nosed leafhoppers (Table 1). In contrast to the sharp-nosed leafhopper, blunt-nosed leafhoppers were most attracted to green, followed closely by red and then yellow; while attraction to blue and white was similar to clear (Fig. 1d–f; Table 2). The response of blunt-nosed leafhoppers to color was influenced by date in 2009 but not in 2006 and 2010 (Table 1). In 2009, attraction of blunt-nosed leafhoppers to green and red was greater in early sampling dates, but this changed in mid-July, when they were more attracted to yellow traps (significant Color × Date interaction; Fig. 1e).

Beneficial arthropod attraction was affected by color (MANOVA, 2009: Wilks’ $\lambda = 0.04$, $F = 11.3$, ndf = 35, ddf = 343, $P < 0.001$; 2010: Wilks’ $\lambda = 0.03$, $F = 15.37$, ndf = 30, ddf = 330, $P < 0.001$), date (MANOVA, 2009: Wilks’ $\lambda = 0.02$, $F = 20.14$, ndf = 28, ddf = 293, $P < 0.001$; 2010: Wilks’ $\lambda = 0.04$, $F = 17.19$, ndf = 24, ddf = 287, $P < 0.001$), block (MANOVA, 2009: Wilks’ $\lambda = 0.45$, $F = 3.55$, ndf = 21, ddf = 233, $P < 0.001$; 2010: Wilks’ $\lambda = 0.46$, $F = 4.05$, ndf = 18, ddf = 232, $P < 0.001$), and color-by-date interaction (MANOVA, 2009: Wilks’ $\lambda = 0.09$, $F = 1.65$, ndf = 140, ddf = 548, $P < 0.001$; 2010: Wilks’ $\lambda = 0.15$, $F = 1.59$, ndf = 120, ddf = 481, $P < 0.001$).

When analyzed separately, trap color had an effect on hoverflies, minute pirate bugs (*Orius* spp.), parasitic wasps, and honey bees in 2009 and 2010; while color had an effect on lady beetles only in 2010 (Table 1). In 2010, lady beetles were most attracted to yellow (Table 2; Fig. 3a). About 22, 13, and 9% of lady beetles in 2009 were identified as *Coleomegilla maculata* (De Geer), *Coccinella septempunctata* L., and *Hippodamia convergens* Guérin-Méneville, respectively. Other coccinellid species included *Harmonia axyridis* (Pallas), *Propylaea quatuordecimpunctata* L., and *Cycloneda munda* (Say). In 2010, 64, 11, and 5% of lady beetles were identified as *C. maculata*, *H. axyridis*, and *C. septempunctata*, respectively. Other, less common coccinellid species included *H. convergens*, *C. munda*, and *P. quatuordecimpunctata*. Hoverflies were most attracted to blue, followed by white (Table 2; Figs. 2b and 3b). The most common hoverfly species (>90% of all individuals found in our samples) on traps was identified as *Toxomerus marginatus* (Say) (see also Rodriguez-Saona et al., 2011). Although flight activity of hoverflies was greatest during bloom (significant Date effect, Table 1; Figs. 2b and 3b), date had no effect on attraction to color (no interaction effect, Table 1). Interestingly, hoverflies were repelled or less attracted to green and red as compared with clear (Table 2; Figs. 2b and 3b). Pirate bugs were most attracted to white, followed by yellow (Table 2; Figs. 2c and 3c). Pirate bugs were primarily abundant during bloom (Figs. 2c and 3c). Attraction of pirate bugs switched unexpectedly from yellow to white soon after bloom in 2009 (significant Color × Date interaction, Table 1). Parasitic Hymenoptera were clearly attracted to yellow, followed

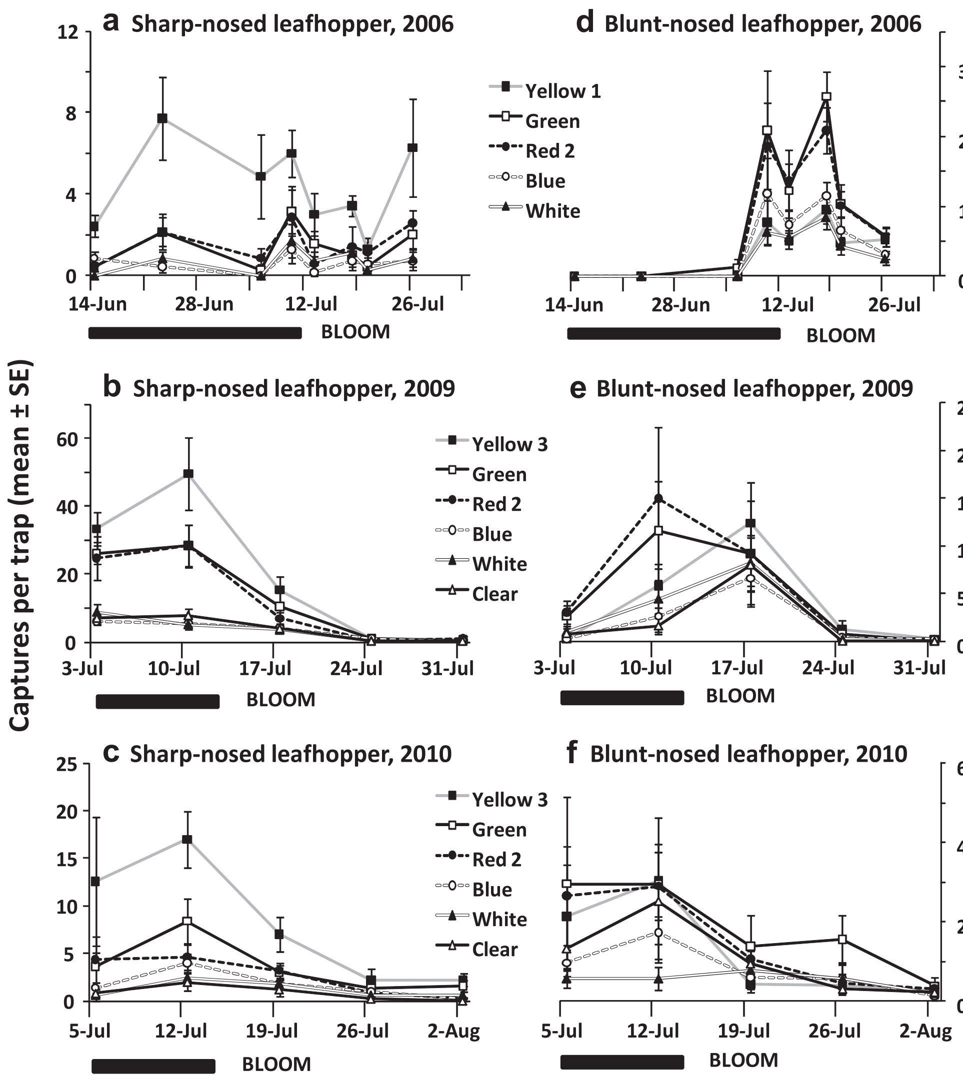

Fig. 1. Seasonal pattern of captures of (a–c) sharp-nosed and (d–f) blunt-nosed leafhoppers on sticky traps of various colors (listed in legends; see Table 4, Figs. 6 and 7 for details) in cranberries in 2006, 2009, and 2010. All traps were made of colored Plexiglas material, except for Yellow 1 which consisted of a clear Plexiglas trap coated with yellow paint.

by red and green, and flight activity increased during bloom (Table 2; Figs. 2d and 3d). Honey bees were highly attracted to white (Table 2; Figs. 2f and 3f), and this attraction declined after bloom (significant Color × Date interaction, Table 1). In contrast, honey bees were less attracted or repelled by yellow, green, and red as compared to clear (Table 2). There was no effect of color on spiders (Tables 1and 2; Figs. 2e and 3e) or on nocturnally-flying green lacewings (*Chrysopa* spp.) (Tables 1and 2; Fig. 2g).

EAR measurements were made on the colored traps in relation to clear traps that were assumed to be merely intercepting the insects in flight. EAR and its transformed EARc of the colored traps were calculated (Table 2) as these can be used to develop monitoring or mass trapping programs (Byers, 2007, 2008). Yellow, green, or red traps had larger EAR and EARc for the two species of pest leafhoppers than did clear traps, while blue and white traps were similar to clear traps (Table 2). Yellow had the largest EAR/EARc for sharp-nosed leafhopper, while green had the largest for blunt-nosed leafhopper. Differences in sizes of EAR and EARc among colored traps are considered significant when the differences in catches on these traps were significantly different (Table 2). EAR and EARc for colored traps were not significantly different from clear traps for lady beetles. In hoverflies, blue and white traps had larger EAR/EARc than clear traps, while green and red traps seem to be repellent (Table 2). Pirate bugs had EAR for yellow or white that were two times larger than clear traps, and five times larger EARc than clear traps. The clear traps consistently caught the lowest numbers for those insects with low visual acuity such as the leafhoppers, lady beetles, pirate bugs, and parasitic wasps. Honey bees and hoverflies with higher visual acuity may have avoided landing on some trap colors like red and green. Clear traps were assumed not attractive or repellent and to catch insects according to the average physical interception area (Table 2).

3.2. Trap height

Trap height had a significant effect on captures of blunt-nosed leafhoppers ($F = 11.11$, df = 2, 28, $P < 0.001$; Fig. 4a) and sharp-nosed leafhoppers ($F = 39.34$, df = 2, 28, $P < 0.001$; Fig. 4b). Traps placed 0.1 m above the canopy captured 28 and 9 times more blunt-nosed and sharp-nosed leafhoppers, respectively, compared with those placed 0.9 m above the canopy. Blunt-nosed leafhoppers showed no preference for red or yellow ($F = 0.02$, df = 1, 28, $P = 0.892$; Fig. 4a), whereas sharp-nosed leafhoppers were more

Table 1
Repeated measures ANOVA for the effects of trap color on attraction of leafhoppers and beneficial arthropods in cranberries.

Year	Color			Date			Color × Date			Block		
Arthropod Taxa	*F*	df	*P*	*F*	df	*P*	*F*	df	*P*	*F*	df	*P*
2006												
Sharp-nosed leafhopper	27.84	4, 234	**<0.001**	7.21	7, 234	**<0.001**	1.06	28, 234	0.393	7.45	6, 234	**<0.001**
Blunt-nosed leafhopper	9.16	4, 234	**<0.001**	390.72	7, 234	**<0.001**	1.16	28, 234	0.271	15.19	6, 234	**<0.001**
2009												
Sharp-nosed leafhopper	10.60	5, 87	**<0.001**	116.31	4, 87	**<0.001**	1.54	20, 87	0.089	4.60	3, 87	**0.005**
Blunt-nosed leafhopper	3.70	5, 87	**0.004**	59.40	4, 87	**<0.001**	1.80	20, 87	**0.033**	5.57	3, 87	**0.002**
Lady beetles	1.79	5, 87	0.122	14.65	4, 87	**<0.001**	0.76	20, 87	0.756	6.94	3, 87	**<0.001**
Hoverflies	112.63	5, 87	**<0.001**	21.47	4, 87	**<0.001**	1.45	20, 87	0.123	1.00	3, 87	0.395
Lacewings	0.96	5, 87	0.446	3.04	4, 87	**0.021**	0.88	20, 87	0.616	1.24	3, 87	0.301
Pirate bugs	9.85	5, 87	**<0.001**	10.36	4, 87	**<0.001**	3.97	20, 87	**<0.001**	1.42	3, 87	0.242
Parasitic wasps	5.50	5, 87	**<0.001**	12.50	4, 87	**<0.001**	0.74	20, 87	0.770	2.85	3, 87	**0.042**
Spiders	0.97	5, 87	0.439	5.29	4, 87	**0.001**	1.20	20, 87	0.275	2.13	3, 87	0.103
Honeybees	17.87	5, 87	**<0.001**	200.67	4, 87	**<0.001**	3.50	20, 87	**<0.001**	14.34	3, 87	**<0.001**
2010												
Sharp-nosed leafhopper	7.93	5, 87	**<0.001**	13.85	4, 87	**<0.001**	1.17	20, 87	0.298	1.30	3, 87	0.279
Blunt-nosed leafhopper	4.32	5, 87	**0.001**	23.49	4, 87	**<0.001**	0.79	20, 87	0.720	17.93	3, 87	**<0.001**
Lady beetles	2.29	5, 87	**0.050**	1.16	4, 87	0.333	0.68	20, 87	0.838	1.84	3, 87	0.145
Hoverflies	71.90	5, 87	**<0.001**	26.53	4, 87	**<0.001**	1.63	20, 87	0.062	8.79	3, 87	**<0.001**
Lacewings[a]	–	–	–	–	–	–	–	–	–	–	–	–
Pirate bugs	17.22	5, 87	**<0.001**	38.40	4, 87	**<0.001**	1.47	20, 87	0.114	2.13	3, 87	0.102
Parasitic wasps	4.69	5, 87	**0.001**	4.40	4, 87	**0.003**	0.49	20, 87	0.966	6.76	3, 87	**<0.001**
Spiders	1.40	5, 87	0.233	0.21	4, 87	0.934	1.14	20, 87	0.325	3.37	3, 87	**0.022**
Honey bees	33.10	5, 87	**<0.001**	146.86	4, 87	**<0.001**	4.09	20, 87	**<0.001**	2.32	3, 87	0.081

Significant *P* values are in bold ($P \leq 0.05$).
[a] Numbers were insufficient for analysis.

attracted to yellow than red ($F = 12.1$, df = 1, 28, $P = 0.002$; Fig. 4b). The effect of trap height on leafhoppers did not vary with color (no height-by-color interaction; blunt-nosed leafhopper: $F = 2.12$, df = 2, 28, $P = 0.139$; sharp-nosed leafhopper: $F = 0.01$, df = 2, 28, $P = 0.992$; Fig. 4a,b), such that both leafhoppers were more attracted to traps closer to the canopy regardless of trap color.

Trap height also had a significant effect on captures of hoverflies ($F = 9.8$, df = 2, 28, $P = 0.001$; Fig. 4c) and lady beetles ($F = 20.45$, df = 2, 28, $P < 0.001$; Fig. 4d). Captures of hoverflies were seven times higher on traps placed 0.1 m above the canopy than those placed 0.9 m above the canopy. In contrast, lady beetle captures were highest on traps 0.5 m above the canopy than on those placed at 0.9 m. Hoverflies showed no preference for red or yellow ($F = 3.23$, df = 1, 28, $P = 0.083$; Fig. 4c), whereas lady beetles were more attracted to yellow than red ($F = 103.18$, df = 1, 28, $P < 0.001$; Fig. 4d). The response of hoverflies ($F = 0.87$, df = 2, 28, $P = 0.43$) and lady beetles ($F = 0.8$, df = 2, 28, $P = 0.46$) to trap height was not influenced by color (Fig. 4c,d).

Catches on yellow or red traps placed at 0.1, 0.5, and 0.9 m above the surface of the cranberries were analyzed for mean flight height. On yellow traps, the blunt-nosed and sharp-nosed leafhoppers had similar mean heights of 0.28 and 0.23 m, respectively (Table 3). The SD of the vertical flight distribution of each species was also similar at 0.25 and 0.27 m. The lowest of the three trap heights had most of the catch, and this was especially true for the red traps. In the case of the blunt-nosed leafhopper, only the lowest red traps caught adults which gave a mean flight height of only 0.1 m, while the sharp-nosed leafhopper had a similar mean height of only 0.13 m, as measured by red traps (Table 2). The hoverfly *T. marginatus*, however, had similar mean flight heights on yellow and red traps of 0.26 and 0.27 m, and these were similar to the leafhoppers in regard to yellow traps. Lady beetles had a slightly higher mean flight height (0.38–0.42 m). The leafhoppers, hoverfly, and lady beetles, all had similar effective flight layers due to the nearly identical SD of their vertical flight distributions (Table 3).

3.3. Sweep net sampling vs sticky traps

Numbers of blunt-nosed leafhoppers on yellow traps did not correlate with those from sweep net samples in both years (2007: Pearson correlation, $r = -0.196$, $P = 0.587$; 2008: $r = 0.197$, $P = 0.586$) (Fig. 5a,b). Numbers of blunt-nosed leafhoppers correlated positively with red traps in both years; however, this correlation was significant in 2008 ($r = 0.872$, $P = 0.001$; Fig. 5a), but not in 2007 ($r = 0.468$, $P = 0.172$; Fig. 5b). Similarly, numbers of sharp-nosed leafhoppers on yellow traps did not correlate with those from sweep net samples in both years (2007: $r = -0.338$, $P = 0.34$; 2008: $r = -0.054$, $P = 0.882$) (Fig. 5c,d). A lack of correlation was also found for red traps (2007: $r = -0.439$, $P = 0.204$; 2008: $r = 0.288$, $P = 0.42$) (Fig. 5c,d).

The female:male ratio of leafhoppers in sticky traps revealed a male bias which was, regardless of color, stronger for sharp-nosed leafhoppers (1:6.3 for yellow, females (mean per trap ± SE) = 3.2 ± 0.7, males = 19.9 ± 5.2; 1:9.2 for red, females = 3.3 ± 0.3, males = 12.6 ± 1.4) than for blunt-nosed leafhoppers (1:1.3 for yellow, females = 0.7 ± 0.2, males = 0.9 ± 0.3; 1:1.4 for red, females = 1.6 ± 0.4, males = 2.2 ± 0.5).

3.4. Color attributes

Digital images of the colored traps were analyzed by software that obtains the mean and SD of R, G, and B values in samples of 1600 pixels (Table 4). The RGB values were also represented as percentages of R, G, and B as well as converted to HSL color system. The RGB and HSL values and their statistical variation obtained with only a digital camera and use of Internet software serve as a more standard method, readily available, of describing colors rather than subjective determinations using words such as “yellow” or “red”. The sticky layer did not appear to affect the RGB values of any colored trap (Table 4). Little variation (low SD) of any component value was observed, as expected since the colors were solid and uniform (Table 4). Little difference was observed between Red 1

Table 2
Mean captures ± SE ($N = 4$) of arthropods and their respective Effective Attraction Radius (EAR) and circular EAR (EARc) values (in m) for different color traps in cranberry bogs of New Jersey in 2009 and 2010. See Table 4, Figs. 6 and 7 for description of colors.

Arthropod taxa	Trap color	2009[a]			2010[a]			Both Years[b]		
		Mean ± SE	EAR	EARc[c]	Mean ± SE	EAR	EARc	Mean ± SE	EAR	EARc
Sharp-nosed leafhopper	Yellow 3	103.5 ± 17.7 a	0.183	0.0760	50.3 ± 8.4 a	0.220	0.1106	76.9 ± 13.5	0.193	0.0846
	Green	63.3 ± 6.4 a	0.143	0.0464	26.0 ± 0.9 ab	0.159	0.0572	44.6 ± 7.7	0.147	0.0491
	Red 2	66.5 ± 5.6 a	0.146	0.0488	19.8 ± 4.8 ab	0.138	0.0435	43.1 ± 9.5	0.144	0.0475
	Blue	19.3 ± 3.8 b	0.079	0.0141	9.0 ± 0.8 bc	0.093	0.0198	14.1 ± 2.7	0.083	0.0156
	White	19.8 ± 3.4 b	0.080	0.0145	10.3 ± 2.4 bc	0.100	0.0226	15.0 ± 2.6	0.085	0.0165
	Clear	20.3 ± 2.1 b	0.081	0.0149	6.8 ± 0.9 c	0.081	0.0149	13.5 ± 2.8	0.081	0.0149
Blunt-nosed leafhopper	Yellow 3	24.5 ± 0.9 ab	0.114	0.0326	75.5 ± 32.9 ab	0.087	0.0187	50.0 ± 18.0	0.091	0.0209
	Green	29.0 ± 5.6 a	0.124	0.0385	111.8 ± 47.6 a	0.105	0.0277	70.4 ± 27.1	0.109	0.0894
	Red 2	34.3 ± 12.7 ab	0.135	0.0455	90.5 ± 24.4 ab	0.095	0.0224	62.4 ± 16.6	0.102	0.0260
	Blue	12.0 ± 4.8 b	0.080	0.0159	48.8 ± 18.3 ab	0.070	0.0121	30.4 ± 11.2	0.071	0.0127
	White	17.3 ± 4.3 ab	0.096	0.0229	31.8 ± 10.6 b	0.056	0.0079	24.5 ± 6.0	0.064	0.0102
	Clear	12.3 ± 3.7 b	0.081	0.0163	65.8 ± 31.3 ab	0.081	0.0163	39.0 ± 17.8	0.081	0.0163
Lady beetles	Yellow 3	5.0 ± 2.8 a	0.128	0.0417	6.5 ± 2.2 a	0.130	0.0434	5.8 ± 1.7	0.129	0.0426
	Green	4.0 ± 2.2 a	0.114	0.0333	2.8 ± 0.9 ab	0.085	0.0183	3.4 ± 1.1	0.099	0.0250
	Red 2	1.8 ± 0.5 a	0.076	0.0146	1.5 ± 0.3 b	0.063	0.0100	1.6 ± 0.3	0.069	0.0120
	Blue	0.8 ± 0.5 a	0.049	0.0063	2.0 ± 1.1 ab	0.072	0.0133	1.4 ± 0.6	0.063	0.0102
	White	3.3 ± 1.9 a	0.103	0.0271	1.5 ± 0.3 ab	0.063	0.0100	2.4 ± 1.0	0.083	0.0176
	Clear	2.0 ± 1.4 a	0.081	0.0167	2.5 ± 1.0 ab	0.081	0.0167	2.3 ± 0.8	0.081	0.0167
Hoverflies	Yellow 3	144.8 ± 12.0 b	0.076	0.0137	39.8 ± 3.5 c	0.051	0.0062	92.3 ± 20.7	0.068	0.0108
	Green	18.0 ± 3.1 c	0.027	0.0017	9.0 ± 1.8 d	0.024	0.0014	13.5 ± 2.4	0.026	0.0016
	Red 2	20.3 ± 4.2 c	0.028	0.0019	15.3 ± 3.3 d	0.032	0.0024	17.8 ± 2.6	0.030	0.0021
	Blue	466.8 ± 17.8 a	0.137	0.0442	248.0 ± 35.9 a	0.128	0.0385	357.4 ± 45.3	0.133	0.0420
	White	298.5 ± 24.6 a	0.109	0.0282	160.5 ± 28.6 ab	0.103	0.0249	229.5 ± 31.4	0.107	0.0270
	Clear	163.0 ± 12.8 b	0.081	0.0154	99.3 ± 17.3 b	0.081	0.0154	131.1 ± 15.6	0.081	0.0154
Lacewings[d]	Yellow 3	0.0 ± 0.0 a	0.000	0.0000	0.0 ± 0.0	–	–	0.0 ± 0.0	0.000	0.0000
	Green	0.3 ± 0.3 a	0.047	0.0057	0.0 ± 0.0	–	–	0.1 ± 0.1	0.047	0.0057
	Red 2	1.5 ± 0.9 a	0.114	0.0342	0.0 ± 0.0	–	–	0.8 ± 0.5	0.114	0.0342
	Blue	0.8 ± 0.8 a	0.081	0.0171	0.0 ± 0.0	–	–	0.4 ± 0.4	0.081	0.0171
	White	0.3 ± 0.3 a	0.047	0.0057	0.3 ± 0.3	–	–	0.3 ± 0.2	0.066	0.0114
	Clear	0.8 ± 0.5 a	0.081	0.0171	0.0 ± 0.0	–	–	0.4 ± 0.3	0.081	0.0171
Pirate Bugs	Yellow 3	21.5 ± 2.5 a	0.187	0.0919	25.5 ± 6.1 a	0.123	0.0396	23.5 ± 3.1	0.143	0.0536
	Green	1.0 ± 0.7 c	0.040	0.0042	6.8 ± 1.8 b	0.063	0.0105	3.9 ± 1.4	0.058	0.0088
	Red 2	2.0 ± 1.1 c	0.057	0.0085	6.5 ± 2.2 b	0.062	0.0101	4.3 ± 1.4	0.061	0.0097
	Blue	1.3 ± 0.8 c	0.045	0.0053	2.3 ± 0.9 b	0.037	0.0035	1.8 ± 0.6	0.039	0.0040
	White	20.8 ± 2.7 ab	0.184	0.0887	77.5 ± 16.7 a	0.214	0.1204	49.1 ± 13.3	0.207	0.1120
	Clear	4.0 ± 1.8 bc	0.081	0.0171	11.0 ± 3.6 b	0.081	0.0171	7.5 ± 2.3	0.081	0.0171
Parasitic Wasps	Yellow 3	123.5 ± 50.2 a	0.159	0.0665	29.8 ± 8.3 a	0.156	0.0636	76.6 ± 29.5	0.159	0.0659
	Green	57.0 ± 10.5ab	0.108	0.0307	18.5 ± 3.9 ab	0.123	0.0395	37.8 ± 8.9	0.111	0.0325
	Red 2	68.3 ± 8.3ab	0.118	0.0367	18.5 ± 4.9 ab	0.123	0.0470	43.4 ± 10.4	0.119	0.0373
	Blue	39.8 ± 9.9 bc	0.090	0.0214	10.0 ± 4.4 c	0.090	0.0236	24.9 ± 7.5	0.090	0.0214
	White	19.8 ± 5.0 c	0.064	0.0106	22.0 ± 8.5 abc	0.134	0.0470	20.9 ± 4.6	0.083	0.0180
	Clear	31.8 ± 6.8 bc	0.081	0.0171	8.0 ± 1.4 bc	0.081	0.0171	19.9 ± 5.5	0.081	0.0171
Spiders	Yellow 3	4.0 ± 2.0 a	0.102	0.0273	7.8 ± 3.8 a	0.150	0.0589	5.9 ± 2.1	0.127	0.0423
	Green	1.8 ± 0.5 a	0.068	0.0120	3.5 ± 1.0 a	0.101	0.0266	2.6 ± 0.6	0.085	0.0189
	Red 2	2.8 ± 1.5 a	0.085	0.0188	3.3 ± 1.4 a	0.097	0.0247	3.0 ± 1.0	0.091	0.0216
	Blue	1.0 ± 0.7 a	0.051	0.0068	2.0 ± 0.7 a	0.076	0.0152	1.5 ± 0.5	0.064	0.0108
	White	3.3 ± 0.9 a	0.092	0.0222	6.5 ± 1.2 a	0.137	0.0494	4.9 ± 0.9	0.116	0.0351
	Clear	2.5 ± 0.9 a	0.081	0.0171	2.3 ± 0.9 a	0.081	0.0171	2.4 ± 0.6	0.081	0.0171
Honey bees	Yellow 3	19.5 ± 5.0 cd	0.043	0.0048	15.0 ± 2.6 c	0.031	0.0026	17.3 ± 2.7	0.037	0.0035
	Green	13.8 ± 2.7 d	0.036	0.0034	11.0 ± 2.7 c	0.027	0.0019	12.4 ± 1.9	0.031	0.0025
	Red 2	13.8 ± 3.5 d	0.036	0.0034	19.0 ± 3.3 c	0.035	0.0033	16.4 ± 2.4	0.036	0.0033
	Blue	49.3 ± 17.3 bc	0.068	0.0122	65.5 ± 8.9 b	0.066	0.0113	57.4 ± 9.5	0.067	0.0117
	White	134.5 ± 38.9 a	0.113	0.0334	211.3 ± 14.0 a	0.118	0.0365	172.9 ± 24.0	0.116	0.0352
	Clear	68.8 ± 17.4 b	0.081	0.0171	99.0 ± 5.4 ab	0.081	0.0171	83.9 ± 10.2	0.081	0.0171

[a] Numbers with different letters within a column refer to significant difference at the 0.05 level according to Tukey tests.
[b] Average numbers in years 2009 and 2010.
[c] EARc calculated from species-specific F_L (Table 3), or if F_L not known, then F_L assumed equal to 0.60 (mean of insects in Table 3).
[d] Numbers of lacewings in 2010 were too low to perform statistics.

and Red 2, but the two color shades could be distinguished. However, a subtle difference is apparent between Yellow 1 and Yellow 2, mainly in the B component, and Yellow 3 also is slightly different in all three components (Table 4).

The individual components of RGB may be composed of pure spectral wavelengths or mixtures of several wavelengths. For example, orange (RGB = 255, 118, 17) may result from a blending of pure red (650 nm) and yellow (570 nm), or be a pure orange (590 nm). Thus, a more accurate and precise description of trap colors, but requiring a spectroradiometer, is an intensity graph of each wavelength over the visible range (Figs. 6 and 7). The colored traps used in our study clearly had different intensities along a spectrum of wavelengths (Fig. 6). It may be that the insect responses were not only to different wavelengths but also to the

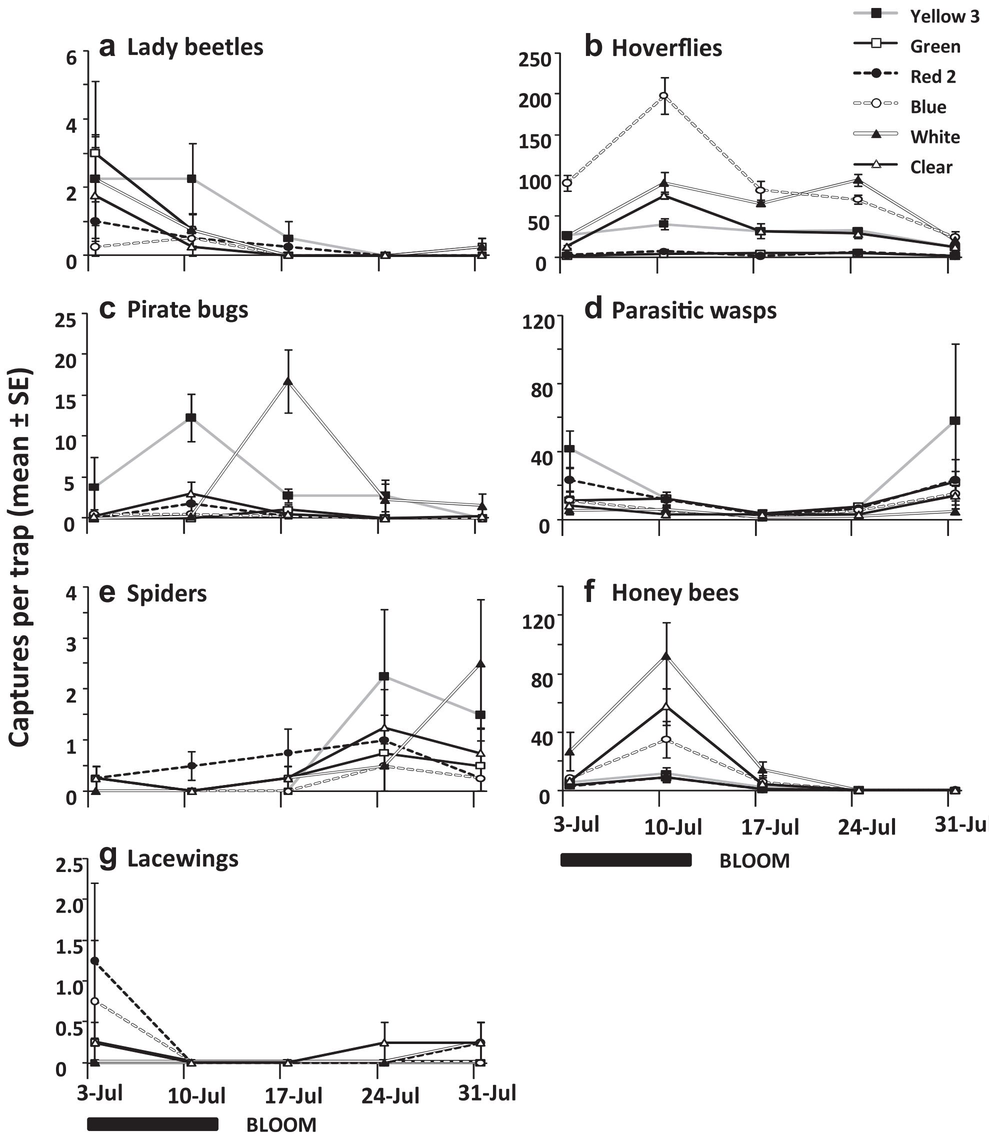

Fig. 2. Seasonal pattern of captures of (a) lady beetles, (b) hoverflies, (c) pirate bugs, (d) parasitic wasps, (e) spiders, (f) honey bees, and (g) lacewings on sticky traps of various colors in cranberries in 2009. All traps were made of colored Plexiglas material. See Table 4, Figs. 6 and 7 for description of colors.

absolute intensities (white > yellow > red > green > blue) (Fig. 6). Minor differences, as with the RGB values, were seen in the intensities of wavelengths among the yellow colors (Fig. 6). All trap colors were rather "pure" in that they were not composed of multiple peaks of wavelengths. There is an indication that the yellow colors did reflect some ultraviolet light compared to white, green, red, and blue (Fig. 6). Superimposing the spectrograms of each of the colors, with and without Tangle-Trap adhesive, indicates that there was very little difference in the wavelength reflectance due to adhesive (Fig. 7). The various colored traps were exposed for different measurement times to aid in comparing the spectrograms (only in Fig. 7).

4. Discussion

Table 5 summarizes the data on arthropod responses to colored sticky traps in cranberries (2006, 2009, and 2010 experiments). Interestingly, the two most economically important species of leafhoppers of cultivated *Vaccinium* spp. in the northeast USA showed differential responses to color: blunt-nosed leafhoppers were most attracted to green (wavelength ∼ 510 nm; Fig. 6) and red (∼650 nm), whereas sharp-nosed leafhoppers were highly attracted to yellow (∼570 nm). Previous studies in blueberry fields have also documented strong sharp-nosed leafhopper attraction to yellow (e.g. Meyer and Colvin, 1985). Several leafhoppers are attracted to colors commonly associated with living foliage, i.e., within the green-yellow spectrum, including the beet leafhopper (*Circulifer tenellus* (Baker)) (Scott, 1976; Meyerdirk and Oldfield, 1985), *Empoasca* spp. (Chu et al., 2000; Demirel and Yildirim, 2008), *Dalbulus* spp. (Todd et al., 1990b), as well as those that attack sugar beet (e.g. Capinera and Walmsley, 1978). Less common are examples of leafhopper attraction to red. Lessio and Alma (2004) showed that the leafhopper *Scaphoideus titanus* Ball, vector of the phytoplasma agent of flavescence dorée in grapevine, is more attracted to red than white, yellow, or blue sticky traps. Whether the differential attraction to color between the blunt-nosed and sharp-nosed leafhoppers is associated with phytoplasma transmission remains unknown, this is particularly important considering that only blunt-nosed leafhoppers vector false blossom disease in cranberries (Dobroscky, 1931). In the case

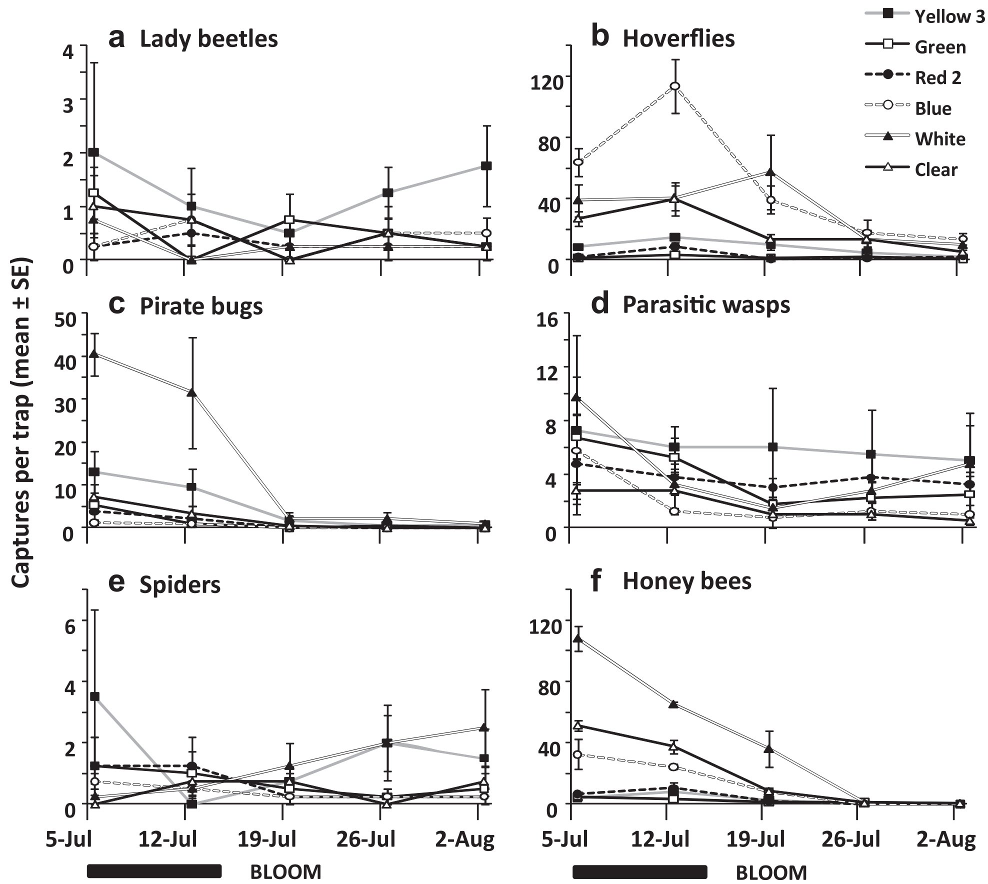

Fig. 3. Seasonal pattern of captures of (a) lady beetles, (b) hoverflies, (c) pirate bugs, (d) parasitic wasps, (e) spiders, and (f) honey bees on sticky traps of various colors in cranberries in 2010. All traps were made of colored Plexiglas material. See Table 4, Figs. 6 and 7 for description of colors.

of blunt-nosed leafhoppers in cranberries, attraction to red could be related to the accumulation of red pigments (anthocyanins) in fruit (Zapsalis and Francis, 1965), because their flight activity coincides with fruit maturation. There was also temporal variation in color preference of adult blunt-nosed leafhoppers, as shown in 2009 where leafhoppers were initially more attracted to red traps earlier in the season and then became more attracted to yellow traps later in the season (Table 2; Fig. 1e). This switch in color preference coincided with the end of bloom; thus, it is possible that background colors or other stimuli may influence the response of adult blunt-nosed leafhoppers to color (Saxena and Saxena, 1975).

Yellow and white traps caught the highest number of non-targets (Table 5). Yellow was particularly attractive to parasitic Hymenoptera but also to lady beetles and pirate bugs. Similarly, Weseloh (1986) found attraction of a variety of hymenopteran parasitoid species to yellow traps. Maredia et al. (1992) reported a strong positive response of *C. septempunctata* to yellow. *C. septempunctata* was a common lady beetle caught on our yellow traps. Attraction to yellow is proposed to constitute a “supernormal” foliage-type stimulus eliciting food- and/or host plant-seeking behavior in insects (Prokopy, 1972). Beneficial arthropods responded similarly to green and red, and in most cases they exhibited low attraction to these colors (Table 5). Interestingly, green and red were repellent to hoverflies and honey bees. Hoverflies and honey bees were highly active during bloom and mostly attracted to blue and white (wavelengths closer to UV spectrum; Fig. 7), respectively. These colors are commonly associated with flowers and often preferred by bee and fly floral visitors (Lunau and Maier, 1995). It is likely that these insects learned to associate floral colors such as blue and white with nectar and pollen rewards during foraging and to reject other colors such as green and red. Knight and Miliczky (2003) also caught the fewest honey bees in red and green traps and the most on white traps. Similar to blunt-nosed leafhoppers, attraction to color by pirate bugs (in 2009) and honey bees (both years) was influenced by time of year (Table 2). This is not surprising for honey bees because attraction to color was influenced by the bloom period. It is also likely that pirate bugs' attraction to colored traps is influenced by background colors and other stimuli.

Our measurements of EAR and EARc for the various colored traps, as compared to clear traps that were assumed to be unattractive (blank), were relatively small (Table 2). While only a few studies have provided data amenable for EAR/EARc calculation, most of the semiochemical attractants of bark beetles have EAR ranging from 0.36 to 3.18 m (Byers, 2009). However, due to the larger F_L of bark beetles (6–12 m), the EARc ranged from 0.03 to 1.23 m, the lower values comparable to insects in our study. Western flower thrips were calculated to have EAR of about 0.17 m for yellow or blue sticky cards, which was nearly identical to sharp-nosed leafhopper EAR of 0.19 m (Table 2). The EARc of sharp-nosed or blunt-nosed leafhoppers of 0.085 or 0.089 m for the optimal color of yellow or green, respectively, is about double the EARc for western flower thrips (0.045 m) because the F_L of leafhoppers (0.69 or 0.63 m) is smaller than for thrips (0.99 m) (Byers, 2009, Table 2).

As mentioned earlier, the EARc is conveniently used in models of monitoring and mass trapping (Byers, 2007, unpublished data). Although we do not know how far sharp-nosed leafhoppers fly in

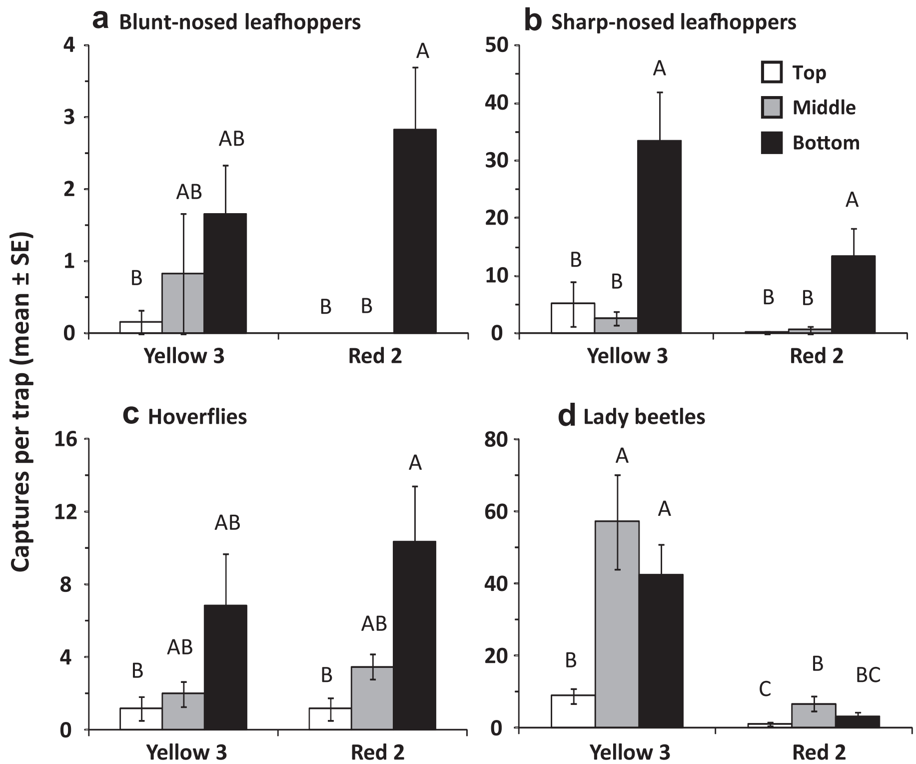

Fig. 4. Mean number of (a) blunt-nosed leafhoppers, (b) sharp-nosed leafhopper, (c) hoverflies, and (d) lady beetles per sticky trap at three different heights: top = 0.9 m above the cranberry canopy, middle = 0.5 m above the canopy, and bottom = 0.1 m from the top of the canopy. The study was conducted in three cranberry bogs in Chatsworth, New Jersey in 2007 using two colored Plexiglas traps. Same letters indicate no significant differences among heights, $P > 0.05$. See Table 4, Figs. 6 and 7 for description of colors.

their lifetime, nor how many are in a 1 ha field, if such data are obtained then predictions as to catch can be made via simulations (or equations, Byers, unpublished data). For example, using the EARc of 0.0846 for the yellow trap and sharp-nosed leafhopper (Table 2), and assuming the average distance a leafhopper travels in two weeks is 3600 m (1 h of flight over 2 weeks at 1 m/s), then in a 1 ha field with one trap and 100 leafhoppers we may catch 7, 4, 2, 5, 6, and 4 insects in six simulations (mean 4.7 ± 1.8, ±95% CL). If there were four traps and 1000 insects/ha and each travels an average of only 36 m (36 s of flight in 2 weeks) then we may catch 2, 1, 3, 4, 1, and 2 in six simulations (mean 2.2 ± 1.2). Thus, the EARc of various colored traps will be useful in developing monitoring programs for the leafhoppers and other insects in cranberries.

Knowledge of the mean of an insect's vertical flight distribution is important to placement of the monitoring trap at the optimal height. This is one reason that there were over 100 studies on determining the flight heights on traps on poles (Byers, 2011). Few studies determined the SD of the vertical height distribution because height must be input tens to thousands of times, however, with a computer implemented algorithm (Byers, 2011), SD can be

Table 3
Analysis of mean flight height ± SD (*m*) and effective flight layer (F_L) of leafhoppers and non-target insects caught on yellow or red sticky cards at three heights above the canopy of a cranberry bog [best-fit normal equation: $A(\exp(-(h-\bar{h})^2/(2SDH^2))/(SD\cdot\sqrt{2\cdot\pi}))$, where *h* is height in m]. See Table 4, Figs. 6 and 7 for description of colors.

Arthropod taxa / Species	Color	Total catch	Height of catch (Mean ± SD)	*A* of normal equation (r^2)[a]	Kurtosis[b]	Skewness[c] (tailing)	F_L (m)
Homoptera: Ciccadellidae							
Blunt-nosed leafhopper	Yellow 3	16	0.28 ± 0.25	6.64 (0.82)	0.63	1.18	0.63
	Red 2	17	0.10 ± 0.00	–	–	–	–
Sharp-nosed leafhopper	Yellow 3	248	0.23 ± 0.27	111.8 (0.51)	L (1.82)**	R (1.88)**	0.69
	Red 2	86	0.13 ± 0.12	24.9 (0.99)	L (23.7)**	R (4.70)**	0.3
Diptera: Syrphidae							
Toxomerus marginatus	Yellow 3	60	0.27 ± 0.28	25.0 (0.51)	0.39	R (1.33)**	0.7
	Red 2	90	0.26 ± 0.25	38.0 (0.73)	0.81	R (1.39)**	0.63
Coleoptera: Coccinellidae							
Species complex[d]	Yellow 3	653	0.38 ± 0.25	256.1 (0.97)	P (−0.65)**	R (0.31)**	0.62
	Red 2	68	0.42 ± 0.24	26.7 (0.99)	−0.37	0.11	0.61

[a] Squared product–moment correlation indicating strength of fit by normal equation to observed data.
[b] Kurtosis values denoting departure from theoretical normal distribution, with P = platykurtic and L = leptokurtic forms, * denotes significant departure at $P < 0.05$ and ** at $P < 0.01$.
[c] Skewness values denoting departure from theoretical normal distribution, with R = right tailing and L = left tailing, * and ** as above.
[d] The three most common coccinellid species were: *Coleomegilla maculata* (65%), *Harmonia axyridis* (18%), and *Coccinella septempunctata* (18%).

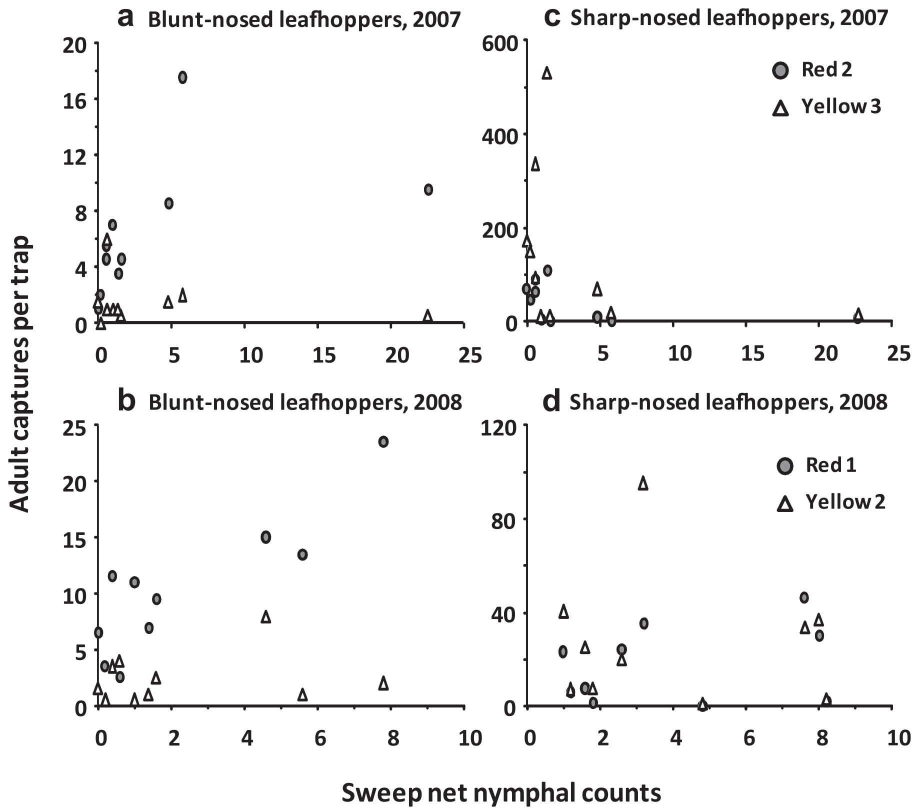

Fig. 5. Correlation between within season adult captures of (a–b) blunt-nosed leafhoppers and (c–d) sharp-nosed leafhoppers on sticky traps with nymphal counts from sweep net samples in 2007–2008. Yellow 2 = commercially-available yellow trap (ISCA Technologies); yellow 3 = yellow trap made of Plexiglas; red 1 = commercially-available red trap (Great Lakes IPM Inc.); red 2 = red trap made of Plexiglas.

Table 4
Mean (±SD) red (R), green (G), blue (B), trichromatic percentages (R, G, B%), and hue (H), saturation (S) and luminosity (L) values from areas of digital photos of colored sticky traps taken under field conditions on 21 February 2008. Areas analyzed in pixels ($N = 1600$) by Java software from Byers (2006).

Trap color	R ± SD	R%[a]	G ± SD	G%	B ± SD	B%	H:S:L[b]
Yellow 1	237 ± 2	46.9	232 ± 2	45.9	36 ± 2	7.1	59:85:54
Yellow 1 + adhesive	233 ± 3	47.9	231 ± 3	47.5	22 ± 7	4.5	59:83:50
Yellow 2	246 ± 1	43.4	240 ± 1	42.3	81 ± 3	14.3	58:90:64
Yellow 2 + adhesive	247 ± 4	43.0	241 ± 4	41.9	87 ± 19	15.1	58:91:65
Yellow 3	219 ± 1	49.0	211 ± 1	47.2	17 ± 2	3.8	58:86:46
Yellow 3 + adhesive	224 ± 5	46.9	215 ± 4	45.0	39 ± 11	8.2	57:75:52
Red 1	209 ± 2	77.7	28 ± 2	10.4	32 ± 2	11.9	359:76:46
Red 1 + adhesive	215 ± 11	68.7	46 ± 15	14.7	52 ± 15	16.6	358:68:51
Red 2	215 ± 2	71.7	46 ± 2	15.3	39 ± 3	13.0	2:69:50
Red 2 + adhesive	222 ± 9	60.8	75 ± 13	20.5	68 ± 14	18.6	3:70:57
Blue	9 ± 3	5.4	41 ± 3	24.7	116 ± 3	69.9	222:86:25
Blue + adhesive	16 ± 3	8.6	49 ± 2	26.2	122 ± 3	65.2	221:77:27
White	249 ± 1	33.3	249 ± 1	33.3	249 ± 1	33.3	0:0:98
White + adhesive	249 ± 1	33.3	249 ± 1	33.3	249 ± 1	33.3	0:0:98
Green	21 ± 3	14.0	79 ± 3	52.7	50 ± 3	33.3	150:58:20
Green + adhesive	31 ± 7	18.8	84 ± 7	50.9	50 ± 7	30.3	142:46:23

Yellow 1 = clear Plexiglas painted with yellow; Yellow 2 = commercially-available yellow trap (ISCA Technologies); Yellow 3 = yellow trap made of Plexiglas; Red 1 = commercially-available red trap (Great Lakes IPM Inc.); Red 2 = red trap made of Plexiglas.

[a] Represents the percent red ($R/(R + G + B) \times 100$), G% and B% defined similarly.

[b] H:S:L from www.chemical-ecology.net/java2/rgb.htm or Coral Photo-Paint 7 (HLS).

easily calculated as well as F_L for use in converting EAR to EARc (Byers, 2008, 2009). Based on catches on the yellow traps, the sharp-nosed and blunt-nosed leafhoppers exhibited a low mean flight height of 0.23 and 0.28 m above the cranberry canopy. Similar findings have been reported for other leafhoppers including the beet leafhopper (Meyerdirk and Oldfield, 1985) and the potato leafhopper (DeGooyer et al., 1998) where higher numbers of adults were caught on traps at ground level or placed even with the top of the canopy. These mean flight heights were lower than 104 other insect species and comparable to only six species analyzed earlier (Byers, 2011). With such a low mean flight height, the SD is constrained to only about 0.26 m, as were other species analyzed with low mean flight heights (Fig. 3 in Byers, 2011). The relatively small SD causes the EARc to be relatively larger for the leafhoppers when compared to insects flying higher and with a larger SD.

Analysis of the RGB attributes and spectral reflectance shows that the presence of Tangle-trap and similar adhesives should not alter the attractive properties of traps, which were in fact measured only with the adhesive. The analyses will allow comparisons of the trap colors with data from future studies that utilize RGB and spectroradiometric measurements. Also, future batches of plastic traps from commercial sources can be checked for consistency with previously used traps so that the attractive properties can be standardized and reliable. It would be interesting to investigate if red is attractive because this color represents the fruits, and why green is more attractive to blunt-nosed leafhoppers while yellow is more attractive to sharp-nosed leafhoppers. It would also be beneficial to determine if clear traps are in fact unattractive compared to wire screen-messed traps that may be even more “invisible”. The “bright” and high intensity colors of white and

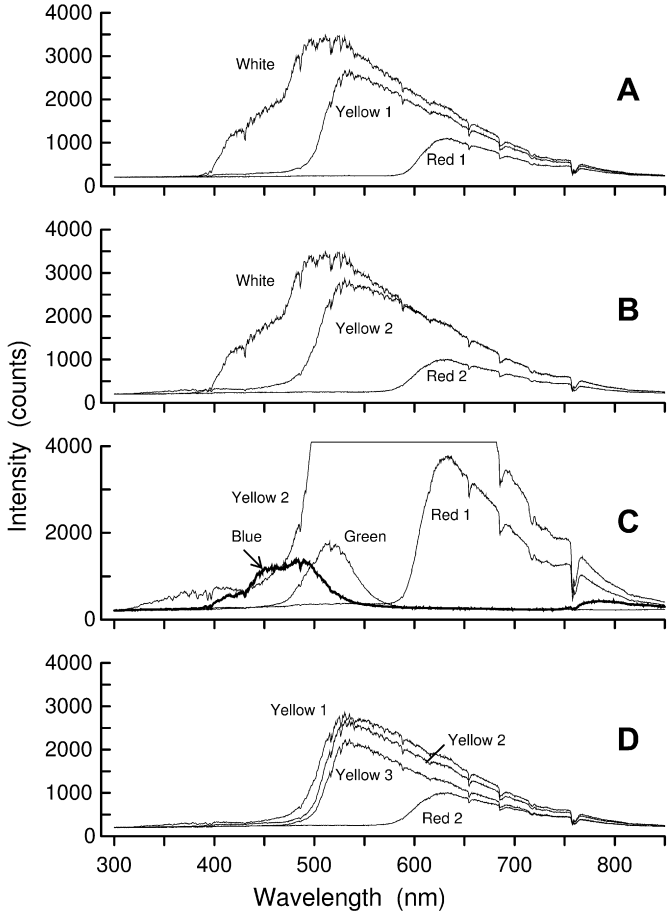

Fig. 6. Spectroradiograms of sunlight reflected from colored traps (without Tangle-Trap) of various hues: A) white, yellow 1, and red 1 at 3 ms exposure, B) white, yellow 2, and red 2 at 3 ms exposure, C) blue, green, yellow 2, and red 1 at 12 ms exposure, and D) yellow 1, yellow 2, yellow 3, and red 2 at 3 ms exposure. Reflectance measurements were taken with a USB2000 spectroradiometer at ~midday, under clear skies in Maricopa, AZ (Jan. 29, 2008).

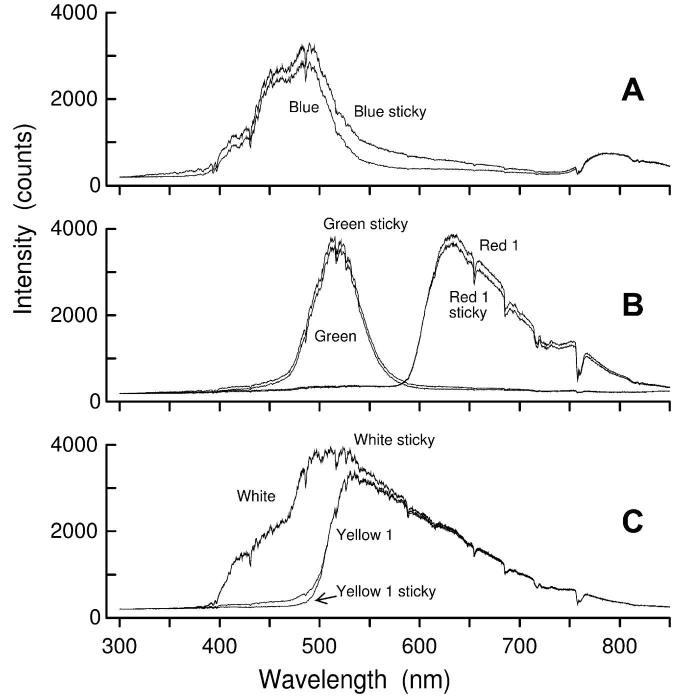

Fig. 7. Spectroradiograms of sunlight reflected from colored plastic (with and without Tangle-Trap adhesive = sticky) traps of various hues: A) blue and blue sticky at 22 ms exposure, B) green, green sticky at 22 ms exposure, red 1 and red 1 sticky at 9 ms exposure, and C) white, white sticky, yellow 1, and yellow 1 sticky at 3 ms exposure. Reflectance measurements were taken with a USB2000 spectroradiometer at ~midday, under clear skies in Maricopa, AZ (Feb. 21, 2008).

yellow may be more attractive simply because they reflect more light compared to the "darker" traps of blue and green which reflected less light (Figs. 6 and 7). It is interesting to note that honey bees that have relatively good visual acuity (number of ommatidia and smaller inter-ommatidial angle) (Land, 1997) were not attracted by yellow, green, or red, but were attracted by white. As indicated before, perhaps the bees had learned that white flowers in the area were providing pollen and nectar.

In summary, if blunt-nosed leafhoppers (and false blossom disease) are a target for pest management in cranberries, green or red traps placed just above the canopy will maximize leafhopper capture while minimizing captures of non-target beneficial arthropods. Although colored sticky traps were effective at capturing leafhoppers, additional studies are needed to determine their practical uses in cranberries. For instance, it is sometimes difficult to identify insects on sticky traps after being on a trap for many days or to remove specimens without damage for later identification. These troubles could be avoided by using alternative sampling methods such as suction sampling (e.g. Summers et al., 2004) or pan traps (e.g. Trebicki et al., 2010); however, if these other sampling methods are not as efficient then the EAR is not valid and the sensitivity of detection/monitoring is reduced. Another limitation of using sticky traps for monitoring leafhoppers in cranberries is the weak or lack of correlation between nymphal counts from sweep net samples and adult counts from sticky traps. These results could be due to the strong male-biased captures of leafhoppers on colored sticky traps. In fact, sticky traps captured ~8 times more sharp-nosed leafhopper males than females and were weakly correlated with nymphal counts from sweep nets. Similar male-biased trapping of leafhoppers has been reported for yellow sticky traps by other authors (e.g. Kersting and Baspinar, 1995; Kersting et al., 1997), including sharp-nosed leafhoppers in blueberries (Meyer and Colvin, 1985). In contrast, blunt-nosed leafhoppers on red traps, where male and female captures were more comparable, were correlated with nymphal counts. Thus, traps may not always reflect the true leafhopper densities. The observed differences between sampling techniques could also be due to different distribution and movement patterns of nymphs and adults within and between cranberry bogs. Future studies on leafhopper behavior will aid in the selection of a reliable sampling method that best estimates leafhopper abundance in relation to disease incidence in cranberries.

Table 5
Summary of arthropod attraction to color traps in cranberry bogs of New Jersey, USA.

Arthropod taxa	Trap color				
	Yellow	Green	Red	Blue	White
Sharp-nosed Leafhopper	XXX	XX	XX	X	X
Blunt-nosed Leafhopper	XX	XXX	XXX	X	X
Lady Beetles	XX	X	X	X	X
Hoverflies	X	R	R	XXX	XX
Lacewings	X	X	X	X	X
Pirate Bugs	XX	X	X	X	XXX
Parasitic Wasps	XXX	XX	XX	X	X
Spiders	X	X	X	X	X
Honey bees	R	R	R	X	XXX

XXX = High attraction, XX = Moderate attraction, *X* = Low to no attraction, R = Repulsion.

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