

UV-blocking High-tunnel Plastics Reduce Japanese Beetle (*Popillia japonica*) in Red Raspberry

Maria E. Cramer¹, Kathleen Demchak, and Richard Marini

Department of Plant Science, The Pennsylvania State University, University Park, PA 16802

Tracy Leskey

USDA-ARS, Appalachian Fruit Research Station, Kearneysville, WV 25430

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Abstract. Insecticides are the primary tool raspberry growers use to control Japanese beetles (*Popillia japonica*), but reliance on pesticides is costly and there are risks to nontarget species. Based on observations that Japanese beetles were less abundant on raspberries in high tunnels than in fields, we investigated the effects of plastic films that transmit different amounts of ultraviolet (UV) light to Japanese beetles. Many insects are sensitive to light in the UV-A range and use it for navigation. High-tunnel plastics that block varying percentages of UV radiation are increasingly available. We grew two primocane-fruiting red raspberry cultivars, Polka and Josephine, in tunnels with six different covering treatments. Five were plastics that blocked the UV range to varying degrees, and one was a no-plastic treatment. In 2016, beetles were counted and removed from the plants by hand daily. In 2017, beetles were removed by hand every 4 to 5 days. Foliage temperature was measured in each tunnel twice in 2017 with an infrared (IR) thermometer. Spectral transmittance characteristics of the plastics were measured with a spectroradiometer in 2015 and 2018. Mean beetle counts by date and for the whole season were compared for the plastics and cultivars. Japanese beetle numbers were significantly greater in the no-cover treatment than in all plastic treatments. The plastic that blocked more than 90% of the UV-A range usually had significantly lower beetle populations than the plastics that blocked the least UV-A. Overall, it appears that using a UV-blocking plastic can reduce Japanese beetle aggregation and feeding damage on raspberries, decreasing the need for other control. This could benefit growers by reducing the cost of insecticides and decreasing exposure risk for nontarget organisms.

The Japanese beetle is a pest that came to the eastern United States more than 100 years ago. It quickly became established as a pest of field crops, ornamentals, and small fruit. Today, Japanese beetles cause significant

damage to these crops throughout the area east of the Mississippi River, and have several populations outside this range, threatening West Coast agriculture (Davis, 1920; Hungate et al., 2016; Potter and Held, 2002). Although Japanese beetle is polyphagous, raspberry is a preferred small-fruit host, inducing significantly more feeding than all other host plants except for European grape (*Vitis vinifera*) and the blossoms of roses (*Rosa* sp.) (Ladd, 1987). Adult beetles skeletonize leaves and cause defoliation, and can also cause direct damage by feeding on ripening fruit (Davis, 1920). Insecticides are used to control the adults before, during, and after peak emergence and mating (Potter and Held, 2002). Using entomopathogenic bacteria and nematodes for biologic control has shown promise, but also challenges. Problems encountered with these biocontrols include slow establishment, lack of cold tolerance, and difficulty in culturing and rearing. These drawbacks can make them poor choices for high-value crops that require fast and effective pest protection (Koppenhöfer et al., 2000; Stahly and Klein, 1992). The problematic reliance on a narrow range of insecticides and increased awareness of the impact of insecticides on nontarget species, as well as

the incomplete development of biocontrols, suggest a need for new integrated pest management (IPM) techniques for Japanese beetle management.

A key step in developing IPM strategies is understanding the biology and behavior of the target pest. Japanese beetles primarily locate host plants via olfaction (Ahmad, 1982), aggregating in response to volatile compounds that plants release as a result of feeding (Loughrin et al., 1996). Although beetles navigate in response to odors, their activity is also influenced by light quantity. They tend to be most active in the field in full-sun conditions (Fleming, 1972). Research involving wind tunnel bioassays and field observations also showed that the degree of Japanese beetle response to attractants was related positively to light quantity and affected by light quality (Heath et al., 2001; Lacey et al., 1994).

High tunnels provide an opportunity to manipulate a crop's light environment. The plastics on high tunnels can influence the amount and spectral distribution of solar radiation inside the tunnel, which could affect insects. In an early demonstration planting there were fewer Japanese beetles on raspberry plants in tunnels than on plants in the field, although the study was not replicated and the differences could not be compared statistically (Demchak, 2009). In another study, outside plantings required an application of carbaryl to control Japanese beetle whereas inside plantings did not require intervention, suggesting lower numbers or reduced damage (Hanson et al., 2011).

These observations support the idea that Japanese beetle accumulation may be affected significantly by the environmental conditions in high tunnels. In greenhouses, manipulation of the light environment has been used for controlling other pests. It has been observed repeatedly that aphid, thrips, and whitefly populations were smaller in greenhouses covered with UV-blocking plastics than in greenhouses with UV-transmitting plastics (Antignus, 2000; Antignus et al., 2001; Doukas and Payne, 2007).

Whether UV light has a similar effect on insect pests in high tunnels, where open sides allow insects to enter more freely than in greenhouses, remains a question (Krizek et al., 2005). When a UV-blocking plastic that reduced insect pest populations in greenhouses was used on high tunnels, numbers of leaf miners, but not whiteflies or thrips, were reduced. The lack of impact on these pests may have been the result of unfiltered light and passive movement through the sides of the tunnels (Costa et al., 2003). However, there are many variables that may affect different insect species in high tunnels—such as the levels and range of UV light, the behavior of the pest, and the specific crop—so additional research is needed. Japanese beetles are not related closely to the insect orders reported to be affected by UV-blocking plastics, but their observed flight activity suggests that spectral sensitivity plays a part in their response to attractants (Heath et al., 2001).

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¹Corresponding author. E-mail: mariacramer5610@gmail.com.

The purpose of this study was to evaluate the influence of plastics with different spectral transmittance properties on Japanese beetle populations on high-tunnel raspberries. We characterized several types of UV-blocking plastics currently available, including their transmittance properties in the UV-B, UV-A, and visible ranges. We also examined data collected on foliage temperature to evaluate whether the plastics were associated with temperature changes that might affect Japanese beetle populations indirectly.

Materials and Methods

High tunnels and experimental design.

The 2-year experiment was conducted at the Russell E. Larson Agricultural Research Center in Rock Springs, PA (lat. 40°42'41" N, long. 77°56'45" W) in 2016 and 2017. The study used research-size high tunnels (5.18 × 10.67 m). The tunnels were vented manually with roll-up sides to a maximum height of 120 cm above the baseboard. They had fixed end walls throughout this study that were covered with the same plastic as the tunnel tops and sides, with a door in the south end. Plastic coverings were installed manually in Aug. and Sept. 2015 and were not replaced during the study. Tunnels were arranged in six rows of three. In 2016, 15 tunnels were used to evaluate five plastic coverings; the experimental design was a split plot, with three replications. Plastic was considered the whole-plot factor and cultivar was the split-plot factor. Outside plants were placed in plots between the tunnels. In 2017, three uncovered tunnels were incorporated into the randomization, and the experiment design was again a split plot with plastic the whole-plot factor and cultivar the split-plot factor. The coverings from one KoolLite Plus (KLP) tunnel and one experimental ultraviolet-opaque (UVO) tunnel were relocated, so there were three replicates of all six treatments. Two primocane-fruiting red raspberry cultivars, Josephine and Polka, were used in 2016 and 2017. These cultivars were double-cropped and were chosen for their ability to provide fruit throughout the entire season, as 'Polka' produces both floricanes and primocane fruit earlier than 'Josephine'. Bare-root plants (Nourse Farms, South Deerfield, MA) were planted in 11.36-L plastic nursery bags (Hydro-Gardens Inc., Colorado Springs, CO) in June 2016 and were repotted into 18.93-L bags in 2017. Plants were grown in a 2:1 peat:perlite medium and fertigated throughout the growing season with 20N-3.1P-16.6K general-purpose fertilizer for alkaline water (Plant Marvel, Chicago Heights, IL), supplying nitrogen at 100 mg·L⁻¹ constant feed and starting in the beginning of the growing season. Fertilization protocols for the fall season varied in the 2 years, but N rates were decreased so that plants received 50 mg·L⁻¹ N for roughly 3.5 weeks in Fall 2016, and for 7 weeks in Fall 2017, before fertilizer injection was discontinued in mid November of each year. Only water was applied thereafter. Each tunnel contained one

row of each cultivar, with 12 plants per row. In both years, plants were spaced on 0.3-m centers within rows, and rows were spaced 2.6 m apart. Cultivars were assigned randomly to the east and west sides of each tunnel. Plants were pruned and trellised to regulate canopy density and to facilitate harvest. Tunnel sides were raised both day and night to provide ventilation throughout the experiment and much of the growing season with the exception of the very early and very late season, when tunnel sides were closed at night and on cold days.

Plastic films. Five 6-mL plastic films were compared in this study, plus an uncovered control. In 2015, percentage transmittance of radiation for the plastics was determined using a StellarNet model EPP2000 spectroradiometer (StellarNet, Inc., Tampa, FL) calibrated to National Institute of Standards and Technology sources at the U.S. Department of Agriculture-Agricultural Research Service Appalachian Fruit Research Laboratory in Kearneysville, WV. These measurements were used to validate the limited descriptions of transmittances from the plastic manufacturers, and to provide information when none was available. The plastics used in this experiment included TuffLite IV (TIV; Berry Global, Inc., Evansville, IN), Ginegar SunSaver (GSS; Ginegar Plastic Products LTD, Kibbutz Ginegar, Israel), KLP (RKW Hyplast NV, Hoogstraten, Belgium), and two custom-manufactured experimental plastics—one ultraviolet transparent (UVT) and one ultraviolet opaque (UVO) (BPI-Visqueen, Stevenston, UK; currently available through Lightworks Poly, Lancashire, UK). A no-plastic (NP) treatment was also included.

Field spectral transmittance. In 2018, spectral distributions within the tunnels were measured at solar noon ±1 h on cloudless days with an Apogee model PS-300 spectroradiometer equipped with a cosine-corrected detector (Apogee Instruments, Logan UT). The sensor was located in the center of the tunnel, varying from the center by a maximum of 20 cm to avoid shadows from the tunnel structure, and at a height of 1.0 m above the ground. Light intensity (measured in micromoles per square meter per second) was measured within each tunnel as well as between tunnels. The sensor was contained in a leveling fixture and thus was held level for each measurement. The transmittances at each wavelength within the UV-B (280–315 nm), UV-A (315–400 nm), and visible (400–700 nm) light ranges were summed and compared with outside light levels and were expressed as percentage transmittance for each plastic within each of these ranges.

Temperature. Foliage temperatures were measured on two dates in 2017 with a model MI-220 IR radiometer with a narrow 18-degree field of view (Apogee Instruments). The first measurement date was 28 June from 1030 to 1130 HR. On 21 Sept., temperature was measured both in the morning (1030–1130 HR) and afternoon (1435–1530 HR). These dates, close to the summer solstice and fall equinox, were chosen to represent the

range of sun angles likely to be experienced throughout the course of the season and were also days when winds were calm to light and variable, as stable readings could not be obtained otherwise. The times chosen on 21 Sept. were spaced equally around solar noon. The sun angle was such that radiation reaching foliage passed through the plastic. Foliage temperature was measured on both the east and west sides of each row, and tunnels were fully vented during temperature measurement.

Japanese beetle population monitoring.

Tunnels were fully ventilated throughout Japanese beetle monitoring. Sides were rolled up to an average opening height of 105 cm, with maximum and minimum heights of 120 and 80 cm, respectively. Japanese beetles on each row of plants were counted while being removed into resealable 3.7-L plastic bags for later disposal. Beetles that flew away were also counted. The proportion of beetles that evaded capture varied between treatments and days, but the proportion was judged to not exceed 20% of the total beetles counted. Beetles were generally counted daily from 12 July until 30 Aug. 2016, for a total of 37 dates. On 18 and 19 July, beetles were counted and removed three times per day (0820–0910 HR, 1320–1410 HR, and 1520–1600 HR) when we observed that beetle populations varied throughout the day. Counts made within ≈1 h of solar noon were approximately four to five times greater than in the morning or late afternoon. Noon and afternoon counts may have been affected by counting earlier in the day. Subsequently, in 2016, beetles were counted near solar noon to maximize beetle removal while minimizing damage from feeding. As a result of intense beetle-feeding damage to NP plants, the plants were moved into tunnels on 20 July, and data collection on those plants was ended. Therefore, there were two sets of data in 2016. One contained all six treatments for the first nine dates, whereas the later 28 dates did not include the NP treatment. In 2017, counts began on 15 July and continued every 4 to 5 d, until 1 Sept., for a total of 11 dates. Beetles were counted between 1100 and 1700 HR on every date except 20 July, when beetles were counted between 0900 and 1300 HR.

Statistical analyses. Data were analyzed with SAS 9.4 (SAS Institute, Carey, NC) and visualized with Tableau Desktop 2018.2 (Tableau Software Inc., Seattle, WA). Transmittance data were analyzed as a randomized complete block design (RCBD) by analysis of variance (ANOVA) with SAS's PROC GLIMMIX (Littell et al., 2006). Mean transmittances for each plastic were compared using Tukey's Studentized range test (honestly significant difference). Foliage temperature data were analyzed as a 2 × 6 factorial (two sides of each row and six plastic treatments) in an RCBD by ANOVA with GLIMMIX, for which a block was considered a random effect, and row side and plastic were considered fixed effects. Cultivar and side of tunnel were confounded, so these variables were not included in the model.

When interactions were significant, the levels of one factor were compared within each level of the other factor with the SLICEDIFF option in the LSMEANS statement.

SAS's Proc Univariate was used to test normality of residuals for each sampling date, and the *P* value from the Kolmogorov-Smirnov test was 0.01. Departure from normality was not considered serious because *N* > 30 (Elliott and Woodward, 2007) and some statisticians do not consider deviation from normality to be serious at *P* values greater than 0.001 (Anderson and McLean, 1974). Japanese beetle count data were analyzed as a split-plot design by ANOVA with PROC GLIMMIX. When there were multiple counts made on a date (18 and 19 July 2016), counts were summed to give a single count for that date. The two data sets in 2016 (the first nine dates with the NP treatment and the final 28 dates without the NP treatment) were analyzed separately. When the cultivar × plastic interaction was significant, the SLICEDIFF option was used to compare cultivar means within each plastic, and means for plastics were compared within cultivars.

The 2017 daily Japanese beetle counts were summed over the 11 dates and were analyzed by ANOVA with GLIMMIX as a split-plot design.

Cumulative Japanese beetle count data from 2016 and 2017 were subjected to multiple regression with PROC MIXED and PROC REG. Percentages of transmittance of UV-A, UV-B, and visible light were included in the models as regressor variables. For PROC MIXED, block was specified as a random variable and the NOINT and SOLUTION options were included in the model statement to request the intercept and regression coefficients. REG was used to produce *R*² values for models that were determined to be significant using MIXED, with the knowledge that variation resulting from block was not accounted for in the model.

Results and Discussion

Plastic film characteristics. Data on the portion of UV-B, UV-A, and visible light transmitted through the five plastics are presented in Table 1. The NP treatment had 100% transmittance in every range because there was nothing to filter wavelengths. TIV and UVT transmitted the greatest percentages of UV-B and UV-A light (74% to 80%), GSS and KLP transmitted medium amounts of UV-B and UV-A light (46% to 68%), and UVO transmitted the least UV-B and UV-A (36% and 7%, respectively). All transmitted similar percentages of visible light (82% to 85%), except for KLP, which transmitted the least (74%).

Temperature. Plastic and side of the row had a significant effect on foliage temperatures for each date/time measurement (*P* < 0.0001, Table 2). In the morning temperatures were significantly warmer on the east side of the rows than the west, which was shaded. In the afternoon, the east side, which

Table 1. The effect of six high-tunnel plastic treatments on transmittance of three ranges of solar radiation as measured on 9 May 2018, a cloudless day, in Rock Springs, PA.

Plastic	Solar radiation transmitted through each plastic (%)		
	UV-B	UV-A	Visible
NP	100 a ²	100 a	100 a
TIV	78 b	74 b	84 b
UVT	80 b	76 b	84 b
GSS	68 c	59 c	85 b
KLP	52 d	46 d	74 c
UVO	36 e	7 e	82 b
<i>P</i> value for plastic	<0.0001	<0.0001	<0.0001

²Least-squared means within columns followed by common letters do not differ at the 5% level of significance, by Tukey's honestly significant difference, *T*.

UV = ultraviolet; NP = no plastic; KLP = KoolLite Plus; TIV = Tufflite IV; UVT = ultraviolet transparent; GSS = Ginegar SunSaver; UVO = ultraviolet opaque.

Table 2. The effect of six high-tunnel plastic treatments on raspberry foliage temperature (measured in degrees Celsius) measured with an infrared radiometer on three date/time combinations (near the summer solstice and the fall equinox) in 2017 in Rock Springs, PA.

Variable	28 June (1030–1130)	21 Sept. (1030–1130)	21 Sept. (1435–1531)
Plastic			
NP	19.5 a ²	20.3 a	24.1 a
GSS	20.3 ab	22.1 b	25.2 bc
KLP	20.5 abc	21.3 b	25.0 bc
UVO	20.9 bc	21.7 b	25.1 bc
TIV	20.9 bc	23.0 c	24.4 ab
UVT	21.5 c	22.0 b	25.7 c
Row side			
East	23.1 a	23.3 a	23.6 a
West	18.1 b	20.2 b	26.2 b
ANOVA <i>P</i> values			
Plastic	0.0002	<0.0001	<0.0001
Row side	<0.0001	<0.0001	<0.0001
Plastic × row side	0.5271	0.2692	0.9976

²Least-squared means within columns and variables followed by common letters do not differ at the 5% level of significance by Tukey's test.

NP = no plastic; KLP = KoolLite Plus; TIV = Tufflite IV; UVT = ultraviolet transparent; GSS = Ginegar SunSaver; UVO = ultraviolet opaque; ANOVA = analysis of variance.

was shaded, was cooler than the west. The interaction between plastic and side of the row was never significant. In each case, the plastic treatments were always warmer than the NP treatment (0.3 to 2.7 °C greater), but the difference was not always significant. Plants under UVT were consistently among the warmest in both the morning and the afternoon. TIV was among the warmest in the morning, but was among the coolest in the afternoon. Leaf temperature differences between plastic treatments within any date and time were never greater than 3 °C. The tunnels were fully vented when data were collected, and the plants were within 1.5 m of the open sides, which may explain the slight difference between inside and outside leaf temperatures. When Wien (2009) measured daytime air temperatures in 10-m-wide high tunnels covered with clear polyethylene plastic treated with IR-blocking material (Tufflite IV "IR"), temperatures in tunnels were at least 10 °C warmer than outside. However, Wien (2009) noted that these differences were reduced through ventilation; the difference between outside and inside temperatures decreased as the size of ventilation opening increased. Our foliar temperature data support those of Wien (2009), as leaf temperatures within the vented tunnels were only slightly higher than outside the tunnels. The five plastics showed relatively small

differences in leaf temperature compared with each other.

Japanese beetle populations. In 2016 and 2017, Japanese beetle numbers were lower on raspberry plants grown inside high tunnels than on plants grown with no cover. Although in 2016 there were no significant differences between plastics on individual dates, plants under all plastics had fewer total beetles accumulated over the first nine dates than plants with no cover (Table 3). For the first nine collection dates, total beetle counts were affected by plastic, cultivar, and the plastic × cultivar interaction (all at *P* < 0.0001). For 'Josephine', the NP treatment had significantly greater mean counts (182 beetles/plot) than all plastics (17–38 beetles/plot), whereas the five plastics did not differ significantly from each other. For 'Polka', NP had the greatest mean counts (*n* = 357), and within the plastics there were significant differences; TIV and UVT had greater counts (64 and 57 beetles/plot, respectively) than UVO (8 beetles/plot). Within the NP treatment, 'Polka' had nearly twice as many beetles as 'Josephine', but cultivars under other plastic treatments did not differ (Table 3). Although the location of cultivar within each tunnel was assigned randomly, it is not possible to separate entirely the effects of cultivar from its location within each tunnel. Thus, cultivar effects could have been influenced by factors

such as when and how much sunlight reached a plot, or the order in which plots were counted resulting from beetle disturbance, which could have increased or decreased counts in neighboring plots. A future study using only one cultivar with standardized beetle removal patterns might help determine whether tunnel side can affect beetle aggregation significantly.

When we analyzed cumulative counts from the entire 2016 season, plastic was significant ($P = 0.0041$), but not cultivar or the cultivar \times plastic interaction. TIV and UVT had more beetles than the other three plastics (Table 3). The order and separation of means between the plastics was similar before and after the termination of the NP treatment. After 29 July, there was a rapid increase in beetle counts (Fig. 1), which did not coincide with the unavailability of the outside hosts. This suggests that the increase was part of a second wave of adult emergence, rather than increased pressure from beetles that would have otherwise been feeding on the NP plots.

Although plastic treatments influenced the cumulative Japanese beetle numbers, and results were similar for individual dates, plastics on any given date were not significantly different in 2016. Because Japanese beetles aggregate in response to feeding-induced volatiles (Potter and Held, 2002), and the frequency and timing of beetle removal can influence the attraction of additional beetles (Switzer and Cumming, 2014), we hypothesized that frequent beetle removal, in some cases multiple times a day, may have altered the process by which beetles locate hosts. Based on this reasoning, in 2017 we reduced our removal frequency to every 4 to 5 d. In 2017, we had much higher counts of beetles overall, which may have been, in part, a result of modifying the sampling method, and populations may also have been generally higher in 2017.

In 2017, beetle counts were affected significantly by plastic and cultivar on individual dates, so we performed analyses on both daily counts and season totals. Cultivar was not significant, but plastic, cultivar \times plastic, date, cultivar \times date, date \times plastic, and cultivar \times date \times plastic were all significant ($P < 0.0001$, 0.0001, 0.0001, 0.0095, 0.0001, and 0.0347, respectively). The NP treatment had the most dates for which cultivars differed (4 of 11 dates), followed by TIV on two dates, and GSS on one date. For the NP treatment, numbers of beetles on 'Josephine' were significantly greater than on 'Polka', but under TIV and GSS, 'Polka' had higher numbers (data not shown). For all plastic treatments, cultivar differences were not significant on the last five dates. Similarly, differences between the plastics decreased throughout the season as Japanese beetles became scarce overall, although the NP treatment consistently had the highest counts. TIV and KLP tended to have the next highest counts, followed by UVT. GSS and UVO tended to have the lowest counts. Overall, with an exception of one date,

Table 3. Least-squared means for cumulative numbers of Japanese beetles collected from 12-plant rows of two raspberry cultivars, Josephine and Polka, grown in high tunnels with six plastic covering treatments in 2016 in Rock Springs, PA. Beetles were counted from 12 July until 30 Aug.

Treatment	Cumulative first nine dates		Cumulative season total	
	Josephine	Polka	Josephine	Polka
NP	182 a ^z	*	—	—
TIV	38 b	64 b	152 a	180 a
UVT	35 b	57 b	142 a	130 a
KLP	25 b	37 bc	65 b	74 b
GSS	17 b	21 bc	48 b	44 b
UVO	28 b	8 c	34 b	11 b

^zLeast-squared means within columns followed by common letters do not differ at the 5% level of significance for the first nine dates, and for the season total, by SLICEDIFF in GLIMMIX. Asterisks indicate that cultivars within the plastic treatment differ at the 5% level.

NP = no plastic; KLP = KoolLite Plus; TIV = Tufflite IV; UVT = ultraviolet transparent; GSS = Ginegar SunSaver; UVO = ultraviolet opaque.

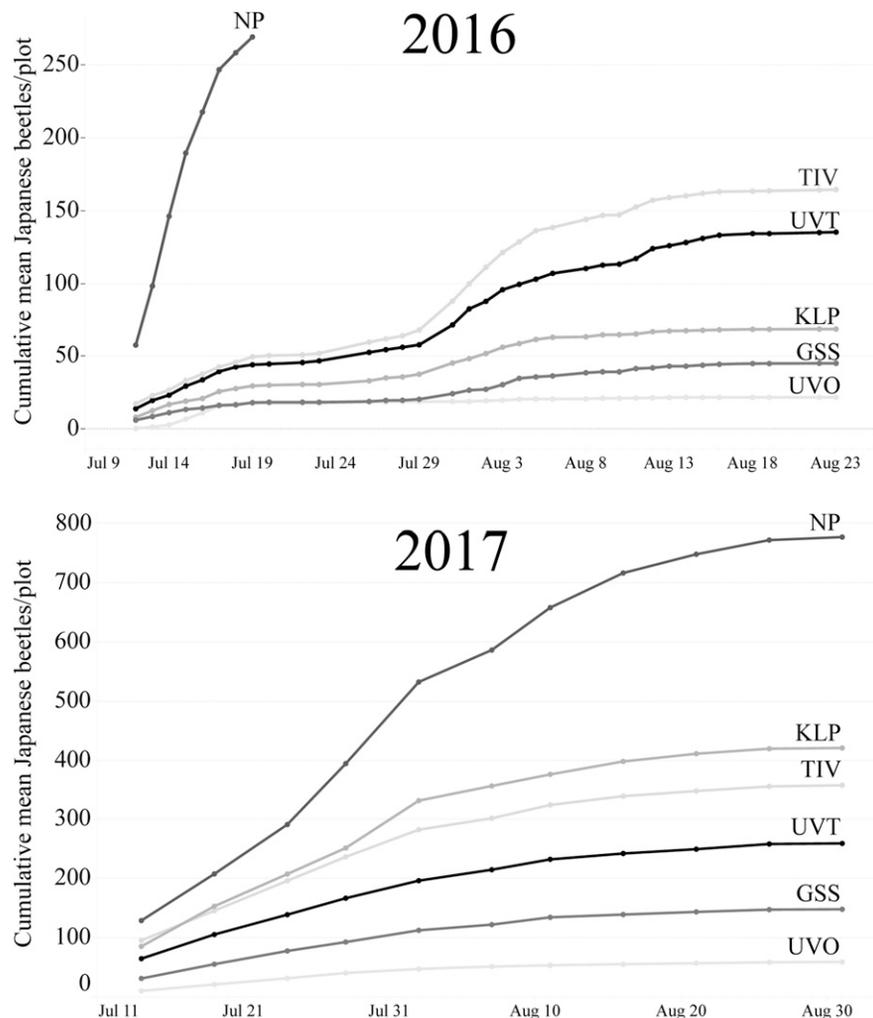


Fig. 1. Mean cumulative numbers of Japanese beetles counted on 12-plant rows over time for two raspberry cultivars, Josephine and Polka, grown in high tunnels with six covering treatments in 2016 and 2017 in Rock Springs, PA. Cultivars were usually not significantly different and have been pooled. NP = no plastic; KLP = KoolLite Plus; TIV = Tufflite IV; UVT = ultraviolet transparent; GSS = Ginegar SunSaver; UVO = ultraviolet opaque.

cultivar was significant only in instances when either no plastic covering was used or under TIV, the plastic that had the slightest effect on beetle abundance. This indicates that plastic covers that discourage beetle presence may override differences in attractiveness of individual cultivars to Japanese beetles.

When the cumulative beetle counts for 2017 were analyzed, cultivar was not significant, whereas plastic and cultivar \times plastic were significant ($P < 0.0001$ and $P = 0.0035$, respectively). For the NP treatment, 'Josephine' had about 36% more beetles than 'Polka' (Table 4). Among plastic treatments,

Table 4. Least-squared means for cumulative numbers of Japanese beetles collected from 12-plant rows of two raspberry cultivars, Josephine and Polka, grown in high tunnels with six covering treatments in 2017 in Rock Springs, PA. Beetles were counted from 15 July until 1 Sept.

Treatment	Josephine		Polka
NP	897 a ²	*	658 a
KLP	403 b		439 b
TIV	287 b	*	429 b
UVT	270 bc		250 c
GSS	138 c		159 cd
UVO	85 c		35 d

²Least squared means within columns followed by common letters do not differ at the 5% level of significance by SLICEDIFF. Asterisks indicate that cultivars within the plastic treatment differ at the 5% level.

NP = no plastic; KLP = KoolLite Plus; TIV = Tufflite IV; UVT = ultraviolet transparent; GSS = Ginegar SunSaver; UVO = ultraviolet opaque.

with the exception of UVO, ‘Polka’ usually had more beetles than ‘Josephine’, but the difference was significant only for TIV. Within cultivars, beetle counts were influenced somewhat differently by plastic treatments. ‘Josephine’ plants under KLP and TIV had more beetles than plants under GSS and UVO. ‘Polka’ plants under KLP and TIV had more beetles than the plants under the other three plastics, and UVO had fewer beetles than all other plastics except GSS (Table 4).

In 2016 and 2017, plastics had similar effects on cumulative beetle counts (Fig. 1). Beetle counts in general were related to UV-A light transmission characteristics, measured by a spectroradiometer in 2018. We consistently counted the fewest beetles under UVO, which transmitted less than 7% of UV-A light. GSS and KLP tended to have slightly more beetles, and transmitted about 59% and 46%, respectively. The most beetles were counted under TIV and UVT, which transmitted between 74% to 76% of UV-A. However, in 2017, KLP had very high counts (among the highest). One tunnel in the first block had extremely high counts that persisted throughout the season; whether this tunnel was affected by nearby crops or non-crop areas in 2017 or the previous year is not known. Without information on locations of beetle emergence, we can only say with certainty that KLP had greater variability in its impact on Japanese beetles than the other plastics, and that the high counts were likely a result of a characteristic of KLP other than UV-A transmission.

Multiple regression was used to evaluate the relationship between season total Japanese beetle counts and percent transmittance of UV-B, UV-A, and visible light. Visible light was not significant, possibly because the plastics transmitted similar amounts in the visible range. UV-B, UV-A, plus a quadratic term for UV-A explained a significant amount of the variation in 2016 (Fig. 2) and 2017 (Fig. 3). When cultivar was included in the model as an indicator variable, it was not

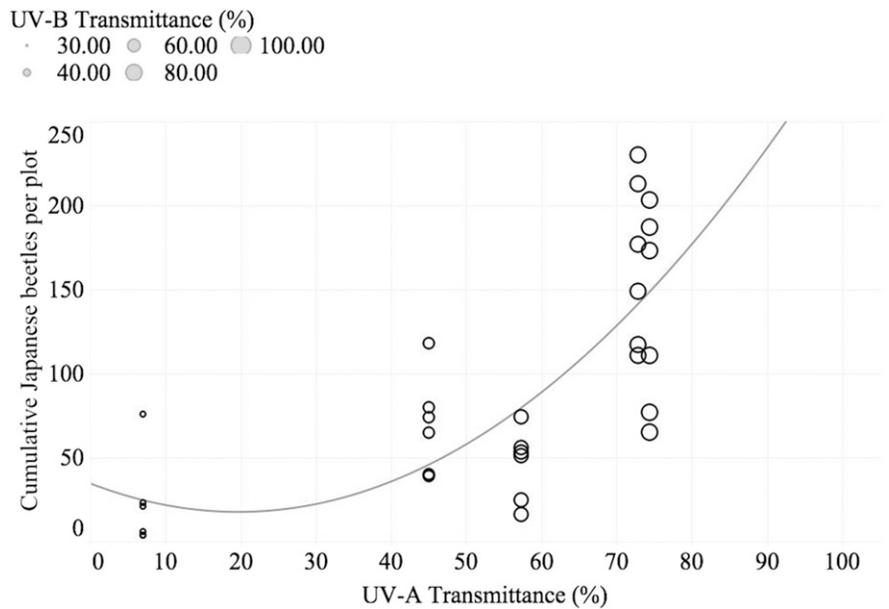


Fig. 2. The relationship between the mean total number of Japanese beetles per plot for two red raspberry cultivars, Josephine and Polka, from 12 July to 30 Aug. 2016 and the percentage of ultraviolet (UV; UV-A and UV-B) transmittance on 9 May 2018 in Rock Springs, PA. Percentage transmittance of UV-B is indicated by the size of the symbol. Cultivars were usually not significantly different and have been pooled. Regression model: Total Japanese beetles = $503 + 2.2(\text{UV-A}) + 0.1(\text{UV-A}^2) - 14.0(\text{UV-B})$. $R^2 = 0.64$, $P < 0.0001$, $N = 30$.

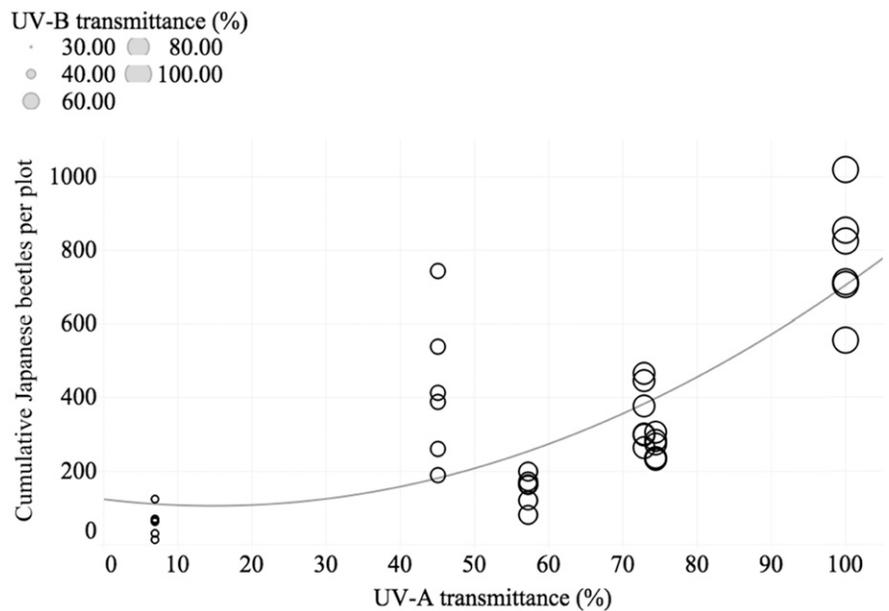


Fig. 3. The relationship between the mean total number of Japanese beetles per plot for two red raspberry cultivars, Josephine and Polka, from 15 July to 1 Sept. 2017 and the percentage of ultraviolet (UV; UV-A and UV-B) transmittance on 9 May 2018 in Rock Springs, PA. Percentage transmittance of UV-B is indicated by the size of the symbol. Cultivars were usually not significantly different and have been pooled. Regression model: Total Japanese beetles = $2644 + 28.2(\text{UV-A}) + 0.3(\text{UV-A}^2) - 78.4(\text{UV-B})$. $R^2 = 0.81$, $P < 0.0001$, $N = 36$.

significant and it did not interact with other variables; therefore, it was not included in the final model.

The same variables explain a significant amount of the variation in both years. One reason why the model had a higher R^2 value in 2017 than 2016 may be the result of the

presence of the NP treatment in 2017, which extended the range of values. In both years, the beetle counts for KLP tended to fall above the range of predicted values, which further suggests that the higher mean count under KLP is not simply the result of one tunnel, but that there is another quality of

this plastic that makes it less discouraging to Japanese beetle.

All plastics evaluated in this study reduced significantly the number of Japanese beetles on both cultivars, and differences between plastics were usually apparent. In addition to transmittance of UV-A radiation, there are a number of other ways that the plastics may alter the environment and influence Japanese beetle behavior. It is possible that diffusion, the scattering of solar radiation as it passes through the plastic, impacts Japanese beetle movement. By scattering the light, diffusing plastics produce light environments that have less direct and intense light (Giacomelli and Roberts, 1993). According to manufacturer descriptions and subjective observations of film clarity vs. haze, TIV was the least light-diffusing plastic in our experiment. TIV and UVT transmitted very similar amounts of UV-B, UV-A, and visible light. In 2016, TIV had 9% to 17% more beetles than UVT (although the difference was not significant), and in 2017, TIV had significantly more (9% to 40%) beetles than UVT. Greater diffusion of light passing through the UVT plastic was the only observable transmittance difference between these plastics. Because Japanese beetle movement is encouraged by direct and bright light (Heath et al., 2001; Lacey et al., 1994), the increased proportion of diffused light might have inhibited beetle activity.

The plastics also altered the amount of UV-B light entering the tunnels. Altering UV-B light in greenhouse environments impacts fungal growth and plant defense pathways (Raviv and Antignus, 2004). Blocking UV-B radiation may influence plant susceptibility to pests indirectly through the secondary production of defense compounds or volatiles. More research is required to determine whether a change in plant defenses might be responsible for reduced beetle populations or differences in cultivar susceptibility.

Temperature may also be a factor that influences beetle populations within the tunnels. Warm temperatures are conducive to beetle activity, with a minimum temperature of 27 °C for flight (Potter and Held, 2002), and increasing activity with warmer temperatures (Heath et al., 2001). Our highest beetle numbers were in the NP treatment, which was the coolest, but had no physical barriers and provided the most intense light. The plastics with the highest Japanese beetle counts (UVT, TIV, and, in 2017, KLP) did not have consistently significantly different temperatures from the other plastics.

Conclusions

Considering the variables we measured that might influence Japanese beetle populations, the observed differences are most likely the result of beetles responding to the amounts of UV-A radiation under the plastics. These results support previous attempts to use UV-blocking plastic as an IPM tactic to reduce direct insect damage and virus

transmission (Johansen et al., 2011; Raviv and Antignus, 2004). Our new information regarding Japanese beetles has practical implications. Many growers have been using high tunnels for small-fruit production in the Northeast and Midwest because of a wide range of benefits, including disease control and season extension (Demchak, 2009; Hanson and Gluck, 2013; Yao and Rosen, 2011). In addition, many growers use organic farming practices or are marketing directly to consumers (Carey et al., 2009) and are not able to use the conventional pesticides typically used for Japanese beetle control, or they may have customers who prefer fruit that is not treated with insecticides. For conventional growers, insecticidal sprays are an additional cost and there is risk of exposure of nontarget and beneficial species. UV-blocking coverings in raspberry production may help growers avoid sprays. Mean cumulative counts under UVO were reduced 75% to 94% compared with standard non-UV-blocking plastic (TIV). This reduction may delay the time before a control is necessary, or even reduce control to one- or two-hand removals. We found that on many collection dates, beetles in UVO tunnels were so scarce that the raspberry canopies had to be scrutinized to find them.

Although these results are extremely promising for raspberry growers, they may be useful for other crops as well. Protected culture has been used increasingly for cherry production and other stone fruit attractive to Japanese beetles (Lamont, 2009; Lang, 2009). Should UV-blocking plastics be used for other crops in high tunnels, research is needed to address whether the effects of the plastics are consistent when covering larger areas. Increasing the size of a tunnel covered with a UV-blocking plastic did not decrease populations of thrips and whiteflies (Costa et al., 2003). However, these pests are typically controlled in greenhouses rather than tunnels. Our research has demonstrated that Japanese beetles are affected by UV-blocking plastic, even without physical barriers to movement. Therefore, tunnels that cover larger areas will likely produce similar results, although research should be performed to test this hypothesis.

A drawback of the UV-blocking UVO plastic is that it is not commercially available in the United States, although similar plastics are available in Europe. The GSS plastic may be a good alternative because it is available for purchase and also reduced the number of beetles significantly—in some cases, on a scale similar to UVO. There is a need for increased objective testing and evaluation of plastic film coverings that are currently available and in development. The results of this study are promising for producers of raspberries and other crops susceptible to Japanese beetles, and the effects of blocking UV on other high-tunnel crop pests should be studied further. The data from the KLP treatment suggest that although UV-A light has been implicated in pest abundance in past studies and can explain much of the variation

in Japanese beetle numbers in this study, it is not the sole factor that influences Japanese beetle abundance. More research into the effects on insects of light transmitted or factors such as diffusion would help elucidate the reasons for this phenomenon.

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