Crop Protection 29 (2010) 1331–1340

Contents lists available at ScienceDirect

Crop Protection

journal homepage: www.elsevier.com/locate/cropro

Color preference, seasonality, spatial distribution and species composition of thrips (Thysanoptera: Thripidae) in northern highbush blueberries

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ARTICLE INFO

Article history:
Received 1 April 2010
Received in revised form
23 June 2010
Accepted 6 July 2010

Keywords:
Scirtothrips ruthveni
Colored sticky traps
Seasonal fluctuations
Degree-day accumulations
Distribution
Plant phenology

ABSTRACT

We investigated color preference, seasonal abundance, spatial distribution and species composition of thrips in northern highbush blueberries, *Vaccinium corymbosum* L., in New Jersey (USA). White sticky traps were more attractive to thrips compared with yellow or blue traps. Thrips captures using white sticky traps showed that their flight activity begins 20–30 d after the onset of flowering, with 10, 50 and 90% of trap captures observed at 383, 647 and 1231 degree-day accumulations, respectively (10 °C base temperature). Two methods were used to study thrips distribution within a blueberry bush. First, white sticky traps were placed within the bush canopy at three different heights. The highest numbers of thrips were caught on traps in the middle and top one-third of the canopy while the lowest numbers were caught in the bottom one-third. A second method determined the distribution of thrips on the blueberry plant at different heights and phenological stages. The highest numbers of thrips were found on young leaves at lower parts of the canopy, whereas flowers and fruit had fewer thrips and none were found on buds; these thrips were identified as, *Scirtothrips ruthveni* (88% of adults) and *Frankliniella tritici* (12%). The distribution of thrips within a blueberry planting was investigated using an evenly-spaced grid of white sticky traps in combination with on bush beating-tray samples. Thrips counts from traps correlated with direct counts on the bush across the entire blueberry field (macro-scale level); however, within the field (micro-scale level), there was no correlation between the number of thrips on traps and on individual bushes near traps. Early in the season, trap counts were higher on bushes closer to the forest, indicative of movement of thrips from wild hosts into blueberry fields. However, this was not the case for direct on bush counts or trap counts for the later part of the season, where there was no clear forest "edge" effect. Percent fruit injury due to thrips feeding was low, and it correlated with thrips counts on bushes but not from counts on traps. Overall, our data show that thrips counts on sticky traps need to be interpreted with care because these numbers weakly correlated with the numbers of thrips on bushes at the micro-scale level and percent fruit injury; however, they can be useful predictors of thrips activity across entire blueberry fields (macro-scale).

1. Introduction

Thrips are common pests in most blueberry growing regions of the United States of America (USA) and Canada. These insects feed on blueberry leaves, flowers and fruit. In blueberries, thrips injury can be recognized by a tight curling of leaves (Polavarapu, 2001). Some thrips preferentially feed on the styles and ovules, as well as the surrounding green tissue within the flower (Arévalo and Liburd, 2007a). This type of injury is considered economically most important because it can affect fertilization and subsequent fruit set (Arévalo, 2006). Based on studies conducted in the USA in Georgia and Mississippi, some thrips can feed on blueberry pollen and, under severe infestations, cause dimpling on the fruit, which can severely affect marketable yields (Horton and Sampson, 2001; England et al., 2006). As much as 60% reduction in fruit set has been attributed to thrips injury in southern highbush blueberries of Georgia and Mississippi (Horton and Sampson, 2001).

There is substantial variability in the thrips species complex that attack blueberries across geographic regions of North America. The eastern flower thrips *Frankliniella tritici* (Fitch) and *Scirtothrips ruthveni* Shull, infest northern highbush blueberries (*Vaccinium corymbosum* L.)

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doi:10.1016/j.cropro.2010.07.006

in New Jersey (USA) (Polavarapu, 2001). *Frankliniella vaccinii* Morgan, *Catinathrips vaccinophilus* (Hood) and *Catinathrips kainos* O'Neil are the main thrips species infesting lowbush blueberries (*Vaccinium angustifolium* Aiton) in New Brunswick and Nova Scotia (Canada), and in Maine (USA) (Langille and Forsythe, 1972). In contrast, the Florida flower thrips *F. bispinosa* (Morgan) and *F. tritici* are the most abundant thrips species in Florida and Georgia (USA), respectively, where southern highbush (*V. corymbosum* × *Vaccinium darrowi* Camp) and rabbiteye (*Vaccinium virgatum* Aiton) blueberries are grown (Arévalo et al., 2006). Recently, Haviland et al. (2009) reported southern highbush as a new host for citrus thrips, *Scirtothrips citri* (Moulton), in California. Other, less common thrips in blueberries include the tobacco thrips *Frankliniella fusca* (Hinds), *Frankliniella hawaiiensis* (Morgan) and the western flower thrips *Frankliniella occidentalis* (Pergande) (Arévalo and Liburd, 2007a).

A variety of sampling methods have been evaluated for monitoring thrips populations (Lewis, 1973; Liburd et al., 2009). Colored sticky traps are often inexpensive and rapid indicators of thrips population density (Finn, 2003), but attraction may vary depending on thrips species and crop. For example, Hoddle et al. (2002) found that white traps are most attractive to *F. occidentalis* in avocado orchards, whereas Cho et al. (1995) caught more *F. occidentalis* on yellow traps than on white in tomato fields.

Thrips counts on sticky traps may not always correlate with other sampling methods. In a greenhouse study on sweet peppers, Shipp and Zariffa (1991) found good correlations of adult thrips counts on whole plants with sticky trap catches, tap samples and blossom samples, whereas leaf samples did not correlate with the previously mentioned techniques. Furthermore, they found that the numbers of immature thrips on whole plants closely followed numbers on tapping and blossom removal samples, with none captured on sticky traps and a weaker correlation with leaf samples. In addition, the distribution of thrips can be uneven on different parts of plants (e.g. Irwin et al., 1979; Reitz, 2002; Hansen et al., 2003), and also within-fields (e.g. Cho et al., 2000; Arévalo and Liburd, 2007b); thus, the number of sampling units often needs to be altered to achieve a more random sample based on thrips population size and distribution (Bullock, 1965).

In southern states of the USA, Liburd et al. (2009) caught more *Frankliniella* spp. on blue and white sticky traps compared with other colors evaluated. White traps were subsequently recommended for growers because thrips were more easily seen on those traps. Earlier, Arévalo and Liburd (2007b) found no differences between a "shake and rinse" sampling method where blueberry flowers were rinsed with water and shaken to collect the thrips, and a technique where flowers were dissected and observed under a microscope for the presence of thrips. Using sticky traps to monitor thrips dispersal within a blueberry field in Florida and southern Georgia, they showed a tendency for thrips to form "hot-spots" 5–7 d after the beginning of flowering.

Little is known about the biology and ecology of thrips in highbush blueberries in the northeast USA. In this study, we investigated thrips preference for different colored traps as well as their seasonal abundance, spatial distribution and species composition in northern highbush blueberries in New Jersey (USA). Our specific objectives were to: 1) evaluate different colors of sticky traps to capture thrips; 2) determine the seasonal abundance of thrips in commercial blueberry farms and compare with degree-day accumulations; and, 3) determine the species composition and distribution of thrips within a bush and within a blueberry field.

2. Materials and methods

2.1. Color preference

Attraction of thrips to color was evaluated using three commercially-available colored sticky traps: white (Tarnished Plant Bug trap, 11 cm wide × 17 cm high; Great Lakes IPM, Inc., Vestaburg, MI, USA), yellow (plastic card, 15.2 cm wide × 29.5 cm high; Great Lakes IPM, Inc.) and blue (plastic card, 15.2 cm wide × 29.5 cm high; Great Lakes IPM, Inc.). These colors were chosen for their reported attractiveness to other thrips species (Hoddle et al., 2002; Liburd et al., 2009). All traps were coated with TangleTrap® (Great Lakes IPM, Inc.). The study was conducted in 2002 in two commercial blueberry farms (cv. Bluecrop) located in Burlington Co., New Jersey. The experiment was established as a randomized block design (blocked by farm) with four replicates. Four traps of each color (treatments) were randomly placed on each farm. Traps were hung on a branch at canopy height (between 1 and 1.5 m from the ground) and at least 15 m apart. Total number of thrips per trap was recorded every 3–5 days from early April until June. Traps were replaced every other week. No pesticides were used for the control of thrips during the course of this study.

Analysis of number of thrips per trap was conducted using analysis of variance (ANOVA) (Minitab 13, Minitab Inc., State College, PA) to determine the effects of color on thrips counts. Data were natural-log (ln) transformed prior to analysis, and means were separated using Tukey tests.

2.2. Seasonal abundance

Thrips seasonal abundance was monitored from 2003 to 2006 in seven commercial blueberry (cv. Bluecrop) farms located in Burlington (2 farms) and Atlantic (5 farms) counties in New Jersey. The number of farms varied slightly during the sampling period: in all years (2003–2006), we sampled 4 different farms (1 in Burlington and 3 in Atlantic Co.); in 2003–2005, we sampled 1 additional farm in Atlantic Co.; and in 2006, we sampled 2 additional farms (1 in Burlington and 1 in Atlantic Co.). White sticky traps were used to monitor thrips populations in all farms because white was the most attractive color for thrips in our previous studies (see results section). On each farm, two 4 to 6 ha fields were sampled from early April until the end of August; this corresponds to the period of bud elongation until after harvest. Two sticky traps were placed per field, and the total number of thrips per trap was counted weekly. If the number of thrips was too numerous to count, we estimated the number by dividing the trap into nine equal squares and counting the three squares in a diagonal. The same was done to the other side of the trap and the numbers were then extrapolated. At each sampling date all thrips were removed from the traps and traps were replaced every other week. No insecticide applications on these farms were applied specifically for thrips management. No attempt was made to identify the species and sex of thrips on traps because the majority of them were in too poor condition to make an accurate identification. A 2-way ANOVA was used to determine the effects of farm and year on the abundance of thrips (season totals) on traps. Prior to analysis, data were ln transformed, and means were separated using Tukey tests.

Seasonal abundance data were then converted to cumulative values (percent trap capture) and these were plotted against day of year (DOY) for each of the four years. From these plots, the dates of 10, 50 and 90% trap captures were determined. Air temperature data were collected using a Campbell Scientific (Logan, Utah) weather station (model ET-106) equipped with a HMP50-ET platinum resistance thermometer housed within a standard radiation shield. Temperature data were recorded hourly and degree-day values were calculated using 5, 10 and 15 °C as base temperatures. Degree-day accumulations using a 10 °C base temperature provided similar or greater accuracy than those using 5 and 15 °C base temperatures (data not shown); also, 10 °C coincides with the lower developmental threshold for several thrips species (e.g. Murai, 2000, 2001). Thus, all our data analyses used 10 °C as a base temperature. Degree-day values were calculated by averaging the hourly calculations.

Since no biofix date was determined, degree-day accumulation was initiated on January 24 (DOY = 24) because complete, uninterrupted data collections were available from that date forward. RISE (Resource Information Serving Everybody) operated by the South Jersey Resource Conservation and Development Council (www.sjrcd.org/rise/) is a network of weather stations designed for agricultural irrigation management. The Hammonton, New Jersey (Atlantic Co.), RISE-station located near a commercial blueberry field was utilized for this study. Analysis of the relationship between degree-day accumulation and percent trap catch utilized least squares linear regression of log-logit transformed data.

2.3. Within-plant distribution

In 2006, a study was conducted to determine thrips distribution within a blueberry bush on two commercial blueberry farms (cv. Bluecrop) in Hammonton, New Jersey. Four bushes, at least six bushes apart, were randomly selected per farm. White sticky traps were placed at three different heights within each bush: one at the top third of the plant (~1.5 m from the ground), another in the middle (~1 m from the ground) and one in the lower third of the plant (~0.5 m from the ground). The total number of thrips per trap was counted weekly as previously described.

In addition to traps, reproductive and vegetative tissues were sampled weekly from early April until the end of August. Five bushes in proximity to each of the traps were randomly selected. From bud elongation until flowering, five branches with leaf and flower buds were collected from each bush (total number per sampling site: flowering buds = 210.9 (SE = 2.6); leaf buds = 196.4 (SE = 7.6)); during flowering, five flower clusters were collected from each bush (total number of flowers per sampling site = 277 (SE = 15.1)); during fruit set until maturation, five fruit clusters were collected per bush (total number of fruit per sampling site = 1052.4 (SE = 61.9)); and from flowering until the end of the experiment, five leaf terminals were collected per bush (total number of leaves per sampling site = 3553.8 (SE = 82.3)). Tissue samples were collected from the three different bush heights described above. All plant material was brought to the laboratory and examined for thrips under the microscope. During the course of the study no insecticides were used for thrips control.

The effects of height and farm on thrips abundance (season totals) on traps and on the bush were tested using 2-way ANOVA. We also compared the effects of plant tissue (vegetative versus reproductive) and farm on thrips abundance on bushes using 2-way ANOVA. Vegetative tissues included leaf buds and leaves, while reproductive tissues included flower buds, flowers and fruit. Before the analyses, number of thrips on different plant tissues and heights were totaled for each of the four trap locations per farm. All data were ln or $\ln(x + 0.1)$ transformed prior to analysis, and means were separated using Tukey tests.

2.4. Within-field distribution

Within-field distribution of thrips in highbush blueberries was monitored using two sampling methods from the 2nd week in April through the 2nd week in July (DOY = 99–190) of 2007. First, white traps were used to detect the initial flight of adult thrips and their movement within a blueberry field. Fifty of these traps were placed in a grid pattern within a 0.3-ha blueberry field located at the Rutgers P.E. Marucci Center (Chatsworth, NJ). The field was selected because of its location near a forest composed of mainly pine (*Pinus* spp.) and oak (*Quercus* spp.) trees with an understory of wild blueberries and huckleberries (*Gaylussacia* spp.), which allowed us to test whether thrips move from wild hosts into blueberry fields. This field received no insecticide sprays. Ten traps were placed in each row, for a total of five rows, with the first row facing the woods. Traps were placed at canopy height (between 1 and 1.5 m). Thrips captured on traps were counted weekly. A second sampling method consisted of using a shaking method (Eckel et al., 1996) to determine the number of thrips present on a bush. Three bushes were randomly chosen from around each trap. Five vegetative branches were chosen from each bush. The branches were beaten sharply with the bare hand (2 thrusts, 2–3 s) at an edge of a white tray (30 cm wide × 40 cm long), and all thrips that fell onto the tray were counted. Thrips were sampled from vegetative branches because this is where they occur in greater numbers on plants (see results section).

In addition, fruit samples (fully ripe berries) were taken on 26 June (DOY = 177) to determine the distribution of thrips injury to fruit within the field. Three bushes were chosen from the bushes surrounding each trap. Five fruit clusters were removed from each of the three bushes: two clusters from the top third of the bush, two from the middle and one from the bottom third. All fruit samples were brought to the laboratory and examined for scarring that could be caused by thrips feeding.

Spatial data were analyzed at two geographic scales: a macro-scale, which included the entire blueberry field, and a micro-scale, which investigated thrips spatial patterns around individual bushes. To determine if thrips counts on traps correlate with counts on bushes across an entire blueberry field, we correlated the average counts of thrips on bushes and traps throughout the season using Pearson correlation coefficient (Minitab). To investigate whether thrips counts on individual bushes and traps correlate within a blueberry field, statistical analysis of within-field data were divided into three tasks and performed using the R Statistical Software (2008). The first task assessed the association between thrips counts on bushes and traps. We computed the bush–trap correlation separately for every weekly period based on the 50 spatial grid locations in the field. The significance of the correlation was assessed using a permutation test; that is, thrips counts on bushes and traps were randomly permuted across the 50 grid locations and the correlation recomputed on this permuted data. We repeated this permutation process 10,000 times, each time computing a correlation between on bush and trap counts on the permuted data. If only a small proportion of the randomly permuted data resulted in correlations as high, or higher, than the correlation observed on the real data, then this indicates that the observed correlation is unlikely to be the result of chance alone; i.e., when there is no real association between on bush and trap counts. On the other hand, if a large proportion of randomly permuted data resulted in correlations as high, or higher, than the correlation observed on real data, then this indicates that the observations can be the result of chance alone and there may not be any real association between on bush and trap counts. The proportion of randomly permuted data that result in correlations as high, or higher, than the correlation observed on real data is the *P*-value of the permutation test.

The second analysis task investigated the spatial distribution of thrips within the field. For this, we constructed a simple spatial model that consisted of four separate edge-effects, one for each side of the field. The edge-effect is a wedge or gradient of increasing thrips counts from the center towards one side of the field (north, west, east and south). This four-component model was fit to the data from each weekly period as follows: a square-root transformation of the count data was applied for variance stabilization (a standard statistical technique when dealing with count data); the four-component model was then fit to the transformed data using a linear regression model. For example, if the fitted model contains a positive coefficient for the north-side edge-effect variable, this would indicate that there were more thrips towards the northern edge of the field than the center. If the coefficient is negative, this would indicate that there were fewer thrips towards the northern edge. The magnitude of the coefficient indicates how much the thrips counts differ from the center to the northern edge of the field. The interpretation of the other edge-effect components was the same. To assess whether thrips were primarily located in the center of the field, or towards one particular edge of the field (e.g. the forest), we used statistical model selection. We assessed the goodness of fit of the four-component model using the coefficient-of-variation, R-square, as well as *t*-tests on the individual edge-effects. We examined all combinations of included and excluded edge-effect components (e.g. north and south edge-effects included, east and west effects excluded). To select which edge-effects were needed to describe the within-field distribution, we used the AIC and BIC model selection criteria (Hastie et al., 2001). For each weekly period, we summarized the within-field distribution with a subset of edge-effects. The fit of the selected models were assessed using the R-squared (percent of variability of thrips counts accounted for by the model). We also compared the predicted thrips counts based on the model, and individual simulated data from the selected model, to the observed data to ascertain the validity of the model and its ability to describe the observed spatial variation in thrips counts.

The third analysis task pertained to fruit injury and its relation to within-field distribution of thrips during the season. We built a model for fruit injury, using a binomial Generalized Linear Model, to predict the expected proportion of injured fruit as a function of thrips counts on bushes and traps, as well as spatial variables (edge-effects as described above). To establish which of the variables were predictive of fruit injury, we performed statistical model selection as described above. Thus, we investigated all combinations of variables included and excluded in the model and selected the best predictive model based on the AIC and BIC model selection criteria.

2.5. *Thrips identification*

To determine the species composition of adult thrips on highbush blueberries, thrips on bushes were collected using beating-trays from 20 April until 24 August 2006. Samples were collected from the same blueberry fields as those described above (within-plant distribution). A total of 57 samples were taken (13, 13, 16, 8 and 7 in April, May, June, July and August, respectively), each sample representing thrips found on a single bush. Thrips samples were placed in vials with 70% EtOH, brought to the laboratory, and kept in a freezer until processed. Thrips were separated by stage under a microscope, and adults were identified to species using keys form Palmer et al. (1989) and Arévalo et al. (2006).

3. Results

3.1. *Color preference*

Color had a significant effect on thrips attraction to traps ($F = 132.3$; df = 2, 18; $P < 0.001$) (Table 1). Thrips abundance on traps also varied between farms ($F = 58.7$; df = 1, 18; $P < 0.001$) (Table 1); however, there was no significant color-by farm effect ($F = 0.61$; df = 2, 18; $P = 0.553$), indicating that the effect of color was not influenced by farm. Overall, thrips were least attracted to blue sticky traps compared with white ($t = 15.43$; $P < 0.001$) or yellow ($t = 12.18$; $P < 0.001$) traps, and were more attracted to white sticky traps than yellow traps ($t = -3.25$; $P = 0.012$). Numbers of thrips on white traps were 1.3 and 8.2 times higher than on yellow and blue traps, respectively. Early in the season (April 5–24), thrips favored yellow traps over white but, as the season progressed, the situation reversed (Table 1). Thus, white color traps were used in subsequent experiments to monitor thrips flight activity in highbush blueberries.

3.2. *Seasonal abundance*

Total thrips counts on traps differed significantly among years ($F = 17.65$; df = 3, 12; $P < 0.001$), but not among farms ($F = 0.83$; df = 4, 12; $P = 0.531$). Total counts were higher in years 2004 and 2005 compared with 2003 and 2006 across all farms (Fig. 1). These differences could not be explained by temperature because spring temperatures (March–May) were higher in 2004 (mean temperature = 12.0 °C) and 2006 (11.3 °C) and lower in 2003 (9.5 °C) and 2005 (11.1 °C); while summer temperatures (June–August) were higher in 2005 (24.2 °C) and 2006 (23.5 °C) and lower in 2003 (22.6 °C) and 2004 (22.2 °C). In all years, thrips counts on traps were low during flowering (May), increased rapidly during fruit set (late May–June), and declined during fruit maturation (July–August) (Figs. 1 and 2).

Within each season, however, thrips counts were highly influenced by temperature. Table 2 and Fig. 3 show the log-logit linear equations for the temperature accumulations and thrips catches with sticky traps. There was a strong linear relationship, as indicated by the high R-squares (> 0.97), between the cumulative percent trap capture of thrips and the degree-day accumulations for each of the sampling years (2003–2006) (Table 2), and for the combined 4-year data (Fig. 3; Table 2).

Table 3 shows the comparison of observed and predicted values for degree-day accumulations and DOY corresponding to the 10, 50 and 90% thrips captures for each year sampled (2003–2006). Overall, the predicted values (based on equations in Table 2) agreed with the observed values, as indicated by the small average error (Table 3). Also, degree-days and DOY had similar predictive powers: in both methods, the lowest errors correspond to values for the 10% thrips capture, while the highest errors to the 90% capture; however, errors were smaller when using DOY (Table 3).

3.3. *Within-plant distribution*

Thrips abundance varied significantly with trap height ($F = 16.9$; df = 2, 18; $P < 0.001$) (Fig. 4). Farm also had a significant effect on

Table 1
Total number of thrips caught on different colored sticky traps in 2003 in two New Jersey blueberry farms.

Location	Trap Color	4/5 - 4/24[a]			4/30 - 5/17			5/22 - 6/7			Season Total		
		Mean	SE		Mean	SE		Mean	SE		Mean	SE	
Farm1	White	13.0	2.5	B	445.5	70.3	A	850.5	101.6	A	1309.0	170.7	A
	Yellow	45.8	10.0	A	253.8	67.9	A	461.0	76.9	B	760.5	125.3	B
	Blue	0.8	0.5	C	48.5	15.3	B	77.3	16.3	C	126.5	28.5	C
Farm 2	White	13.3	3.0	B	546.8	29.8	A	2130.8	307.5	A	2690.8	276.7	A
	Yellow	45.5	15.6	A	477.0	54.7	A	1327.5	134.2	B	1850.0	175.0	B
	Blue	1.0	0.4	C	20.5	6.4	B	316.8	20.3	C	338.3	23.8	C

[a] For each farm, different letters within a column are significantly different ($P \leq 0.05$).

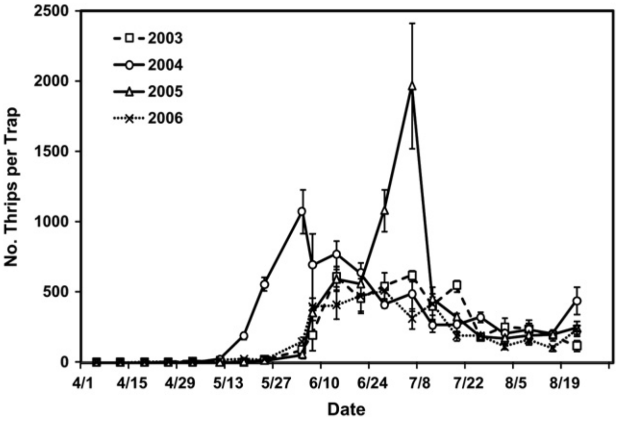

Fig. 1. Mean number of thrips caught on white sticky traps during 2003–2006. Data are means for five New Jersey blueberry farms, except for 2006 where six farms were sampled, and represent counts from two traps placed in two 4–6 ha fields per farm. Error bars represent SE, with $n = 4$ traps per farm.

thrips abundance on traps ($F = 9.61$; df = 1, 18; $P = 0.006$) (Fig. 4); however, there was no significant height × farm interaction ($F = 0.82$; df = 2, 18; $P = 0.454$). A greater number of thrips was caught on traps placed on the top one-third ($t = 5.76$; $P < 0.001$) and middle ($t = 3.55$; $P = 0.006$) of the plant compared with the bottom one-third of the plant. There were no differences in the numbers of thrips caught on traps placed on the top one-third of the plant compared with those on the middle of the plant ($t = 2.21$; $P = 0.096$).

When we counted the number of thrips on the bush, as compared with traps, there was also a significant effect of farm ($F = 4.7$; df = 1, 18; $P = 0.044$) but no effect of height ($F = 2.26$; df = 2, 18; $P = 0.133$) or height × farm interaction ($F = 3.21$; df = 2, 18; $P = 0.064$). Thrips were absent during bud elongation; their densities were low during flowering and increased during fruit set and maturation (Table 4). Overall, vegetative tissues had 10 times more thrips than reproductive tissues (Table 4); that is, significantly more thrips were found on leaves than on flowers or fruit ($F = 19.08$; df = 1, 12; $P = 0.001$), and this effect was not influenced by farm ($F = 1.19$; df = 1, 12; $P = 0.296$).

3.4. *Within-field distribution*

At a macro-scale level (i.e., across an entire blueberry field), the number of thrips on traps was highly correlated with thrips counts on bushes (Pearson correlation = 0.841; $P < 0.001$). However, at a micro-scale level (i.e., around individual bushes), a simple correlation analysis of thrips on traps and bushes revealed that trap and bush counts were largely uncorrelated. Only on 2 July (DOY = 183) were trap and bush counts positively correlated ($P = 0.04$). Thus, correlations of thrips on bushes and traps varied according to the geographic scale.

A second level of analysis was conducted to establish if trap and bush counts around individual bushes were lag-correlated.There was no significant and persistent lag-correlation between trap and bush counts. That is, we cannot say that, across the field, bush counts lead the trap counts by e.g. 2 weeks. Therefore, trap counts cannot be used to predict the peak of the bush counts. However, a third level of analysis indicates that the bush counts tend to peak earlier compared with the trap counts. A statistical comparison was made by computing the area under the cumulative counts for traps and counts per bush. Across the 50-grid locations, the average area under the cumulative counts is 0.27 for trap counts, and 0.33 for the bush counts. A paired *t*-test comparing the area under the curves for traps and bush cumulative counts was highly significant ($P < 0.001$). Thus, thrips influx on the bush seems to be earlier in the season than thrips counts on traps.

The model for within-field distribution of thrips using trap counts showed an increase in the number of thrips towards the forest side of the field during flowering (7–13 May; DOY = 127–133; R-square = 67%; Fig. 5A), at fruit set (21–27 May; DOY = 141–147; R-square = 25%; Fig. 5B) and during immature-green fruit (4–10 June; DOY = 155–161; R-square = 21%; Fig. 5C).

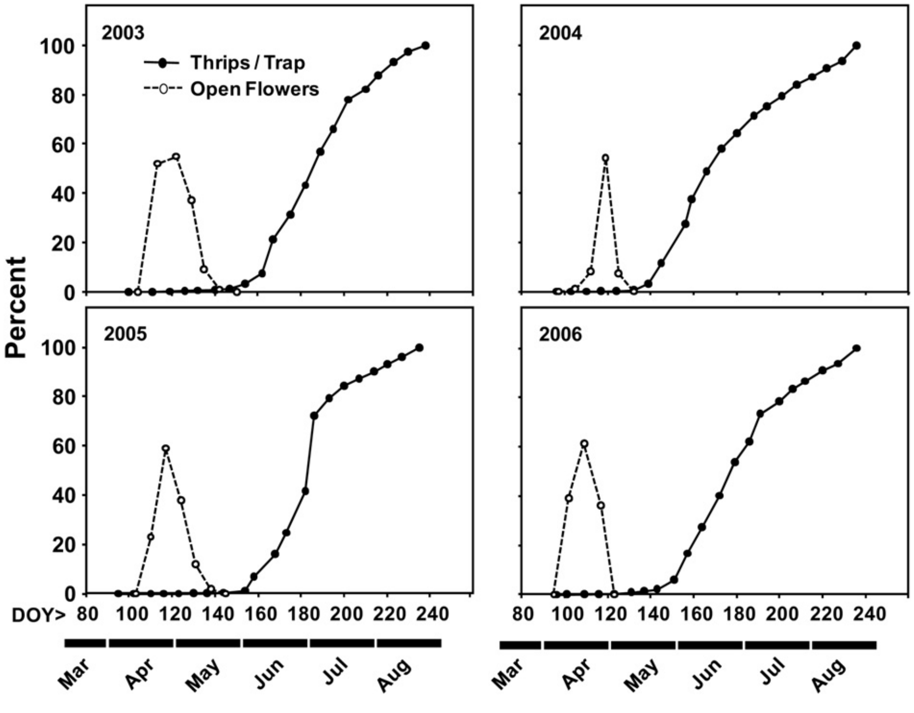

Fig. 2. Cumulative percent trap captures of thrips (●) and open flowers (○) during 2003–2006. DOY = day of year.

Table 2
Log-logit linear equations for the relationship between degree-day accumulations and cumulative percent trap catches of thrips on white sticky traps (10 °C base temperature).

Year	Regression Line[a]	d.f.	F	R-square	Standard Error Slope	Standard Error *Y*-intercept
2003	*y* = 4.25x-12.08	54	3663.2	0.986	0.14	0.41
2004	*Y* = 4.28x-12.10	53	3122.6	0.974	0.15	0.45
2005	*Y* = 4.07x-11.54	53	3167	0.984	0.14	0.43
2006	*Y* = 4.27x-12.04	52	2847.1	0.982	0.16	0.47
All	*Y* = 4.22x-11.95	71	4099	0.983	0.13	0.39

[a] x = log degree-days; y = logit (n) or log (*n*/(1-n)), where n = proportion of thrips captured in traps.

On 18–24 June (mature fruit; DOY = 169–174), more thrips on traps were found towards the northeast part of the field (R-square = 42%; Fig. 5D).

The distribution of thrips on bushes within a blueberry field differed from their distribution based on trap counts. The model showed an increased in the number of thrips towards the west end of the field during flowering (R-square = 55%; Fig. 6A), towards the north-west and north of the field during fruit set (R-square = 18%; Fig. 6B), towards the south-west of the field during green fruit (R-square = 11%; Fig. 6C) and towards northeast of the field during mature fruit (R-square = 44%; Fig. 6D).

In general, percent fruit injury ranged from nearly 0 to 15%, and all predicted models based on thrips counts within a field had limited predictive power of fruit injury. The correlation between thrips counts on traps and percent fruit injured at each grid location yielded no significant *P*-values (all *P*-values > 0.2). Percent fruit injury was, however, significantly correlated with the thrips counts per bush ($P \leq 0.05$): it was weakly but positively correlated with the counts per bush on 21–27 May (*P* = 0.15) and 4–10 June (*P* = 0.11), and significantly positively correlated for the average of these two counts (21 May – 10 June; DOY = 141–161; *P* = 0.008) (Fig. 7). Although the correlation of thrips counts with fruit injury was significant using the latter model (average counts), the percent of variability was quite low (8% at best). The narrowest confidence interval was around counts of 8 thrips per bush (the mean in the data), and if we doubled this number (worst-case scenario) the predicted percent injury was 6–12%, with an upper limit of 8–20% (Fig. 7).

3.5. Thrips identification

Out of a total of 99 thrips collected, 40% were adults while the rest were larvae. Out of these adults, 88 and 12% were identified as *S. ruthveni* and *F. tritici*, respectively. All samples from April collections contained only larvae, no larvae were found in May samples, while 38% percent of the samples collected in June and July contained 1–4 larvae. Only 1 larva was collected in August samples. Sixty-one percent of samples collected from May through August contained 1–5 *S. ruthveni* adults, indicating that, although generally present at low densities (see also Table 4), this is the most common thrips on blueberry bushes in New Jersey. Only 4 samples taken in May and June contained 1–2 *F. tritici* adults.

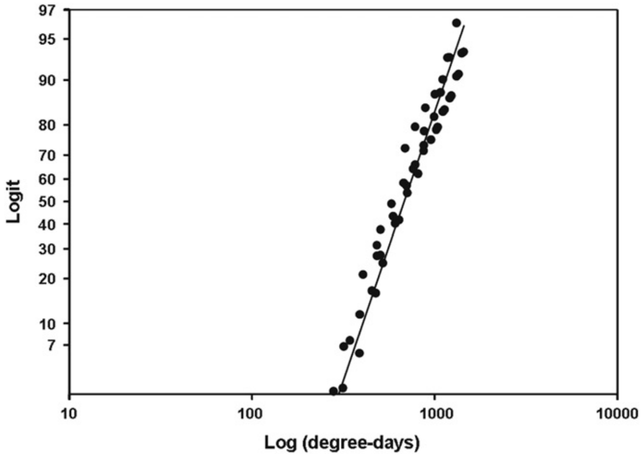

Fig. 3. Linear regression of cumulative percent trap captures of thrips (logit) versus degree-days accumulations (log(degree-days)). Data are for all years (2003–2006) sampled. Details on the regression equation are presented in Table 2.

4. Discussion

This 5-year study highlights several biological, behavioral and ecological parameters of thrips in New Jersey's northern highbush blueberries: 1) thrips showed high, intermediate and low attraction to white-, yellow and blue-colored traps, respectively; 2) populations increased rapidly following flowering and with increasing degree-day accumulations; 3) thrips were more abundant on vegetative than reproductive tissues, with *S. ruthveni* being the dominant thrips species; 4) thrips captures were greater in traps placed at the top and middle of the canopy than in the low parts of the canopy; 5) traps correlated with bush counts across an entire field but not around individual bushes; 6) abundance of thrips within a field was higher on traps closer to the forest; although this was not the case for on bush counts; and 7) only counts on bushes may be used as a predictor of thrips injury to fruit.

Overall, white sticky traps were the most effective colored traps for monitoring thrips in New Jersey blueberries. Blueberry flowers are white; thus, this color is the most predominant color in blueberry fields during flowering, which coincides with the beginning of thrips flight activity, so the attraction of thrips to white is not surprising (Lewis, 1997). A high attraction to white has also been reported for *F. occidentalis* in avocados (Hoddle et al., 2002), and for *Frankliniella bispinosa* in Florida blueberries (Finn, 2003; Liburd et al., 2009) and citrus (Childers and Brecht, 1996). In contrast, *F. tritici* was most attracted to yellow compared with blue or white traps in tomatoes (Cho et al., 1995). *F. tritici* was a species of flower thrips found on highbush blueberries in New Jersey (this paper; Polavarapu, 2001). White colored traps, as compared to yellow or blue, also provide the best color contrast with the yellow color of thrips. Thus, we and others (e.g. Finn, 2003; Arévalo and Liburd, 2007b; Liburd et al., 2009) recommend white traps for monitoring thrips in blueberries.

The reason thrips were initially attracted to yellow is unclear, but we propose three possible explanations. First, it may be related to the physiological state of maturity (young versus older sexually mature thrips). For example, Rull and Prokopy (2000) found differences in attraction between immature and mature apple maggot flies, *Rhagoletis pomonella* (Walsh), to lure-baited traps. We noticed that early in the season a high percentage of newly emerged adults are present in the field (O. E. Liburd, personal observation). Second, early in the season, very little foliar tissue is exposed and because yellow is considered to be a supernormal visual stimulus for foliar cues (Prokopy and Owens, 1983), it could account for the early-season yellow preference. Then, as the season

Table 3
Comparison between predicted versus observed degree-day accumulations (DD) and day of year (DOY) values corresponding to 10, 50 and 90% trap captures of thrips.

% Capture		2003		2004		2005		2006		Average[a] error
		Observed	Predicted	Observed	Predicted	Observed	Predicted	Observed	Predicted	
10	DD[b]	414	360	402	374	401	382	397	416	54
	DOY[c]	168–169	163	145–146	144	162–163	161	151–152	153	3
50	DD	695	637	671	598	688	668	665	683	76.5
	DOY	188–189	185	172	167	184–185	183	175–176	177	3.3
90	DD	1165	1123	1121	1310	1181	1130	1112	1361	238.3
	DOY	221–222	219	206–207	221	216–217	214	206	220	8.8

[a] Average difference of observed and predicted values for the four years.
[b] DD = degree-days; predicted degree-days calculated based on equation in Table 2.
[c] DOY = Day of year.

progressed and more foliar tissue was apparent, perhaps contrast becomes important and white emerged as more visually stimulating. Alternatively, species dominating the trap samples could change throughout the season and be attracted to different colors. Because our objective was to assess attraction of all thrips species to color traps for general monitoring purposes, we did not determine whether differences in color preference exist between the two most abundant thrips in New Jersey blueberries, *F. tritici* and *S. ruthveni*. Testing these possible hypotheses will be a topic for future research.

Our multi-year field data using white sticky traps indicate that thrips in New Jersey blueberries initiate most of their flight activity 20–30 d after flowering begins, i.e., mid–late May, which coincides with fruit set. Peak thrips flight activity often occurred in mid–late June, and then declined slowly until the end of the season. Considering that one thrips generation in warm weather lasts 21 d or less (Lewis, 1973; Funderburk and Stavisky, 2004), thrips could complete more than 5 generations from bud elongation through end of harvest in blueberries in New Jersey. In contrast, Arévalo and Liburd (2007b) found that thrips peak flight activity in Florida blueberries occurs 5–7 d after flowering initiation, which coincides with peak flowering. These differences are due to different species complexes which behave differently. For instance, flower thrips, *F. bispinosa*, is the dominant species in Florida inflicting most of the injury, as opposed to *S. ruthveni*, causing most of the injury to leaves in New Jersey.

We found that thrips flight activity is highly influenced by temperature. In this study, we developed equations based on degree-day accumulations to predict 10, 50 and 90% thrips activity in highbush blueberries in New Jersey. These equations consistently and accurately forecasted thrips activity for our 2003–2006 trap data. The lowest error between predicted and observed values was obtained for 10% thrips trap captures (Table 3). Because early thrips infestation was our best predictor of fruit injury (Fig. 7), if high

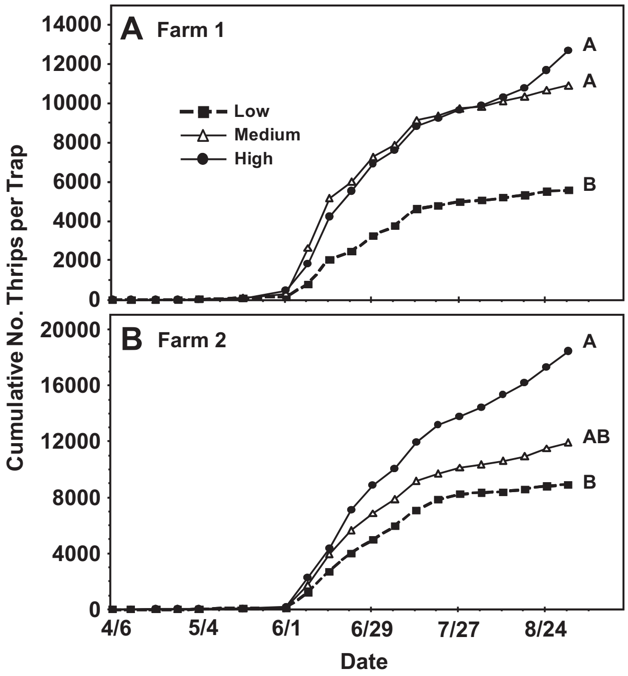

Fig. 4. Mean cumulative number of thrips per trap at three different heights: top third of the plant (~1.5 m from the ground), middle (~1 m from the ground), and lower third of the plant (~0.5 m from the ground). The study was conducted in 2006 at two blueberry farms in Hammonton, New Jersey. For each farm, same letters indicate that total numbers of thrips are not significantly different between heights, $P \leq 0.05$.

Table 4
Number of thrips on bushes at different phenological stages and different heights in northern highbush blueberries in New Jersey.

Plant Phenology	Height[a]	Number of Thrips[b]					
Plant Tissue		Farm 1		Farm 2		Both[c]	
Flowering		Mean	SE	Mean	SE	Mean	SE
Flowers	Low	0.0	0.0	0.0	0.0	0.0	0.0
	Middle	0.0	0.0	0.3	0.3	0.3	0.3
	High	0.3	0.3	0.5	0.3	0.8	0.5
	All[d]	0.3	0.3	0.8	0.3	1.0	0.4
Leaves	Low	0.5	0.3	0.3	0.3	0.8	0.5
	Middle	0.0	0.0	0.0	0.0	0.0	0.0
	High	0.5	0.3	0.0	0.0	0.5	0.3
	All	1.0	0.0	0.3	0.3	1.3	0.3
Fruit set - Harvest							
Fruit	Low	1.0	0.7	0.0	0.0	1.0	0.7
	Middle	0.0	0.0	0.0	0.0	0.0	0.0
	High	0.0	0.0	0.3	0.3	0.3	0.3
	All	1.0	0.7	0.3	0.3	1.3	0.6
Leaves	Low	11.3	5.9	0.5	0.5	11.8	5.7
	Middle	3.3	0.5	1.3	0.8	4.5	1.0
	High	1.8	0.5	0.3	0.3	2.0	0.4
	All	16.3	6.3	2.0	0.4	18.3	6.5
Post-harvest							
Leaves	Low	0.3	0.3	0.8	0.3	1.0	0.4
	Middle	0.0	0.0	1.0	0.6	1.0	0.6
	High	0.5	0.5	1.3	0.6	1.8	1.1
	All	0.8	0.5	3.0	0.4	3.8	0.6
Total No. of Thrips							
Reproductive Tissue[e]	Low	1.0	0.7	0.0	0.0	1.0	0.7
	Middle	0.0	0.0	0.3	0.3	0.3	0.3
	High	0.0	0.3	0.8	0.5	1.0	0.6
	All	1.3	0.8	1.0	0.4	2.3	0.5
Vegetative Tissue[f]	Low	12.0	5.9	1.5	0.6	13.5	5.5
	Middle	3.3	0.5	2.3	0.3	5.5	0.6
	High	2.8	1.0	1.5	0.5	4.3	1.4
	All	18.0	6.8	5.3	0.5	23.3	7.0

[a] Location in the canopy.
[b] $n = 4$ sampling sites per farm.
[c] Total number of thrips for both farms.
[d] Total number of thrips for all canopy locations.
[e] Number of thrips on flowering buds + flowers + fruit.
[f] Number of thrips on leaf buds + leaves.

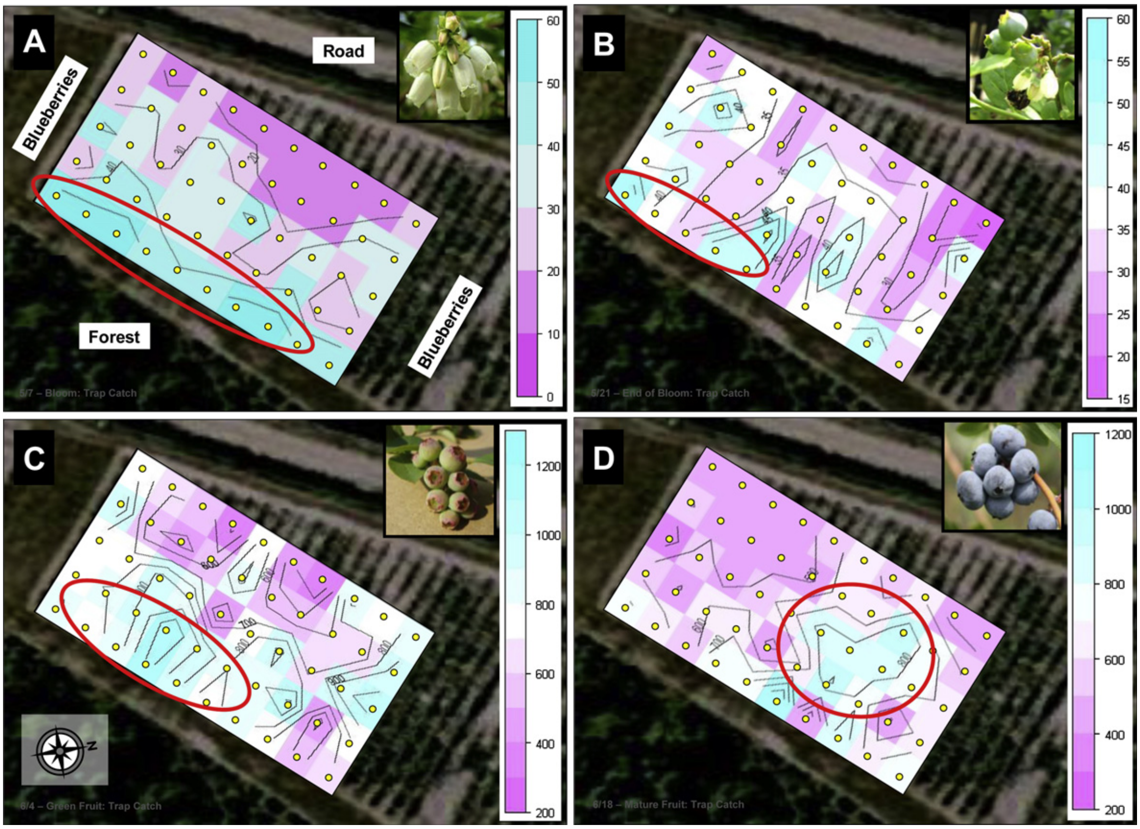

Fig. 5. Within-field distribution of thrips caught on white sticky traps in 2007 in a 0.3-ha blueberry field located at the Rutgers P.E. Marucci Center, Chatsworth, New Jersey. Scale on the right side of each picture indicates number of thrips on traps within the field, from lowest (darker red) to highest (darker blue). Yellow dots are traps locations. Red oval or circle indicates areas of highest thrips density or "hot-spots". Samples were taken during flowering (A), fruit set (B), early fruit maturation (C), and late fruit maturation (D).

thrips populations justify action, insecticide applications should be timed when reaching ~400 degree-days (which predicts 10% of thrips activity), using the linear equation for all sampled years presented in Table 2.

In New Jersey, thrips in highbush blueberries were found feeding mainly on leaves instead of flowers or fruit. This also differs from thrips in Florida blueberries, where they have a preference and can cause significant injury to flowers (2007a). Injury to blueberry leaves in New Jersey can be attributed mainly to *S. ruthveni*, the dominant thrips species found on bushes. Traps are useful for monitoring thrips activity. Arévalo and Liburd (2007a) found traps to be useful for timing flower thrips activity. However, in our situation, traps cannot be used as a stand-alone tactic to manage thrips. Degree-days could be used as an additional tool to predict the onset of thrips activity and its relation to plant phenology, and thus prevent possible thrips injury to flowering highbush blueberries in the northeast. We are currently using, and further verifying, the "all" equation in Table 2 as a predictive model for thrips activity in blueberries in New Jersey.

Arévalo and Liburd (2007b) found greater number of thrips on sticky traps placed within or above the canopy of blueberry bushes. Yet, we found variation on thrips captures even within the blueberry canopy, where thrips captures were highest on sticky traps placed in the middle and top one-third of the canopy and lowest in the bottom one-third. This result is not surprising, considering that most thrips caught on our traps are likely adults flying to or away from the bush. The distributions of thrips on bushes followed a different pattern than those from traps, where there was a trend towards finding higher densities of thrips on the middle and bottom one-third of the bush than on the top one-third. Since sampling from bushes included both nymphs and adults, while only adults are expected from trap captures, it is reasonable to assume that feeding and behavior by immatures may be at least partly responsible for the differences in within-bush distribution of thrips between sampling methods. In blueberries, new shoots are produced from the crown at the base of the plant; thus, most of the new growth is concentrated in the lower parts of the canopy. Thrips seem to prefer young over old blueberry foliage (C. Rodriguez-Saona, personal observation), which explains their distribution on the blueberry canopy.

When considering the entire field, number of thrips on traps correlated with counts on bushes. This was not true, however, when considering the distribution of thrips within the field, where thrips counts on bushes did not correlate with counts on traps. Based on our data, there are two potential sources of thrips in New Jersey blueberry fields. First, sticky traps showed that thrips fly into the fields from adjacent forest areas. Dispersal of thrips from wild hosts, i.e., some early-flowering *Vaccinium* spp., to blueberry fields occurred primarily during the flowering stage and early stages of fruit development, disappearing later in the season. However, there were differences in the distribution of thrips on bushes compared with traps. In addition, thrips were detected first on bushes and then on traps, and all thrips found on bushes early in the season were larvae, which indicates a second source of thrips originating from the interior of the field; i.e., a "resident" population. Langille and Forsythe (1972) suggested that thrips can overwinter as adults in the soil of blueberry fields in the northeast USA. Thus, both external and internal sources of thrips infestations are likely in blueberry farms in New Jersey. Our data show that the distribution of thrips on bushes within a blueberry field varied greatly throughout the season. Thrips tended to aggregate in certain areas of the field for a short period of time. Arévalo and Liburd (2007b)

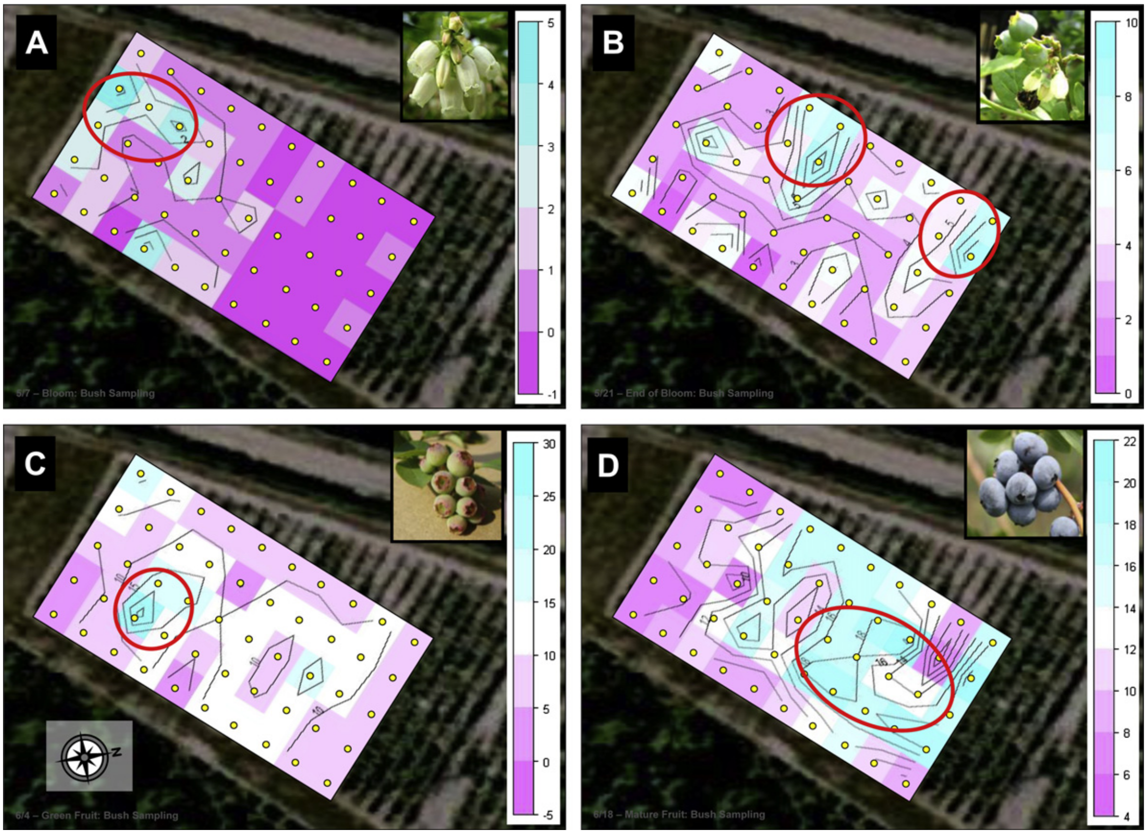

Fig. 6. Within-field distribution of thrips on bushes in a 0.3-ha blueberry field located at the Rutgers P.E. Marucci Center, Chatsworth, New Jersey. Counts represent number of thrips from shaking five branches within a bush. Individual counts are averages from 3 bushes near each trap (yellow dots). Scale on the right side of each picture indicates counts of thrips on bushes within the field, from lowest (darker red) to highest (darker blue). Red oval or circle indicates areas of highest thrips density or "hot-spots". Samples were taken during flowering (A), fruit set (B), early fruit maturation (C), and late fruit maturation (D).

observed similar aggregated distribution of thrips in Florida blueberries. They called these areas of large thrips numbers "hot-spots," and concluded that their formation within a blueberry field was random, with unknown factors responsible for their occurrence.

The numbers of thrips on fruit were low, which explains the low percent of fruit injury and limited predictive power of thrips abundance on bushes with respect to fruit injury. This suggests a low preference of thrips for blueberry fruit compared with other tissues. Our simple correlation-based analysis indicates that injury is correlated mainly with thrips abundance during 141–161 DOY; suggesting that preventative measures need to be undertaken prior to the first week in June and within 141 ≤ DOY ≤ 161, which also coincides with 10% trap captures. Fruit injury was uncorrelated with thrips trap counts. Similar attempts to correlate trap captures of citrus thrips with fruit scarring failed in California; although, other monitoring techniques employed were not much better than traps (Grout et al., 1986). As indicated above, most feeding injury by thrips in highbush blueberry fields of New Jersey is done to young leaves; whether this type of injury reduces yield in subsequent years has yet to be determined.

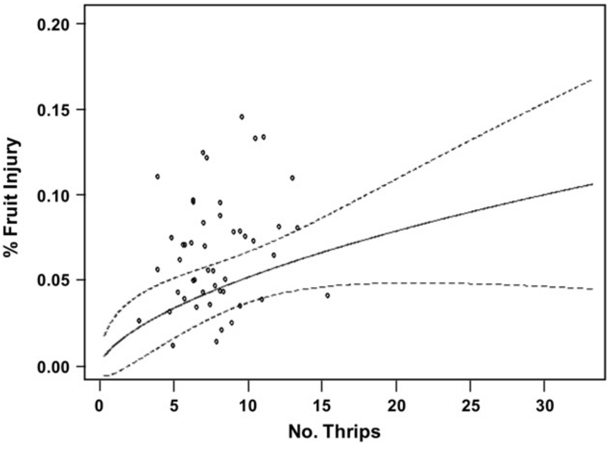

Fig. 7. Correlation between percent fruit injury and thrips counts on bushes from 21 May through 10 June (days of year = 141–161). Plotted solid line is the predicted percent of fruit injury as a function of thrips counts on bushes; broken lines are the 95% confidence intervals.

In conclusion, thrips can be classified as potentially important pests of northern highbush blueberries in New Jersey. We determined the presence of thrips mainly on young blueberry leaves, although the potential exists for thrips to cause injury to more valuable tissues such as flowers and fruit. Thrips numbers on white sticky traps should be interpreted with care, because these are poor indicators of thrips abundance on bushes within a blueberry field. Thus, traps should not be used as the only monitoring tool for making site-specific management decisions to control thrips in blueberries in our region. However, trap data were useful in predicting flight activity of thrips during the growing season and may be used for timing insecticide sprays. Thus, the most appropriate monitoring strategy would be to combine sticky traps with a shaking method, such as beating-tray sampling, to precisely determine thrips flight activity and abundance in blueberries. We also determined that, if needed, control measures taken early during fruit maturation may prevent fruit injury, and that this timing can be predicted with the accumulation of degree-days. Considering that blueberries are now grown worldwide in climatic regions similar to ours and that most thrips species attacking blueberries are generalists, this study provides ecologically-based management tools for thrips control in New Jersey blueberries that might also be applicable to other regions of the northeastern USA and around the world.

Acknowledgements

We thank Vera Kyryczenko-Roth for field assistance, Craig Roubos and Elena Rhodes for thrips identification, and Robert Holdcraft for assistance with graphics. Many thanks to Atlantic Blueberry Company, Macrie Brothers Blueberry Farm, Pine Island Cranberry Company, Mill Rock Farms, Whalen Farm and Variety Farms for providing field sites. Thanks also to Jennifer Johnson-Cicalese, Faruque Zaman and three anonymous reviewers for helpful comments on an earlier draft. Funding for this study was provided by the USDA-CSREES-Risk Avoidance and Mitigation Program (project No.2002-51101-01903) and the New Jersey Blueberry and Cranberry Research Council.

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