Impact of Abiotic Factors on Onion Thrips (Thysanoptera: Thripidae) Aerial Dispersal in an Onion Ecosystem

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Abstract

Onion thrips, Thrips tabaci Lindeman, is a significant pest of onion crops worldwide, but little is known about its patterns of aerial dispersal in the context of abiotic environmental factors. Thrips tabaci adults were passively collected from the air column above onion fields in western New York using clear sticky cards over a series of sampling periods in 2012, 2013, and 2014 while on-site weather conditions were recorded. Results indicated that T. tabaci adult densities on aerial traps during daylight averaged 279 times greater per hour than densities on similar traps at night. Adult dispersal also tended to spike during presunset, indicating that thrips initiated flight diurnally and within 1 h before sunset. Densities of T. tabaci on aerial traps increased significantly as temperature increased above 17 °C and 90% of the thrips were captured between 20.8 and 27.7 °C; no thrips were captured above 30.6 °C. Densities of T. tabaci on aerial traps decreased significantly as wind speed increased, with no thrips captured at winds exceeding 3.8 m/s (13.7 kph). In 2013 and 2014, T. tabaci densities on aerial traps prior to the passage of a cold front (relatively high atmospheric pressure and temperature with low wind speed) were significantly greater than densities after passage of the front, suggesting that T. tabaci disperses on synoptic weather systems.

Key words: Thrips tabaci, dispersal, abiotic factor, Allium cepa

Dispersal has significant ecological importance for most insects (Wellington 1979, Drake and Gatehouse 1995, Lewis 1997, Isard and Gage 2001). Abiotic factors such as atmospheric change (weather) and temporal dynamics (season, diel) play a major role influencing insect dispersal (Wellington 1979, Drake and Gatehouse 1995, Isard and Gage 2001). Dispersal may be defined in a number of ways; however, for the purpose of this paper, dispersal refers to active and passive aerial movement of individuals.

Onion thrips, Thrips tabaci Lindeman, is an important global crop pest (Lewis 1997), causing direct plant damage via feeding (Fournier et al. 1995, Childers 1997) and indirect damage via transmission of bacterial (Dutta et al. 2014) and viral plant pathogens (Bailey 1935, Ullman et al. 2002). Smith (2010) suggested that T. tabaci adults colonize onion fields from adjacent weed hosts in the spring, and Smith et al. (2015) reported T. tabaci adults engage in both trivial (short-range dispersal between plant hosts within the immediate habitat; e.g., meters of distance) and long-distance flight (movement out of the immediate habitat; e.g., kilometers of distance) during the onion-growing season. The proportion of T. tabaci adults in onion fields engaging in aerial dispersal increases as the onion season progresses, peaking when onion crops become mature (Smith et al. 2015). Thrips dispersal enables plant pathogens and insecticide-resistant alleles to move among fields in close proximity as well as potentially region-wide. For example, dispersing T. tabaci adults tested positive for Iris yellow spot virus (IYSV) (Bunyaviridae: Tospovirus) at all times of the growing season and at all altitudes sampled (0.5 to > 50 m aloft; Smith et al. 2015).

Time of day, temperature, wind, and atmospheric pressure affect insect dispersal (Burt and Pedgley 1997, Patterson et al. 1999, Dillon and Frazier 2006, Pelligrino et al. 2013), including thrips (Ben Yakir and Chen 2008; Morsello et al. 2008, 2010). In an Israeli study, Ben Yakir and Chen (2008) observed a greater proportion of T. tabaci adults dispersed aerially during the morning crepuscular period than at other times of day; however, diel patterns of T. tabaci dispersal are not known in other regions or climates. While numbers of dispersing T. tabaci adults are known to be positively correlated with degree-day accumulations during the onion-growing season (Smith et al. 2015), the more immediate effect of daily and hourly temperature fluctuations on T. tabaci dispersal are not known. The lower temperature threshold for thrips flight in temperate regions was reported as ~17–21 °C (Hurst 1964, Lewis 1997), but flight thresholds for T. tabaci have not been reported. Convective wind currents occur on a local scale, assisting small airborne insects in gaining altitude, which allows individuals to emigrate on prevailing wind currents aloft (Wellington 1979, Isard and Gage 2001). Thrips tabaci have been observed > 50 m aloft (Smith 2010).
et al. 2015), altitudes where long-distance movement (either emigration or immigration) likely occurs (Isard and Gage 2001). Ben Yakir and Chen (2008) suggested a correlation between high winds (>2.8 m/s) and decreased thrips flight; however, the effect of wind speed on *T. tabaci* flight activity has not been reported.

Synoptic-scale weather systems assist long-distance, aerial insect dispersal. For example, potato leafhopper, *Empoasca fabae* (Harris), initiates migratory flight in advance of low-pressure fronts, migrating northeasterly in spring, suggesting that decreasing atmospheric pressure may induce flight (Pienkowski and Medler 1964, Carlson et al. 1992). However, initiation of autumnal migratory flight in potato leafhopper is observed in response to rising atmospheric pressure; the associated winds from north to south assist with return migration to overwintering habitats in the southern United States (Shields and Testa 1999). Eastern flower thrips, *Frankliniella tritici* (Fitch), migrates north each spring on synoptic weather systems (Felland et al. 1994), but the influence of synoptic weather systems on *T. tabaci* dispersal has not been reported.

The purpose of this study was not to create a predictive model for *T. tabaci* dispersal. Rather, we wanted to identify the impact of diel cycles (specifically, the effect of daylight), local temperature, and wind speed on *T. tabaci* adult dispersal activity, and to investigate the broader effect of atmospheric variables on *T. tabaci* dispersal activity during the passage of synoptic weather systems. We chose to conduct this study in an onion ecosystem that was known to support high populations of *T. tabaci*.

### Materials and Methods

*T. tabaci* adult dispersal activity was monitored in commercial onion fields in the Elba Muck region in western New York (43.1 N, 78.1 W). Adults were captured using clear, rectangular (98.6 cm²) sticky card traps (Catchmaster model number 904, AP&G Co., Inc, Brooklyn, NY). Traps were mounted on 6-m-tall, vertical aluminum poles (see Smith et al. 2015). Traps were wrapped around the poles, adhesive facing outward, secured in place by pole-mounted clothespins, and were positioned at regular height intervals (0.5, 1, 2, 4, and 6 m) along the pole. Because we were not interested in comparing numbers of thrips captured at these different height intervals, numbers of thrips were summed across all five traps to tally the total number of adult *T. tabaci* captured per pole. Poles were placed in four locations (commercial onion fields between 0.5 and 2.0 km apart) within the Elba Muck region (one pole per location). *Thrips tabaci* were identified using the thysanopteran key authored by Moritz et al. (2001).

The airmass above onion fields was continuously sampled during three 120-h (5 d) sampling periods in the 2012 and 2013 growing seasons: “early-season” (16–21 June, 2012; 10–15 July, 2013), “mid-season” (26–31 July, 2012; 31 July–5 August, 2013), and “late-season” (21–26 August, 2012; 26–31 August, 2013). Early-season sampling in both years began when *T. tabaci* presence in onion crops was first observed (3–5 onion leaf stage). Mid-season sampling occurred when onion plants approached their full height (concurrent with the 8–9 leaf stage), and late-season sampling occurred when onion plants were nearly mature (10+ leaves), but not lodged. These sample periods were selected to provide a maximum range of temperatures, wind speeds, and fast-moving atmospheric weather fronts.

In 2012 and 2013, traps were collected and replaced five times daily. Sampling period 1 was sunrise to solar noon (“morning”; 6.5–8 h), period 2 was solar noon to 1 h prior to sunset (“afternoon”; 6.5–8 h), period 3 was the entire hour prior to sunset (“presunset”; 1 h), period 4 was the entire hour after sunset (“twilight”; 1 h), and period 5 was 1 h after sunset to sunrise (“night”; 6–9 h). Periods 1–4 will be collectively referred to as “daylight.” All *T. tabaci* adults captured on traps were recorded in 2013. In 2012, high densities of thrips on ~4% of traps (62 of 1,460 traps) precluded counting all thrips, so densities on these cards were estimated by extrapolating from the number of *T. tabaci* counted in the surface area of a subsample (20% of the card surface).

Temperature (°C), wind speed (m/s), and atmospheric pressure (millibars) were monitored and recorded using a Davis Vantage Pro2 Plus portable weather station (Davis Instruments, Hayward, CA). The weather station was installed ~2 m above the soil surface at one of the four trapping locations (the same location each year and season). Values were recorded every 10 min during all sampling times. All values recorded during each sampling period were averaged in order to obtain a single value for each of the five periods per day. For example, all temperatures recorded during the 10-min intervals during sampling period 1 on 28 August in late-2012 would be averaged in order to assign a single temperature value to that sampling period’s *T. tabaci* trap catch. Wind speed and atmospheric pressure values were also calculated in this way. This procedure was repeated for all sampling periods.

### Thrips tabaci Dispersal During Synoptic Frontal Systems

Between 31 July and 1 August 2013, a low pressure center above northeastern Manitoba, Canada (57.2 N, 94.0 W) moved eastward across northern Ontario (55.2 N, 84.6 W) and Quebec, Canada (54.7 N, 79.0 W) resulting in a cold front passing over the Elba Muck during mid-morning on 2 August 2013. *Thrips tabaci* captured in time periods 1–4 were totalled for each of the four trapping locations each day from 31 July–4 August to identify *T. tabaci* dispersal patterns during this synoptic weather event. A similar front passed over the Elba Muck the following year, between 25–27 August 2014. *Thrips tabaci* and weather variables were sampled over 5 d (25–29 August 2014).

In 2014, *T. tabaci* adults were sampled using pole-mounted sticky cards in the same manner as in 2012 and 2013; however, traps were only deployed during daylight hours until 1–2 h after sunset (15–16 h per day). At each of four locations, traps were replaced four times each day and the total number of *T. tabaci* captured over the 15–16 h day period was recorded (n = 4 locations). *Thrips tabaci* adults were also sampled each late afternoon or early evening (18:00–22:00), in the air column above onion fields using unmanned aerial vehicles (UAVs; 50–60 m altitude; Smith et al. 2015). Total *T. tabaci* captured on UAV-mounted traps were recorded.

### Statistical Analyses

**Diel Cycle (daylight) and Subsynoptic-Scale Weather Effects**

The response variable for this analysis was the number of *T. tabaci* adults captured per pole per hour and was created by summing the *T. tabaci* adults captured per pole (the sum of *T. tabaci* on the five sticky card traps attached to each respective pole) within a single sampling period and then dividing that sum by the number of hours during that sampling period. This procedure was repeated for each sampling period. Because the number of hours differed among sampling periods, this approach standardized the thrips capture data and enabled comparisons to be made among sampling periods.

Average trap capture of *T. tabaci* adults during daylight hours (sampling periods 1–4) was compared with average trap capture at
night (sampling period 5) using an ANOVA ($\alpha = 0.05$), and means separation was conducted using Tukey’s test at $P < 0.05$. Because low numbers of $T. tabaci$ were captured during the overnight period, the remaining statistical analyses were conducted using only the daylight sampling periods. Because variation in $T. tabaci$ capture numbers between seasons and years was high, each of the six seasons (= early, mid-, and late seasons $\times$ 2012 and 2013) was analyzed separately using a mixed model (JMP Version 12, SAS Institute 2013). Degrees of freedom in the remaining statistical analyses were conducted using only the daylight sampling periods. Because variation in $T. tabaci$ trap capture during all daylight sampling periods was pooled to investigate dispersal patterns across the ranges of temperatures and winds speeds observed in 2012 and 2013.

Post Hoc Analysis of Diel and Subsynoptic-Scale Weather Effects

In some instances, selected data were pooled across all seasons in 2012 and 2013 to identify and illustrate possible impacts of abiotic factors on $T. tabaci$ adult dispersal activity that were not modeled within each season. Specifically, $T. tabaci$ densities on traps during daylight and night were compared across only the range of average temperatures and wind speeds observed at night using an ANOVA ($\alpha = 0.05$), and $T. tabaci$ trap capture during all daylight sampling periods were pooled to investigate dispersal patterns across the ranges of temperatures and winds speeds observed in 2012 and 2013.

Synoptic-Scale Weather System Effect

For this analysis, the response variable was calculated in a similar manner as described above, except that the total number of $T. tabaci$ adults captured over the entire daylight period (periods 1–4 in 2013, and over the 15–16-h daylight period in 2014) was divided by the number of hours sampled each day. Average daily trap capture of $T. tabaci$ adults during the 5-d sampling period was analyzed using a mixed model (Log($x + 1$)$\sim$ Date) (random variables = Pole location, $n = 4$) and means were compared among dates using Tukey’s test at $P < 0.05$. Average temperature, wind speed, and atmospheric pressure were calculated for each sampling date during 2012 and 2013. The average number of $T. tabaci$ captured on UAV-mounted traps in 2014 was calculated per hour on each day. Because flights were only recorded in 2014, no statistical analysis was performed.

Results

More than seven times the number of $T. tabaci$ adults were captured on sticky card traps in 2012 ($n = 58,157$) than in 2013 ($n = 7,981$). In 2012 and 2013, most $T. tabaci$ were captured during the late-season sampling period (88.3% of total and 77.2% of total, respectively).

Most $T. tabaci$ (>99.7%) were captured during daylight. The number of airborne $T. tabaci$ averaged 279 times greater per hour during daylight than during the night ($F = 5.3$; $df = 1, 118$; $P = 0.0231$). Patterns of trap capture suggested that $T. tabaci$ dispersal activity differed within the diel cycle (Fig. 1). Numbers of thrips captured on sticky cards significantly differed among some of the sampling periods in four of six sampling seasons in 2012 and 2013. The effect of Sampling period was significant in mid- and late-2012 ($F = 3.2$; $df = 3, 22.9$; $P = 0.0445$); and $F = 8.9$; $df = 3, 25.1$; $P = 0.0004$, respectively) and in mid- and late-2013 ($F = 4.1$; $df = 3, 19.6$; $P = 0.0207$; and $F = 8.3$; $df = 3, 19.9$; $P = 0.0009$, respectively). $T. tabaci$ were captured in greatest numbers during the presunset period (period 3) in all four of these seasons (Fig. 1). These data also suggested that dispersal activity was lowest during twilight (period 4) in three of the four seasons (all but mid-season 2012).

In early, mid-, and late-season 2012, temperatures ranged from 18.0 to 32.0°C (mean = 25.7°C; SD = 3.5°C), 14.8 to 28.5°C (mean = 22.8°C; SD = 3.6°C), and 10.7 to 30.6°C (mean = 22.2°C; SD = 5.0°C), respectively. In early, mid-, and late-season 2013, temperatures ranged from 15.3 to 30.3°C (mean = 22.6°C; SD = 3.6°C), 10.2 to 25.2°C (mean = 19.0°C; SD = 3.0°C), and 16.4 to 27.7°C (mean = 23.1°C; SD = 2.7°C), respectively. The effect of average temperature on numbers of $T. tabaci$ adults captured was significant in mid-season 2012 and 2013 ($F = 15.3$; $df = 11, 33.7$; $P = 0.0004$, and $F = 6.1$; $df = 1, 57.0$; $P = 0.0167$, respectively). In these two seasons, $T. tabaci$ dispersal activity increased slightly as temperature increased ($y = 0.02x + 0.63$; $R^2 = 0.044$, and $y = 0.06x - 0.99$; $R^2 = 0.11$, respectively). However, average temperature only explained 0.4% and 11% of the variation in these data sets. In a post hoc analysis of the pooled data from all seasons in 2012 and 2013, the relationship between average temperature and numbers of $T. tabaci$ adults captured was slightly quadratic; 90% of dispersing $T. tabaci$ were captured when average temperatures across all daylight sampling periods were between 20.8°C and 27.7°C. Minimum and maximum temperatures when $T. tabaci$ were captured were 16.1°C and 30.6°C, respectively.

Average temperatures during daylight periods ranged from 15.2 to 32.0°C, while average night periods ranged from 10.2 to 24.8°C. Within the range of temperatures observed at night, numbers of $T. tabaci$ adults captured were significantly greater during daylight periods than at night ($F = 75.4$; $df = 1, 402$; $P < 0.0001$; $n = 404$), indicating that temperature was not a factor influencing the absence of $T. tabaci$ captured at night (Fig. 2).

Peak wind speeds were highest in the early-seasons of both 2012 (5.9 m/s) and 2013 (5.4 m/s), while peak wind speeds decreased from mid- to late-season in 2012 (3.8 and 2.0 m/s, respectively), and increased from mid- to late-season in 2013 (3.8 and 4.6 m/s, respectively). Average speeds varied dramatically between seasons in 2012 (2.9, 1.1, and 0.7 m/s in early, mid-, and late-season, respectively), but were less variable in 2013 (1.4, 1.8, and 1.3 m/s in early, mid-, and late-season, respectively). The effect of average wind speed on numbers of $T. tabaci$ adults captured was significant in mid-season ($F = 8.0$; $df = 1, 33.7$; $P = 0.0079$, $y = -0.26x + 1.41$; $R^2 = 0.16$) and late-season 2012 ($F = 10.2$; $df = 1, 47.8$; $P = 0.0025$, $y = -0.10x + 1.84$; $R^2 = 0.01$) and late-season 2013 ($F = 15.3$; $df = 1, 44.0$; $P = 0.0003$, $y = -0.29x + 1.19$; $R^2 = 0.29$). The relationship between numbers of $T. tabaci$ adults captured and wind speed was negative, suggesting that $T. tabaci$ adults were less likely to disperse as wind speed increased. In mid- and late-season 2012, and late-season 2013, wind speed only explained 16, 0.9, and 29% of the variation in these data sets, respectively.

In a post hoc analysis of the pooled data from the daylight periods in both years and all seasons, there was a negative exponential relationship between numbers of $T. tabaci$ adults captured and wind...
July), mid- (31 July–5 August), and late (26–31 August) 2013 (Fig. 2).

Mean numbers of *T. tabaci* adults captured on colorless sticky cards during daylight (periods 1-4) and night (period 5) across the range of average temperatures observed in this study indicated significantly more *T. tabaci* adults were captured within this wind speed range during daylight hours compared with nighttime hours (0–2.5 m/s), significantly more *T. tabaci* adults were captured during the day when average wind speeds exceeded 3.8 m/s. Within the range of average wind speeds observed during nighttime hours (0–2.5 m/s), wind speed explained 27% of the variation in these data (\( y = 0.04x^2 - 0.49x + 1.36; R^2 = 0.27 \)). No *T. tabaci* were captured when average wind speeds exceeded 3.8 m/s. Within the range of average wind speeds observed during nighttime hours (0–2.5 m/s), significantly more *T. tabaci* adults were captured within this wind speed range during daylight hours compared with nighttime hours (\( F = 135.5; df = 1, 459; P < 0.0001; n = 461; \) Fig. 3). These results indicated that wind speed also was not important for explaining why thrips were more likely to initiate dispersal during the day than at night. Another post hoc analysis of the pooled data examining the impact of wind speed on *T. tabaci* dispersal activity across the range of average temperatures observed in this study indicated that numbers of *T. tabaci* adults captured tended to decrease as wind speeds increased (Fig. 4).

A total of 436 *T. tabaci* were collected on pole-mounted traps from 31 July to 4 August 2013, 266 of which (61% of total) were captured on 31 July 2013. Only 54, 49, 48, and 19 *T. tabaci* were captured on August 1st, 2nd, 3rd, and 4th, respectively (altogether = 39.0% of total). Mean number of adults captured on 31 July was significantly greater than those captured on 4 August (\( F = 5.0; df = 4, 12; P = 0.0135; \) Fig. 5A). Mean daily temperature decreased with passage of the cold front on 1 August, and remained constant through 3 August; lowest mean daily temperature was observed on 4 August. Mean daily wind speed increased from 31 July to 1 August, and means remained relatively higher through 4 August. Atmospheric pressure decreased rapidly from 31 July to 1 August, and gradually increased from 1–4 August as the trough passed over the region.

Fig. 1. Mean numbers of *T. tabaci* adults per pole (\( n = 4 \) poles) in the early (16–21 June), mid- (26–31 July), and late (21–26 August) 2012 (A) and early (10–15 July), mid- (31 July–5 August), and late (26–31 August) 2013 (B) onion-growing seasons (left axis). The dashed line represents mean atmospheric pressure during each sampling period (right axis). Time periods: 1. Sunrise – solar noon; 2. Solar noon – 1 h before sunset; 3. 1 h before sunset – sunset; 4. Sunset – 1 h after sunset; 5. 1 h after sunset – sunrise. Shaded portion indicates night (period 5).

*Due to an electrical storm during the second day of sampling in early 2012, traps from period 3 remained through period 4, resulting in no data for period 4 on this day. Densities for this period were calculated like all other periods: total *T. tabaci* captured/total sampling hours.

Fig. 2. Mean numbers of *T. tabaci* adults captured on colorless sticky cards during daylight (A) and night (B) across the range of average temperatures observed during night for all seasons in 2012 and 2013 in the Elba Muck.
A total of 2,772 *T. tabaci* adults were collected on pole-mounted traps from 25–29 August 2014, and approximately two-thirds (1,843 adults; 66.5% of total) of *T. tabaci* were captured on 25 August 2014. Only 285, 52, and 256 *T. tabaci* adults were captured on August 27th, 28th, and 29th, respectively (altogether 21.4% of total). Mean number of adults captured on 25 August was significantly greater than those captured on 28 August (*F* = 7.7; *df* = 4, 12; *P* = 0.0026; Fig. 5B). Mean temperatures increased from 25 to 26 August 2014, then decreased dramatically after the passage of the frontal system on 27 August; however, *T. tabaci* dispersal activity was nearly identical on days with the highest and lowest temperatures (26 and 29 August, respectively). Wind speeds also increased prior to the passage of the front, but continued to remain relatively high (>2.0 m/s) after the front passed, eventually decreasing to <1.0 m/s on 29 August. Atmospheric pressure gradually decreased from 25 to 27 August and increased again from 27 to 29 August as the trough passed over the region and was replaced by a cold airmass of high pressure.

A total of nine *T. tabaci* adults were captured on UAV-mounted traps in 2014. Seven of the nine adults (78%) were captured on 25 August (Fig. 5B). Results from these UAV samples indicate that the highest numbers of *T. tabaci* engaging in high-altitude flight that likely resulted in long-distance dispersal (Smith et al. 2015) did so prior to the passage of a frontal system.

**Discussion**

Dispersal activity of *T. tabaci* adults occurred almost exclusively during daylight hours, peaking before sunset and dropping sharply after sunset. The low numbers of thrips captured at night (period 5) may have initiated flight at night, or could have taken flight during daylight (periods 1–4) and did not become trapped until the night period. Spikes in *T. tabaci* flight occurred during the presunset period (period 3) in 11 of 30 sampling days, 4 sampling days in the twilight period (period 4), 2 sampling days in the morning (period 1), and never occurred during the afternoon sampling period (period 2). In Israel, Ben Yakir and Chen (2008) also captured the fewest numbers of dispersing *T. tabaci* adults during the afternoon, but captured the highest numbers of dispersing *T. tabaci* adults in the morning. An explanation for why more thrips adults were captured in the morning rather than before sunset in the Israel study is not known, but may reflect the influence of other abiotic factors, which are discussed later in this section.

During daylight, *T. tabaci* flight tended to occur most frequently when temperatures were warm, between 20.8 and 27.7°C. The upper temperature threshold for *T. tabaci* flight is not known; however, Hurst (1964) suggested that 29°C may be a reasonable hypothesis for a temperature at which thysanopteran flight activity begins to decline. *Thrips tabaci* were captured during sampling intervals with average temperatures above 29°C; however, this temperature was exceeded in only 6 of 150 sampling intervals throughout our study. *Thrips tabaci* were not captured when the average temperature exceeded 30.6°C. Low temperatures also appeared to inhibit *T. tabaci* flight. Sixteen of 30 d experienced temperatures <17°C at some point during daylight hours and no *T. tabaci* were captured during sampling periods when temperatures <17°C.

During daylight, *T. tabaci* dispersal tended to occur most often when winds were relatively low, <0.6 m/s. Wind speeds were typically low at sunrise, tended to increase through the day, and decreased again at sunset. More *T. tabaci* tended to fly as wind speed decreased during daylight hours (Fig. 4). In contrast, *Limothrips cerealium* preferred to fly in greatest numbers between 1.1 and 1.7 m/s (Lewis 1963). *Limothrips cerealium* flight decreased below 1.1 m/s (Lewis 1963), unlike *T. tabaci*. No *T. tabaci* were captured when average wind speeds were >3.8 m/s. Lewis (1997) mentioned that *Frankliniella* spp. did not fly when wind speeds exceeded an average
of ~2.5 m/s. However, average wind speeds do not necessarily represent sustained winds. As insects may take flight during lulls in sampling intervals when average wind speeds are high, absolute upper wind speed thresholds for flight may be masked.

Low wind speed was implicated for why high numbers of dispersing T. tabaci adults were captured early in the morning compared with other times of the day in Israel (Ben Yakir and Chen 2008). In our study, we also had relatively low wind speeds early in the morning as well as around sunset, but trapped more T. tabaci around sunset than sunrise. Thus, there must be another factor to explain why more thrips were captured in the morning in their study, and in the evening in our study. Perhaps, the difference is attributed to higher overnight temperatures in Israel compared with other times of the day in Israel (Ben Yakir and Chen 2008).

The majority of T. tabaci were captured 50–60 m aloft on UAV-mounted traps, indicating that T. tabaci engaged in average overnight temperatures are above the temperature threshold for flight, ~17–21 °C (Hurst 1964, Lewis 1997).

Only one major frontal system passed over the Elba Muck region during the 2012 and 2013 study periods (mid-2013) and one passed during the 2014 study. The majority of T. tabaci were captured <48 h prior to the passage of cold fronts in both 2013 and 2014 study periods, on 31 July 2013 and 25 August 2014 (Fig. 5). The fewest T. tabaci were captured on 4 August 2013 and 27 August 2014, after each front had passed. These results suggest that T. tabaci adults were more likely to disperse during periods of rapidly decreasing pressure (typically in advance of a passing frontal system) and less likely to disperse immediately afterward. There was a brief period of light precipitation on the morning of 1 August 2013 (EAS, personal obs.). Although heavy rains are known to cause T. tabaci mortality (North and Shelton 1986) and prevent dispersal of thrips, light rain probably did not contribute to the reduction in T. tabaci flight in the days afterward. In August 2014, there was no precipitation associated with the passing front, yet the trend in T. tabaci dispersal activity was similar as in 2013.

In the context of a low pressure center in the northern hemisphere, taking flight prior to the passage of the front would facilitate northward movement. In 2014, T. tabaci were captured 50–60 m aloft on UAV-mounted traps, indicating that T. tabaci engaged in
long-distance dispersal (Smith et al. 2015) during periods of rapidly decreasing pressure in advance of low pressure systems (conducive to northerly movement) late in the onion-growing season. Similar results were observed with E. fabae and F. tritici in advance of frontal systems as they migrated north (Pienkowski and Medler 1964, Carlson et al. 1992, Felland et al. 1994).

When attempting to identify the effect of specific environmental factors on insect dispersal, factors may confound each other and can complicate efforts to analyze field data. Daylight, temperature, and wind speed are linked in cause and effect in many cases (Isard and Gage 2001). The sun heats the surface of the earth, causing convective wind currents; as temperatures rise in the day, wind velocity typically increases. Furthermore, temperature and wind are heavily influenced by atmospheric pressure. Low-pressure systems are responsible for the influx of warm air masses into temperate climates, yet are also associated with frontal winds and precipitation. Like precipitation (MacGill 1929, Bonnemaison and Bournier 1964, North and Shelton 1986), our results suggest the effect of wind will negate any conducive effects of increased temperature on T. tabaci flight (Fig. 4), and both precipitation and wind likely outweigh any effect that atmospheric pressure dynamics may have on its own. Our results indicate that daylight cycles have the greatest effect on T. tabaci flight during the onion-growing season.

Our study provides substantial new information about the general impact of various abiotic factors on adult T. tabaci aerial dispersal under natural conditions. The benefit of this approach was to generate information under natural environmental conditions, but a weakness of this approach was the inability to accurately isolate and evaluate each abiotic factor’s influence on thrips dispersal, while keeping all other abiotic factors constant. Additional studies in a controlled environment could examine more specifically the impact of each abiotic factor’s influence on T. tabaci dispersal.

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References Cited


