View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by RERO DOC Digital Library

Temperature and Precipitation Affect Seasonal Patterns of Dispersing Tobacco Thrips, *Frankliniella fusca*, and Onion Thrips, *Thrips tabaci* (Thysanoptera: Thripidae) Caught on Sticky Traps

SHANNON C. MORSELLO,[1,2] RUSSELL L. GROVES,[3] BRIAN A. NAULT,[4] AND GEORGE G. KENNEDY[1]

Environ. Entomol. 37(1): 79–86 (2008)

ABSTRACT Effects of temperature and precipitation on the temporal patterns of dispersing tobacco thrips, *Frankliniella fusca*, and onion thrips, *Thrips tabaci*, caught on yellow sticky traps were estimated in central and eastern North Carolina and eastern Virginia from 1997 through 2001. The impact that these environmental factors had on numbers of *F. fusca* and *T. tabaci* caught on sticky traps during April and May was determined using stepwise regression analysis of 43 and 38 site-years of aerial trapping data from 21 and 18 different field locations, respectively. The independent variables used in the regression models included degree-days, total precipitation, and the number of days in which precipitation occurred during January through May. Each variable was significant in explaining variation for both thrips species and, in all models, degree-days was the single best explanatory variable. Precipitation had a comparatively greater effect on *T. tabaci* than *F. fusca*. The numbers of *F. fusca* and *T. tabaci* captured in flight were positively related to degree-days and the number of days with precipitation but negatively related to total precipitation. Combined in a single model, degree-days, total precipitation, and the number of days with precipitation explained 70 and 55% of the total variation in the number of *F. fusca* captured from 1 April through 10 May and from 1 April through 31 May, respectively. Regarding *T. tabaci* flights, degree-days, total precipitation, and the number of days with precipitation collectively explained 57 and 63% of the total variation in the number captured from 1 April through 10 May and from 1 April through 31 May, respectively.

KEY WORDS insect dispersal, tomato spotted wilt virus, epidemiology

Thrips infestations are known to cause economic damage to many crops including cabbage, cotton, onion, tomato, pepper, peanut, and tobacco. Loss may be attributed directly to injury resulting from thrips feeding or oviposition and indirectly by transmission of plant viruses, such as Tomato spotted wilt virus (TSWV; family *Bunyaviridae*, genus *Tospovirus*) (North and Shelton 1986a, 1986b, Shelton and North 1986, Broadbent et al. 1987, German et al. 1992, Lewis 1997, Cho et al. 1995, Brecke et al. 1996, Eckel et al. 1996, Gitaitis et al. 1998, McPherson et al. 1999, Garcia et al. 2000, Nault and Speese 2002). The continual pressure of TSWV and thrips damage on the production of peanut, tobacco, and other solonaceous crops in the southeastern United States has increased interest in the ecology of thrips vector species (Hobbs et al. 1993, DuRant et al. 1994, Eckel et al. 1996, Prins and Goldbach 1998, Groves et al. 2001, 2002, 2003, Wells et al. 2002, Kahn et al. 2005).

Throughout the southeastern United States, the western flower thrips, *Frankliniella occidentalis* (Pergande), and the tobacco thrips, *Frankliniella fusca* (Hinds), are considered important vectors of TSWV (Morgan et al. 1970, McPherson and Beshear 1990, Salguero Navas et al. 1991, Cho et al. 1995). The role of the onion thrips, *Thrips tabaci* Lindeman, as a competent vector has been disputed over the last few years (Wijkamp et al. 1995), but recent studies indicate that at least some populations transmit TSWV effectively and could play a role in the primary spread of TSWV in Europe and in the United States (Chatzivassiliou et al. 1999, 2002, Cabrera-LaRosa and Kennedy 2007). The seasonal population dynamics and dispersal of thrips vector species in the southeast and mid-Atlantic regions of the United States also have been described on several noncrop and crop host plants during the cropping season (Barbour and Brandenburg 1994, Chamberlin et al. 1992, Eckel et al. 1996, Groves et al. 2003, Kahn et al. 2005, McPherson et al. 1992, 1999, Nault et al. 2003).

In North Carolina, where *F. fusca* is the predominant early-season vector of TSWV, both the virus and

[1] Department of Entomology, North Carolina State University, Raleigh, NC 27695.

[2] Corresponding author, e-mail: shannon_morsello@ncsu.edu.

[3] Department of Entomology, University of Wisconsin-Madison, Madison, WI 53706.

[4] Department of Entomology, Cornell University, New York State Agricultural Experiment Station, 630 W. North Street, Geneva, NY 14456.

0046-225X/08/0079–0086$04.00/0 © 2008 Entomological Society of America

its thrips vectors overwinter on winter hosts growing in and around agricultural fields (Cho et al. 1995, Groves et al. 2001, 2002). Populations of *F. fusca* overwintering on winter weeds typically begin to increase in April and peak in late May (Groves et al. 2001, 2003, S.C.M. and G.G.K., unpublished data). The populations on crops, such as tobacco, tomato, and pepper, typically peak in late May and early June (Eckel et al. 1996). In a 4-yr study, Groves et al. (2003) observed peaks in the numbers of dispersing *F. fusca* adults caught on yellow sticky traps during May or early June, although the numbers of *F. fusca* varied among locations and years. They also observed that the seasonal patterns of TSWV-spread corresponded with the number of *F. fusca* caught on yellow sticky traps. Factors affecting the numbers of *F. fusca* caught on yellow sticky traps during the period when they are dispersing from their winter hosts and infest crops have not been quantified.

Temperature and rainfall have long been viewed as major factors affecting population dynamics of thrips. Davidson and Andrewartha (1948b) reported that the abundance of adult *Thrips imaginis* Bagnall found in flowers during spring was determined largely by natural population growth, the influence of weather throughout the season on thrips multiplication rate, and the influence of current weather on thrips activity. Temperature influences population dynamics principally because it affects the developmental rate of insects (Logan et al. 1976). Rainfall tends to negatively affect thrips populations (Bailey 1933, 1934) because heavy precipitation events can kill larvae (Kirk 1997) and suppress dispersal (Lewis 1963). In contrast, rainfall may positively impact thrips population growth and dispersal by delaying senescence of host plants (S.C.M. and G.G.K., unpublished data), allowing more time for thrips to proliferate and ultimately colonize crops. Based on these studies, we would expect dispersing thrips populations to be positively affected by increasing temperature and negatively affected by heavy rainfall throughout the spring. However, we also expect the negative effect of heavy rainfall might be at least partially offset by a positive effect of frequent rain resulting from delayed senescence of noncrop hosts.

Our study was conducted to determine and quantify the effects of temperature and rainfall on the numbers of *F. fusca* and *T. tabaci* caught on yellow sticky traps in spring. *Frankliniella occidentalis* was not included in our analyses because too few specimens were collected. Using thrips aerial trapping data collected during the spring seasons of 1997 through 2001, we evaluated the influence of temperature (developmental degree-days), the amount of precipitation, and the number of days in which precipitation occurred on the numbers of *F. fusca* and *T. tabaci* caught on our traps during the period 1 April through 31 May, when the populations are dispersing from their winter hosts and infest summer hosts, including newly planted crops.

Materials and Methods

Aerial Trap Collection. From 1997 to 2001, thrips spring dispersal was monitored along field borders at 21 locations in central and eastern North Carolina and eastern Virginia. Trapping was initiated before the crops were planted. In North Carolina, the fields were planted to tobacco, soybean, or cotton during the trapping period. In Virginia, the fields were planted to tomato (Fig. 1). Traps in North Carolina consisted of cylindrical yellow (John Deere Yellow model 981; Spray Products, Norristown, PA) PVC pipe (7.5 cm length by 2.5 cm diameter) wrapped with Tanglefoot-coated plastic wrap (Great Lakes Integrated Pest Management, Vestaburg, MI) and fastened to a wooden dowel 1 m above the soil. At each location, four traps, separated by 10 m, were arranged in a linear pattern along one side of the field to avoid interference with any cultural practices. Any vegetation within an area of $\approx$0.4 m^2 surrounding each trap was removed. Between 1 April and 31 May, traps were replaced at $\approx$7-d intervals. Recovered traps were returned to the laboratory where the coated plastic was removed from the PVC cylinder and sandwiched between two pieces of transparent plastic wrap (S.C. Johnson & Son, Racine, WI) (Groves et al. 2003).

In Virginia, yellow sticky cards (7.6 cm by 12.7 cm, both sides exposed) were fastened to trellis supports in the center of tomato fields and adjusted weekly to the height of the canopy. At each field location, cards were placed in three rows, and the middle row had one card and was flanked by rows that each had two cards (five cards total). Rows containing cards were separated by >10 m. All cards were within 20 m of field edges. Traps were replaced at 7-d intervals and returned to the laboratory for processing (Nault et al. 2003). Data from Virginia traps were multiplied by 0.31 per trap to adjust for the larger surface area of the traps used in Virginia.

Thrips Identification. When 25 or fewer adult thrips per trap were collected on a trap, all thrips were identified to species. When there were >25 thrips on a trap, the total number of adult thrips was counted, and a random subsample of 25 thrips was removed for identification to species. The proportion of each species within the subsample was multiplied by the total number of thrips captured on that trap to estimate the total number of each species present on the trap. Individual thrips recovered for identification were removed from the plastic wrap by soaking in HistoClear solvent (National Diagnostics, Atlanta, GA) for 10 min. A microscope slide was prepared for each trap collection ($\leq$25 thrips per slide) using CMC-10 (Masters Chemical Co., Elk Grove, IL) as a clearing and mounting medium. Species of adult thrips mounted on slides were determined using a key to adult thrips of Terebrantia suborder (Palmer et al. 1992). Voucher specimens are held at the North Carolina State University museum and Eastern Shore Agricultural Research and Extension center near Painter.

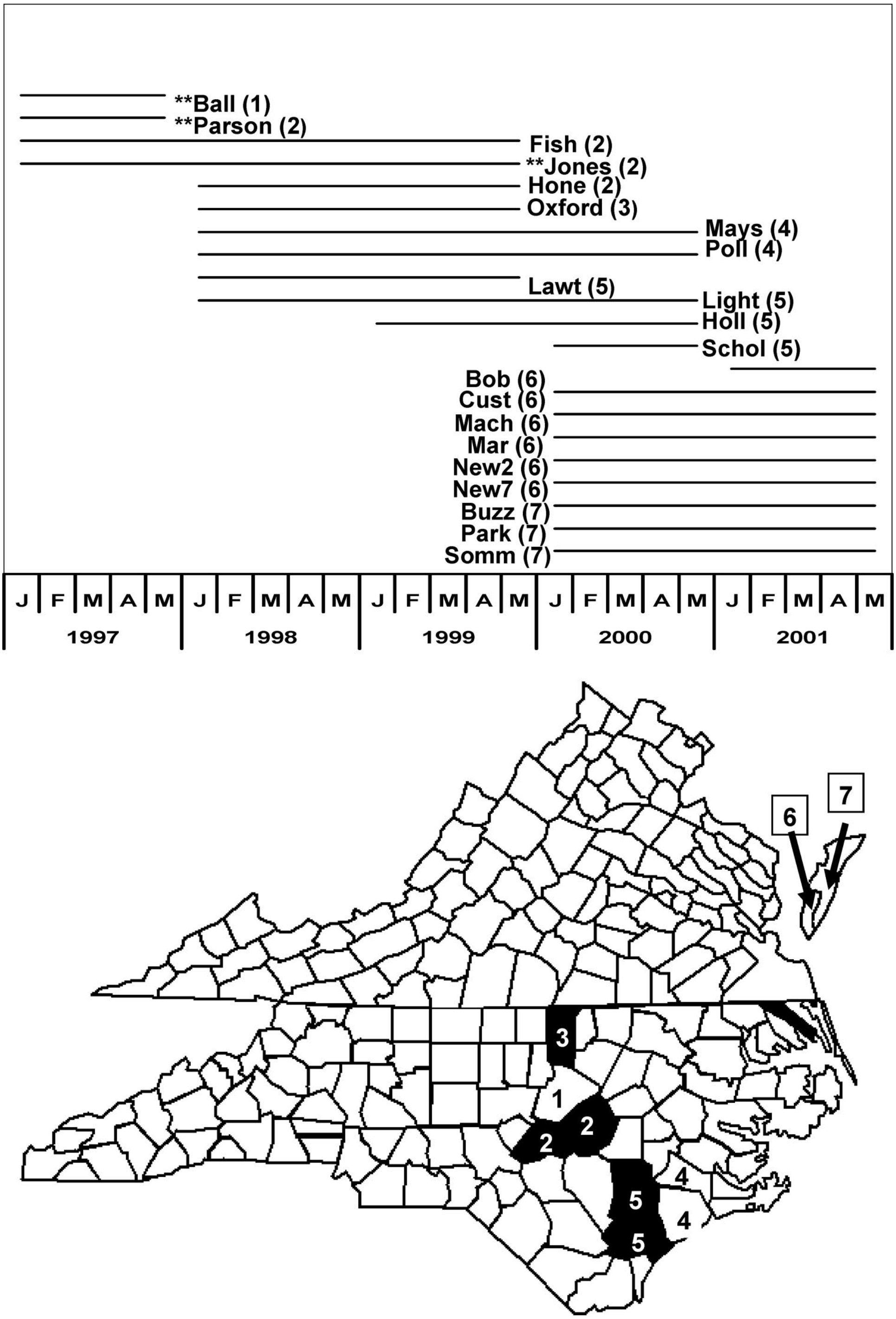

Fig. 1. Aerial trap collection intervals for the 21 sample sites and locations of the NOAA weather stations in central and eastern North Carolina and eastern Virginia. Value in parentheses corresponds to the position on the map. ***Thrips tabaci* was not collected at these sites.

Weather Data. All sites were assigned weather data based on proximity to the nearest National Oceanic and Atmospheric Administration (NOAA; http://cdo.ncdc.noaa.gov/dly/DLY) weather station (Table 1; Fig. 1). Daily degree-day data were estimated by averaging daily high and low temperature observations and subtracting the lower developmental threshold values of 10.5°C for *F. fusca* and

Table 1. NOAA weather stations and trapping intervals for all 21 collection sites

Station no.	State	County	Station name	Nearest city	Distance from station	Site no.	Sites	Year
1	NC	Wake	Raleigh State	Raleigh	9.0 mi S	1	Ball[a]	1997
2	NC	Johnston	Smithfield	Angier	14.2 mi W	2	Parson[a]	1997
2	NC	Johnston	Smithfield	Angier	17.2 mi W	3	Fish	1997–1999
2	NC	Johnston	Smithfield	Angier	13.0 mi W	4	Jones[a]	1997–1999
2	NC	Harnett	Smithfield	Angier	21.1 mi W	5	Hone	1998–1999
3	NC	Granville	Oxford AG	Oxford	<1.0 mi N	6	Oxford	1998–1999
4	NC	Onslow	Hofmann Forest	Maysville	<1.0 mi S	7	Mays	1998–2000
4	NC	Jones	Hofmann Forest	Pollocksville	5.1 mi N	8	Poll	1998–2000
5	NC	Duplin	Willard 4 SW	Wallace	12.3 mi E	9	Lawt	1998–1999
5	NC	Duplin	Willard 4 SW	Wallace	10.7 mi NE	10	Light	1998–2000
5	NC	Pender	Willard 4 SW	Wallace	12.8 mi E	11	Holl	1999–2000
5	NC	Duplin	Willard 4 SW	Wallace	12.0 mi NE	12	Shol	2000
6	VA	Accomack	Painter 2W	Melfa	1.0 mi NW	13	Bob	2001
6	VA	Accomack	Painter 2W	Melfa	6.0 mi SE	14	Cust	2000–2001
6	VA	Accomack	Painter 2W	Melfa	14.0 mi SE	15	Mach	2000–2001
6	VA	Accomack	Painter 2W	Melfa	1.8 mi SW	16	Mar	2000–2001
6	VA	Accomack	Painter 2W	Melfa	15.5 mi SE	17	New2	2000–2001
6	VA	Accomack	Painter 2W	Melfa	15.0 mi SE	18	New7	2000–2001
7	VA	Accomack	Wallops	Parksley	6 mi SW	19	Buzz	2000–2001
7	VA	Accomack	Wallops	Parksley	9 mi S	20	Park	2000–2001
7	VA	Accomack	Wallops	Parksley	6.5 mi SW	21	Somm	2000–2001

[a] *T. tabaci* was not collected at these sites.

11.5°C for *T. tabaci* (Edelson and Magaro 1988, Lowry et al. 1992).

$$\{(\text{Daily high T [°C]} + \text{Daily low T [°C]})/2\} - \text{Developmental Threshold (°C)} = \text{DD (for day)}$$

Degree-days were summed from 1 January through 10 May and from 1 January through 31 May each year at each weather station. The date 10 May was chosen because most spring planted crops at risk from *F. fusca* or TSWV are planted by this time and would be vulnerable to infestation and TSWV. Additionally, the number of dispersing *F. fusca* and *T. tabaci* would still be increasing. The date 31 May also was chosen because the majority of the spring dispersal of *F. fusca* has generally occurred in North Carolina (Groves et al. 2003). Recorded precipitation was summed as total precipitation and as the number of days with precipitation from 1 January through 10 May and from 1 January through 31 May. Total precipitation and the number of days with precipitation data were analyzed for correlation to determine whether both could be included as independent variables in a regression analysis with the total number of *F. fusca* and *T. tabaci* as the dependent variable using SAS for Windows (version 9.1; PROC CORR; SAS Institute 2005). No significant correlation was detected between total precipitation and the number of days with precipitation in data used for *F. fusca* and *T. tabaci* analyses ($r = 0.212, N = 44, P = 0.166$ and $r = 0.206, N = 29, P = 0.284$, respectively).

Regression Analysis. For each species on each sampling date, the total number of thrips was averaged across all traps located within a site. For each site, the number of *F. fusca* and *T. tabaci* captured between 1 April and 10 May and 1 April and 31 May were recorded. In some years and at some sites, *T. tabaci* were not identified or not collected; consequently, only 38 site-years of data (18 sites) were used in the analyses for *T. tabaci*. *Frankliniella fusca* were captured at all sites (21) in all years, resulting in 43 site-years of data, all of which were included in the analyses for *F. fusca*. Data on the total number of dispersing thrips were log-transformed, based on an inspection of residuals (SAS 9.1; PROC PLOT; SAS Institute 2005), to stabilize variance before stepwise regression. Stepwise regression (SAS 9.1; PROC REG; SAS Institute 2005) was used to test for relationships between the total number of *F. fusca* or *T. tabaci* captured between 1 April and 10 May and 1 April and 31 May and the independent variables degree-days, total precipitation, and the number of days with precipitation from 1 January to 10 May and 1 January to 31 May, respectively.

Results

Seasonal aerial trapping from 1997 through 2001 showed very little movement of both *F. fusca* and *T. tabaci* from January through March of each year (Fig. 2, A and B). During early April and May, movement increased for either *F. fusca* or *T. tabaci* and, on average, peaked between 10 and 31 May each year. The magnitude and the timing of the peak flights varied greatly among individual sites and years.

Frankliniella fusca. Seventy percent of the total variation in the number of *F. fusca* adults captured between 1 April and 10 May each year was explained by a regression model that included degree-days (DD), total precipitation (PRECIP), and the number of days with precipitation (DP) as independent variables ($F = 30.50$; df = 3, 40; $P = <0.001$; Table 2) in the following equation:

$$\text{Ln } F. fusca \text{ (1 April – 10 May) count} = 0.013(\text{DD}) - 0.045(\text{PRECIP}) + 0.060(\text{DP}) - 3.831$$

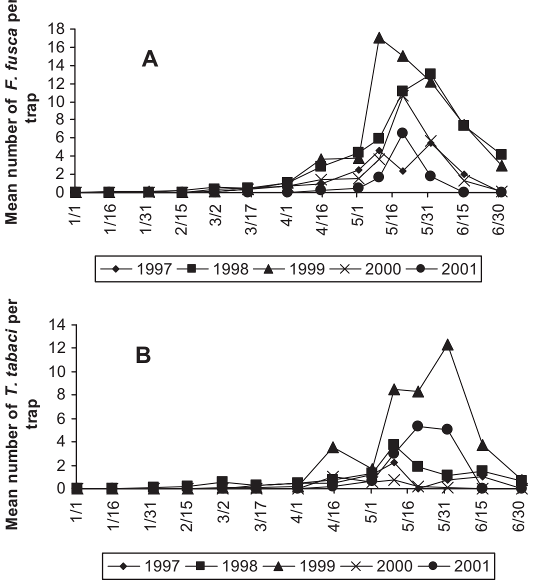

Fig. 2. Mean number of (A) *F. fusca* captured at each date over 21 field locations and (B) *T. tabaci* captured at each date over 18 field locations in central and eastern North Carolina and eastern Virginia from 1997 through 2001. Values are means across all sites within a year.

Degree-days alone accounted for 61% of the total variation, PRECIP explained an additional 5%, and DP explained the final 4%. The total number of *F. fusca* captured between 1 April and 10 May was positively related to DD and DP but negatively related to PRECIP from 1 January to 10 May.

Results for the number of *F. fusca* adults captured between 1 April and 31 May were similar to those captured between 1 April and 10 May except that the regression model explained only 55% of the total variation ($F = 16.39$; df = 3, 40; $P = <0.001$; Table 2). The estimated regression equation is as follows:

$$\text{Ln } F. fusca \text{ (1 April – 31 May) count} = 0.007(\text{DD}) - 0.034(\text{PRECIP}) + 0.040(\text{DP}) - 1.531$$

Degree-days alone accounted for 46% of the total variation, PRECIP explained an additional 5%, and DP explained the final 4%. The total number of *F. fusca* captured between 1 April and 31 May was positively related to total DD and DP but negatively related to PRECIP from 1 January to 31 May.

Thrips tabaci. Fifty-seven percent of the total variation in the number of *T. tabaci* adults captured between 1 April and 10 May each year was explained by a regression model that included DD, PRECIP, and DP as independent variables ($F = 10.42$; df = 3, 24; $P = <0.001$; Table 3) in the following equation:

$$\text{Ln } T. tabaci \text{ (1 April – 10 May) count} = 0.010(\text{DD}) + 0.160(\text{DP}) - 0.061(\text{PRECIP}) - 6.239$$

Degree-days alone accounted for 22% of the total variation, DP explained an additional 13%, and PRECIP explained the final 21%. The total number of *T. tabaci* captured between 1 April and 10 May was positively related to total DD and DP but negatively related to PRECIP from 1 January to 10 May.

Results for the number of *T. tabaci* adults captured between 1 April and 31 May from 38 site-years of data were similar to those captured between 1 April and 10 May, except now the regression model explained 63% of the total variation ($F = 14.42$; df = 3, 25; $P = <0.001$; Table 3). The estimated regression equation is as follows:

$$\text{Ln } T. tabaci \text{ (1 April – 31 May) count} = 0.010(\text{DD}) - 0.088(\text{PRECIP}) + 0.114(\text{DP}) - 3.999$$

Degree-days alone accounted for 19% of the total variation, PRECIP explained an additional 29%, and DP explained the final 15%. The total number of *T. tabaci* captured between 1 April and 31 May was positively related to total DD and DP but negatively related to PRECIP from 1 January to 31 May.

Discussion

In our study from 1997 to 2001, the numbers of dispersing *F. fusca* and *T. tabaci* caught on yellow sticky traps in spring peaked, on average, between 10 and 31 May each year (Fig. 2, A and B). This is consistent with previous surveys that have described thrips populations as smaller during the winter, increasing rapidly with large peak flights during the spring, followed by an abrupt decline in numbers associated with senescence of winter hosts (Davidson

Table 2. Regression statistics for populations of *F. fusca* related to degree-days (DD), total precipitation (PRECIP), and days with precipitation (DP)

Species	Capture interval	Variable	Parameter	Estimate	SE	*F* value	*P* value	Partial R^2	Model R^2
F. fusca	1 April to 10 May		Intercept	−3.831	1.065	12.94	<0.001	—	—
		DD	B_1	0.013	0.001	82.05	<0.001	0.607	—
		PRECIP	B_2	−0.045	0.014	10.22	0.003	0.047	—
		DP	B_3	0.060	0.025	5.58	0.023	0.042	—
		Full model		—	—	30.50	<0.001	—	0.696
F. fusca	1 April to 31 May		Intercept	−1.531	1.167	1.72	0.197	—	—
		DD	B_1	0.007	0.001	44.66	<0.001	0.464	—
		PRECIP	B_2	−0.034	0.013	7.27	0.010	0.051	—
		DP	B_3	0.040	0.022	3.29	0.077	0.037	—
		Full model		—	—	16.39	<0.001	—	0.552

Table 3. Regression statistics for populations of *T. tabaci* related to degree-days (DD), total precipitation (PRECIP), and days with precipitation (DP)

Species	Capture interval	Variable	Parameter	Estimate	SE	*F* value	*P* value	Partial R^2	Model R^2
T. tabaci	1 April to 10 May		Intercept	−6.239	1.605	15.11	<0.001	—	—
		DD	B_1	0.010	0.002	22.75	<0.001	0.224	—
		DP	B_2	0.160	0.041	15.32	<0.001	0.132	—
		PRECIP	B_3	−0.061	0.018	11.58	0.002	0.210	—
		Full model		—	—	10.42	<0.001	—	0.566
T. tabaci	1 April to 31 May		Intercept	−3.999	1.850	4.67	0.0405	—	—
		DD	B_1	0.010	0.002	39.28	<0.0001	0.193	—
		PRECIP	B_2	−0.088	0.016	29.01	<0.0001	0.295	—
		DP	B_3	0.114	0.036	9.95	0.0042	0.146	—
		Full model		—	—	14.42	<0.0001	—	0.634

and Andrewartha 1948b, Andrewartha and Birch 1954, North and Shelton 1986 a, b, Shelton and North 1986, McPherson et al. 1992, DuRant et al. 1994, Cho et al. 1995, Eckel et al. 1996, Gitaitis et al. 1998, Moriones et al. 1998, Groves et al. 2003).

The varying number of thrips captured on yellow sticky traps throughout the spring season is, no doubt, influenced by many factors beyond weather, including trap attractiveness relative to surrounding vegetation, host plant composition, thrips population size and proportion of the population that is dispersing, behavior, and agricultural practices. However, long-term weather variables are able to explain a majority of the year to year and location to location variation observed in spring trap catches spanning nearly 300 miles from north to south and 150 miles from west to east over a 5-yr period in Virginia and North Carolina, despite of the collective impact of any other factors.

Regression analyses determined that temperature, measured as degree-days accumulated from 1 January, was the single most influential factor positively affecting *F. fusca* and *T. tabaci* populations. Presumably, increasing temperatures in the spring influenced both thrips population growth rate and the suitability of their winter annual host plants by affecting when the plants senesce. Degree-days accumulated between 1 January and 10 May explained 61% of the variation about the total number of *F. fusca* captured between 1 April and 10 May. When the trapping interval was extended to 31 May, degree-days was still the single best explanatory variable, explaining 46% of the total variation in *F. fusca* captures. The 15% reduction in explanatory power reflects the fact that degree-days continued to accumulate throughout the period of analysis, but in some years and locations, thrips trap catches peaked and began to declined before 31 May; therefore, the power of cumulative degree-days to estimate the total number of adult *F. fusca* declines after the population peaks. Although degree-days summed from 1 January was also the best explanatory variable for the number of *T. tabaci* captured between 1 April and 10 May and 1 April and 31 May, it explained only 22 and 19%, respectively. Part of the disparity between the power of degree-days to explain variation in captures of dispersing *F. fusca* and *T. tabaci* in spring may result from differences in the host plant preferences of these two species. Groves et al. (2002) observed that spring dispersal of *T. tabaci* in eastern North Carolina occurred over a longer period of time and extended later into the spring than was the case for *F. fusca.* Moreover, reproducing populations of *T. tabaci* occurred on fewer plant species than *F. fusca,* with the majority of immature *T. tabaci* collected from biennial or perennial plant species that are less likely to senesce in response to increasing springtime temperatures than winter annual species, which are the predominant winter and spring hosts of *F. fusca.* Therefore, to the extent that yellow sticky trap catches reflect the size of the dispersing thrips population, it is possible that the observed effect of temperature on spring dispersal of *T. tabaci* primarily reflects the direct effect of temperature on population growth rate, whereas the effect of temperature on *F. fusca* reflects not only its influence on population growth rate but also a strong effect on the timing of host plant senescence.

In these models, both the amount and frequency of precipitation were important. The total number of *F. fusca* and *T. tabaci* captured were negatively affected by total precipitation but positively affected by the number of days with precipitation. We expected these results based on previous studies. Hard or prolonged precipitation events can kill young thrips larvae and depress the population (Kirk 1997), as well as suppress dispersal of adult thrips (Lewis 1963). In contrast, precipitation can promote plant growth and delay senescence of winter hosts, allowing for increased production of thrips over a longer period (S.C.M. and G.G.K., unpublished data).

Precipitation had a relatively greater effect on *T. tabaci* than *F. fusca.* The combined effects of total precipitation and the number of days with precipitation accounted for only 9% of the total variation in the *F. fusca* models versus 34–44% of the total variation explained by the *T. tabaci* models. After accounting for the effect of degree-days in both *F. fusca* models, total precipitation and the number of days with precipitation accounted for an additional 5 and 4% of the total variation, respectively. After accounting for the effect of degree-days in the regression model for the total number of *T. tabaci* captured between 1 April and 10 May, the number of days with precipitation explained an additional 13% and total precipitation explained the final 21% of the total variation. In the regression model for the total number of *T. tabaci* captured between 1 April and 31 May, total precipitation explained an additional 29%, and the number of days with precipitation explained the final 15% of the total variation, after accounting for the effect of degree-days.

Temperature and precipitation have varying effects on thrips populations. With increasing temperature throughout the spring, there is increased thrips activity, development, and population growth up to the point when winter hosts begin to senesce and thrips flights decline (Lowry et al. 1992, Lewis 1997, Kirk 1997). Dry weather favors thrips population growth (Bailey 1933, 1934, 1944, Fennah 1965, Evans 1967). Franssen and Huisman (1958) reported that infestations of *Thrips angusticeps* Uzel during rainy and cool seasons were significantly lower than those during dry and hot seasons, presumably because of high larval mortality and slower population growth rates (Kirk 1997). Warm temperatures may be required before thrips flight can occur. Lewis (1963) described a temperature threshold for take-off by *Limothrips cerealium* (Haliday) that was above their developmental threshold. In this situation, large populations of thrips can develop during spring while temperatures fluctuate between developmental and flight thresholds. Once temperature increases above the flight threshold, thrips dispersal may occur en masse. However, direct rain or heavy dew can prevent thrips take-off as their wing setae become saturated (Kirk 1997), despite conducive temperatures for flight. Thrips populations tend to recover slowly after rain events because of high larval mortality, but adults and late stage juveniles, after maturity, will ultimately fly when environmental conditions become favorable again (Cho et al. 1989, Kirk 1997, Lewis 1997, Groves et al. 2001). As suggested by our models, a portion of the negative effect of precipitation can be offset by the positive effects on host plants, including delayed senescence of winter hosts, enabling them to provide a suitable habitat for thrips growth and reproduction over a longer period.

Groves et al. (2003) previously reported temporal similarities between the numbers of dispersing *F. fusca* caught on yellow sticky traps and the spread of TSWV in eastern North Carolina. Our results showing that temperature and precipitation variables account for 55 and 63% of the variation in the total number of dispersing *F. fusca* and *T. tabaci* caught on yellow sticky traps in spring suggests that it may be possible to develop weather-based models to predict the near-term risk of thrips flights and TSWV, although additional research is needed. Because our analyses indicate that specific weather variables affect thrips species differently, species-specific models that include degree-days, amount of rainfall, the number of rainfall events, and perhaps other variables would have to be developed. Weather-based models based on the work of Davidson and Andrewartha (1948a, 1948b) and incorporating a more complex set of weather variables have been used with success as part of an early-warning system to predict damaging populations of thrips in apples in the Adelaide Hills area of Australia (Kirk 1997).

Acknowledgments

Assistance with statistical analyses by C. Brownie (Department of Statistics, North Carolina State University) was greatly appreciated. This work was supported, in part, by the E. G. Moss and Phillip Morris Foundations and grants from the North Carolina Tobacco Research Commission and USDA Southern Regional IPM Program.

References Cited

Andrewartha, H. G., and L. C. Birch. 1954. The distribution and abundance of animals. University Chicago Press, Chicago, IL.

Bailey, S. F. 1933. The biology of the bean thrips. Hilgardia 7: 467–522.

Bailey, S. F. 1934. A winter study of the onion thrips in California. CADA Bull. 23: 149–152.

Bailey, S. F. 1944. The pear thrips in California. University of California, College of Agriculture, Agricultural Exp. Station Bull. 687.

Barbour, J. D., and R. L. Brandenburg. 1994. Vernal infusion of thrips into North Carolina peanut fields. J. Econ. Entomol. 87: 446–451.

Brecke, B. J., J. E. Funderburk, I. D. Teare, and D. W. Gorbet. 1996. Interaction of early-season herbicide injury, tobacco thrips injury, and cultivar on peanut. Agron. J. 88: 14–18.

Broadbent, A. B., W. R. Allen, and R. G. Foottit. 1987. The association of *Frankliniella occidentalis* (Pergrande) (Thysanoptera: Thripidae) with greenhouse crops and the tomato spotted wilt virus in Ontario. Can. Entomol. 119: 501–503.

Cabrera-LaRosa J. C., and G. G. Kennedy. 2007. *Thrips tabaci* and tomato spotted wilt virus: inheritance of vector competence. Entomol. Exp. Appl. 124: 161–166.

Chamberlin, J. R., J. W. Todd, R. J. Beshear, A. K. Culbreath, and J. W. Demski. 1992. Overwintering hosts and wingform of thrips, *Frankliniella* spp., in Georgia (Thysanoptera: Thripidae): implications for management of spotted wilt disease. Environ. Entomol. 21: 121–128.

Chatzivassiliou, E. K., T. Nagata, N. I. Katis, and D. Peters. 1999. Transmission of tomato spotted wilt tospovirus by *Thrips tabaci* populations originating from leek. Plant Pathol. 48: 700–706.

Chatzivassiliou, E. K., D. Peters, and N. I. Katis. 2002. The efficiency by which *Thrips tabaci* populations transmit *Tomato spotted wilt virus* depends on their host preference and reproductive strategy. Phytopathology 92: 603–609.

Cho, J. J., R.F.L. Mau, T. L. German, R. W. Hartmann, L. S. Yudin, D. Gonsalves, and R. Provvidenti. 1989. A multidisciplinary approach to management of tomato spotted wilt virus in Hawaii. Plant Dis. 73: 375–383.

Cho, K., C. S. Eckel, J. F. Walgenbach, and G. G. Kennedy. 1995. Overwintering of thrips (Thysanoptera: Thripidae) in North Carolina. Environ. Entomol. 24: 58–67.

Davidson, J., and H. G. Andrewartha. 1948a. Annual trends in a natural population of *Thrips imaginis* (Thysanoptera). J. Anim. Ecol. 17: 193–199.

Davidson, J., and H. G. Andrewartha. 1948b. The influence of rainfall, evaporation and atmospheric temperature on fluctuations in the size of a natural population of *Thrips imaginis* (Thysanoptera). J. Anim. Ecol. 17: 200–222.

DuRant, J. A., M. E. Roof, and C. L. Cole. 1994. Early season incidence of thrips (Thysanoptera) on wheat, cotton, and three wild host plant species in South Carolina. J. Agric. Entomol. 11: 61–71.

Eckel, C. S., K. Cho, J. F. Walgenbach, G. G. Kennedy, and J. W. Moyer. 1996. Variation in thrips species composition in field crops and implications for tomato spotted wilt epidemiology in North Carolina. Entomol. Exp. Appl. 78: 19–29.

Edelson, J. V., and J. J. Magaro. 1988. Development of onion thrips, *Thrips tabaci* Lindeman, as a function of temperature. Southwest. Entomol. 13: 171–176.

Evans, D. E. 1967. Insecticide field trials against the coffee thrips (*Diarthrothrips coffeae* Williams) in Kenya. Turrialba 17: 376–380.

Fennah, R. G. 1965. The influence of environmental stress on the cacao tree in predetermining the feeding sites of the cacao thrips, Selenothrips rubrocinctus (Giard) on leaves and pods. Bull Entomol. Res. 56: 333–349.

Franssen, C.J.H., and P. Huisman. 1958. The biology and control of *Thrips angusticeps* Uzel. (In Dutch.) Verslagen Landbouwkundige Onderzoekingen 64: 1–104.

Garcia, L. E., R. L. Brandenburg, and J. E. Bailey. 2000. Incidence of tomato spotted wilt virus (Bunyaviridae) and tobacco thrips in Virginia-type peanuts in North Carolina. Plant Dis. 84: 459–464.

German, T. L., D. E. Ullman, and J. W. Moyer. 1992. Tospoviruses: diagnosis, molecular biology, phylogeny, and vector relationships. Annu. Rev. Phytopathol. 30: 315–348.

Gitaitis, R. D., C. C. Dowler, and R. B. Chalfant. 1998. Epidemiology of tomato spotted wilt in pepper and tomato in southern Georgia. Plant Dis. 82: 752–756.

Groves, R. L., J. F. Walgenbach, J. W. Moyer, and G. G. Kennedy. 2001. Overwintering of *Frankliniella fusca* (Thysanoptera: Thripidae) on winter annual weeds infested with tomato spotted wilt virus and patterns of virus movement between susceptible hosts. Phytopathology 91: 891–899.

Groves, R. L., J. F. Walgenbach, J. W. Moyer, and G. G. Kennedy. 2002. The role of weed hosts and tobacco thrips, *Frankliniella fusca*, in the epidemiology of tomato spotted wilt virus. Plant Dis. 86: 573–582.

Groves, R. L., J. F. Walgenbach, J. W. Moyer, and G. G. Kennedy. 2003. Seasonal dispersal patterns of *Frankliniella fusca* (Thysanoptera: Thripidae) and tomato spotted wilt virus occurrence in central and eastern North Carolina. J. Econ. Entomol. 96: 1–11.

Hobbs, H. A., L. L. Black, R. N. Story, R. A. Valverde, W. P. Bond, J. M. Gratti Jr., D. O. Schaeffer, and R. R. Johnson. 1993. Transmission of tomato spotted wilt virus from pepper and three weed hosts by *Frankliniella fusca.* Plant Dis. 77: 797–799.

Kahn, N. D., J. F. Walgenbach, and G. G. Kennedy. 2005. Summer weeds as hosts for *Frankliniella occidentalis* and *Frankliniella fusca* (Thysanoptera: Thripidae) and as reservoirs for tomato spotted wilt tospovirus in North Carolina. J. Econ. Entomol. 98: 1810–1815.

Kirk, W.D.J. 1997. Distribution, abundance and population dynamics. *In* T. Lewis (ed.), Thrips as crop pests. CAB, Oxon, United Kingdom, pp. 217–257.

Lewis, T. 1963. The effect of weather on emergence and take-off of overwintering *Limothrips cerealium* Haliday (Thysanoptera). Ann. Appl. Biol. 51: 489–502.

Lewis, T. 1997. Flight and dispersal. *In* T. Lewis (ed.), Thrips as crop pests. CAB, Oxon, United Kingdom, pp. 175–196.

Logan, J. A., D. J. Wolkind, S. C. Hoyt, and L. K. Tanigoshi. 1976. An analytical model for description of temperature dependent rate phenomena in arthropods. Environ. Entomol. 5: 1130–1140.

Lowry, V. K., J. W. Smith, and F. L. Mitchell. 1992. Life-fertility tables for *Frankliniella fusca* (Hinds) and *F. occidentalis* (Pergande) (Thysanoptera: Thripidae) on peanut. Ann. Entomol. Soc. Am. 85: 744–754.

McPherson, R. M., and R. J. Beshear. 1990. Thrips fauna in Georgia flue-cured tobacco plant beds and fields. J. Entomol. Sci. 25: 559–561.

McPherson, R. M., R. J. Beshear, and A. K. Culbreath. 1992. Seasonal abundance of thrips (Thysanoptera: Suborders Terebrantia and Tubulifera) in Georgia flue-cured tobacco and impact of management on the incidence of tomato spotted wilt virus. J. Entomol. Sci. 27: 257–268.

McPherson, R. M., H. R. Pappu, and D. C. Jones. 1999. Occurrence of five thrips species on flue-cured tobacco and impact on spotted wilt disease incidence in Georgia. Plant Dis. 83: 765–767.

Morgan, L. W., J. W. Snow, and M. J. Peach. 1970. Chemical thrips control; effects on growth and yield of peanuts in Georgia. J. Econ. Entomol. 63: 1253–1255.

Moriones, E., J. Aramburu, J. Riudavats, J. Arno, and A. Lavina. 1998. Effect of plant age at time of infection by tomato spotted wilt tospovirus on the yield of field-grown tomato. Eur. J. Plant Pathol. 104: 295–300.

Nault, B. A., and J. Speese, III. 2002. Major insect pests and economics of fresh-market tomato in eastern Virginia. Crop Prot. 21: 359–366.

Nault, B. A., J. Speese, III, D. Jolly, and R. L. Groves. 2003. Seasonal patterns of adult thrips dispersal and implications for management in eastern Virginia tomato fields. Crop Prot. 22: 505–512.

North, R. C., and A. M. Shelton. 1986a. Colonization and intraplant distribution of *Thrips tabaci* (Thysanoptera: Thripidae) on cabbage. J. Econ. Entomol. 79: 219–223.

North, R. C., and A. M. Shelton. 1986b. Ecology of Thysanoptera within cabbage fields. Environ. Entomol. 15: 520–526.

Palmer, J. M., L. A. Mound, and G. J. du Haeume. 1992. IIE guides to insects of importance to man, vol. 2. Thysanoptera *In* C. R. Betts (ed.), International Institute of Entomology. CAB International, Wallingford, United Kingdom, 73 pp.

Prins, M., and R. Goldbach. 1998. The emerging problem of Tospovirus infection and nonconventional methods of control. Trends Microbiol. 6: 31–35.

Salguero Navas, V. E., J. E. Funderburk, R. J. Beshear, S. M. Olson, and T. P. Mack. 1991. Seasonal patterns of *Frankliniella* spp. (Thysanoptera: Thripidae) in tomato flowers. J. Econ. Entomol. 84: 1818–1822.

SAS Institute. 2005. SAS 9.1.3 intelligence platform: single-user installation guide. SAS Institute, Cary, NC.

Shelton, A. M., and R. C. North. 1986. Species composition and phenology of Thysanoptera within field crops adjacent to cabbage fields. Environ. Entomol. 15: 513–519.

Wells, M. L., A. K. Culbreath, J. W. Todd, A. S. Csinos, B. Mandal, and R. M. McPherson. 2002. Dynamics of spring tobacco thrips (Thysanoptera: Thripidae) populations: implications for tomato spotted wilt virus management. Environ. Entomol. 31: 1282–1290.

Wijkamp, I., N. Almazara, R. Goldbach, and D. Peters. 1995. Distinct levels of specificity in thrips transmission of tospoviruses. Phytopathology 85: 1069–1074.

Received for publication 5 April 2007; accepted 11 September 2007.