Tactics for Management of Thrips (Thysanoptera: Thripidae) and Tomato Spotted Wilt Virus in Tomato

D. G. RILEY[1] AND H. R. PAPPU[2]

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ABSTRACT Four studies were conducted in Georgia during spring 1999, 2000, 2001, and 2002 to evaluate various management tactics for reducing thrips and thrips-vectored tomato spotted wilt virus (TSWV) in tomato and their interactions relative to fruit yield. Populations of thrips vectors of TSWV, *Frankliniella occidentalis* (Pergande) and *Frankliniella fusca* (Hinds), were determined using flower and sticky trap samples. The management practices evaluated were host plant resistance, insecticide treatments, and silver or metallic reflective mulch. Averaged over all tests, the TSWV-resistant tomato 'BHN444' on silver mulch treatment had the largest effect in terms of reducing thrips and spotted wilt and increasing marketable yield. Of the insecticide treatments tested, the imidacloprid soil treatment followed by early applications of a thrips-effective foliar insecticide treatment provided significant increase in yield over other treatments. Tomato yield was negatively correlated with the number of *F. fusca* and percentage of TSWV incidence. *F. occidentalis* per blossom was positively correlated with percentage of TSWV incidence, but not with yield. No significant interactions were observed between cultivar reflective mulch main plot treatments and insecticide subplot treatments; thus, treatment seemed to be additive in reducing the economic impact of thrips-vectored TSWV. Control tactics that manage thrips early in the growing season significantly increased tomato yield in years when the incidence of TSWV was high (>17%).

KEY WORDS *Frankliniella occidentalis*, *Frankliniella fusca*, Bunyaviridae, *Tospovirus*, host plant resistance

THRIPS-VECTORED TOMATO SPOTTED wilt virus (TSWV), of the genus *Tospovirus* (Family Bunyaviridae), is a serious disease of tomato, *Lycopersicon esculentum* Mill. (Peters and Goldbach 1995, Moyer 2000). In Georgia, TSWV has reduced yields by an estimated $8.8 million in a single year in 2000 (Riley 2000). In the Georgia tomato crop, TSWV is primarily transmitted by western flower thrips, *Frankliniella occidentalis* (Pergande), and tobacco thrips, *Frankliniella fusca* (Hinds) (Salguero Navas et al. 1991, Riley and Pappu 2000). Tobacco thrips have been found to be more prevalent than western flower thrips on preflowering tomato in Georgia (Joost and Riley 2004). Management of the thrips vector can be difficult because immature thrips can acquire TSWV from infected weed host plants surrounding vegetable fields (Groves et al. 2001b). Also, because the virus replicates in the vector as it matures, viruliferous adults can quickly spread the virus when they move into the field before thrips can be controlled (Ullman et al. 1997). However, some success in control tactics for thrips vectors has been documented (Riley and Pappu 2000, Riley 2001b). Some of the primary control tactics available in tomato include the use of reflective plastic mulch (Greenough et al. 1990, Stavisky et al. 2002, Reitz et al. 2003), host plant resistance to the virus (Kumar et al. 1993, 1995), and insecticides combined with other tactics (Brown and Brown 1992, Riley and Pappu 2000). We initiated the simultaneous evaluation of multiple control tactics for thrips and tomato spotted wilt management in tomato (Riley and Pappu 2000), but several improvements in commercially available materials have occurred since that time, specifically the release of TSWV-resistant tomatoes 'BHN-444', 'BHN-555', and 'BHN-640' (BHN Research Inc., Bonita Springs, FL) and the metallic reflective plastic mulch RepelGro (ReflecTec Foils Inc., Lake Zurich, IL). We investigated host plant resistance, early season insecticides, and reflective mulch for developing an integrated management program for TSWV in tomato. The objective was to determine the impact of various levels of insecticide treatment, reflective plastic mulch, and host plant resistance in combination with reflective plastic mulch for managing thrips and TSWV in tomatoes. We also investigated interactions between certain control tactics using a split plot experimental design.

[1] Department of Entomology, University of Georgia, Coastal Plain Experiment Station, Tifton, GA 31793.
[2] Department of Plant Pathology, P.O. Box 646430, Washington State University, Pullman, WA 99164–6430.

Materials and Methods

The first study was conducted in 1999 at the Coastal Plain Experiment Station, Tifton, GA, to simultaneously evaluate different early season insecticide treatment programs, a TSWV-resistant tomato cultivar, and a reflective plastic mulch. The tomato production system used was raised, black plastic covered beds fumigated with methyl bromide (277 kg [AI]/ha, Albemarle Corp., Magnolia, AK) with plants staked and tied at 0.6-m spacing in a single row with single buffer rows between plots. Insecticide efficacy studies in tomato by using single rows have provided significant treatment differences (Riley 2001a). Tomatoes were transplanted on 31 March. A split plot design with four replicates was used. The three main plots (12 by 19.8 m) were 1) 'Sunny Hybrid' (TSWV-susceptible hybrid, Asgrow Seed Company, Tifton, GA) on black plastic mulch (1.25 mil, North American Film, Philadelphia, PA); 2) 'Sunny Hybrid' on silvered mulch (black plastic painted with silver-aluminum paint, Super Brite, Sherwin Williams, Cleveland, OH); and 3) 'BHN444' (TSWV-resistant variety, BHN Research Inc., Bonita Springs, FL) planted on silvered mulch. The subplot size was 12 m of row on a 1.8-m-wide plastic bed, flanked by 1.8-m-wide bare ground rows on either side. The subplots consisted of a range of treatment dates for insecticide as follows: 1) untreated; 2) imidacloprid (Admire 2F, Bayer CropScience, Kansas City, KS) @ 0.067 ml in 104 ml of water per plant based on 4,356 plants per 0.405 hectare [acre] at transplant) drench at transplant plus 1 wk of foliar sprays; 3) imidacloprid drench plus 2 wks of foliar sprays; 4) imidacloprid drench plus 4 wk of foliar sprays; and 5) imidacloprid drench plus 8 wk of foliar sprays. Imidacloprid treatment alone evaluated in a previous trial did not provide adequate control of TSWV in tomato (D.G.R., unpublished data). The foliar insecticide treatment consisted of a spray treatment of methamidophos (Monitor 4, Valent U.S.A. Corporation, Walnut Creek, CA) at 0.84 kg (AI)/ha plus lambda-cyhalothrin (Warrior 1 EC, Syngenta, Greensboro, NC) at 0.017 kg (AI)/ha on Monday and spinosad (Spintor 2 SC, Dow Agro Sciences, Indianapolis, IN) at 0.1 kg ([AI])/ha on Friday of each week of spray. The dates of application were weekly beginning on 2 April and ending on 25 May 1999. In this and other tests, tomatoes were treated weekly in April and May with a fungicide (Ridomil Gold-Bravo WP 2.2 kg product/ha, Syngenta) and *Bacillus thuriengensis* (DiPel 2.2 kg product/ha, Valent U.S.A. Corporation) to prevent disease and reduce lepidopteran damage without affecting thrips populations. Tomatoes were harvested from the center 10 plants per plot on 4 and 21 June and graded using USDA standards plus an evaluation of TSWV damage. Also, a subsample of 10 fruit of each grade size of marketable fruit from each plot was held in paper bags for 1 wk, and the percentage of TSWV-irregular ripened fruit, completely regularly ripened fruit, and green-to-pink ripe fruit were recorded. Reported yields were based on the number of fruit of marketable appearance at the time of harvest, because the method used for evaluating irregular ripening provided only a relative estimate. Fruit from plants with severe TSWV infection (wilted) and fruit with visible signs of TSWV at harvest were not included in the marketable fruit category.

In 2000, a repeat of the 1999 test was done at the same location but with an increase in the number of replicates to six. Tomatoes were transplanted on 13 March and the treatments were the same as in 1999. The dates of spray applications were weekly beginning on 14 March and ending on 9 May 2000. Tomatoes were harvested from the center 10 plants per plot on 30 May and 5 and 12 June 2000 with the same restrictions as in 1999. Also, a subsample of 10 fruit from medium, large, and extra-large grade sizes of fruit from each plot was held in paper bags for 1 wk and the percentage of TSWV-irregular ripened fruit, completely regularly ripened fruit, and green-to-pink ripe fruit were recorded.

In 2001, six replicates were used with slight modifications in the treatment regimes. First, the silvered (painted) plastic mulch was replaced with a metallic reflective mulch (Repelgro-Full Reflective, ReflecTek Foils Inc., Lake Zurich, IL, similar to Clarke Ag Plastics, silver on black, Greenwood, VA), which has more reflectance and greater soil root-zone warming effect than the painted plastic (Diaz-Perez and Batal 2002). Second, the 8-wk spray treatment was eliminated and a 3-wk spray treatment was added, so that insecticides were applied for either 1-, 2-, 3-, or 4-wk programs. Tomatoes were transplanted on 23 March in replicates 1, 2, and 3 at the Lang Farm and on 2 April in replicates 4, 5, and 6 at the Hort Hill Farm, both in Tift County. The dates of spray applications for the Lang and Hort-Hill Farms, were 26 March, 5, 12, and 19 April, and 2, 9, 15, and 23 April, respectively. Imidacloprid drenches were applied at transplant at each location as described previously. Tomatoes were harvested from 10 plants per plot on 13 and 18 June 2001, the same restrictions as in 1999.

In 2002, four replicates of only four treatments were evaluated in a randomized complete block design. The treatments applied to tomato 'Sunoma' (TSWV-susceptible Roma-type hybrid, Seminis Vegetable Seeds Inc., Tifton, GA) were 1) black plastic mulch (1.25 mil, North American Film), 2) metallic reflective mulch (Repelgro-Full Reflective), 3) heat-trap, metallic reflective mulch with a black strip down the middle (Repelgro-Heat Trap I), and 4) the same black plastic mulch as treatment 1 plus imidacloprid drench plus four weekly foliar sprays of methamidophos (Monitor 4) at 0.84 kg (AI)/ha plus lambda-cyhalothrin (Karate 1 EC) at 0.017 kg (AI)/ha applied weekly. The size of the plastic-mulched plot was two 1.8-m-wide beds by 15.2-m-length. Tomatoes were transplanted on 25 March at the Lang Farm, Tift County, and harvested in a single harvest of all fruit from five plants in the center of the plot on 13 June 2002 regardless of TSWV infection. This was done to assess total impact on yield.

A single, fully expanded terminal leaflet was randomly collected from the top one-third of each of three plants in 1999 and six plants in 2000–2002 from each subplot to detect TSWV with enzyme-linked immunosorbant assay (ELISA) by using a TSWV detection kit (Agdia Inc., Elkhart, IN). The number of

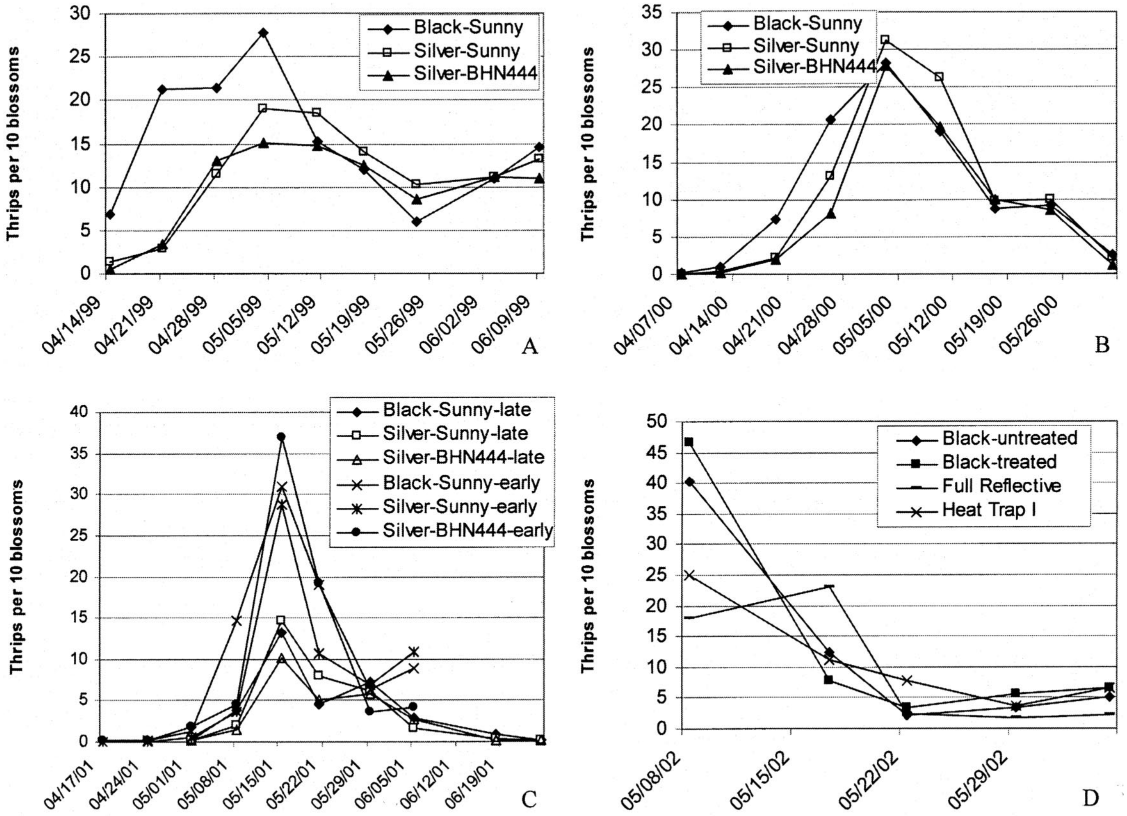

Fig. 1. Vector thrips (*F. occidentalis* and *F. fusca*) per main plot treatment per 10 tomato blossoms by date at Tifton, GA, in 1999 (A), 2000 (B), and 2001 (C).

samples was increased in 2000–2002 to improve sampling precision. A sample was deemed positive for TSWV if the absorbance reading was 3 times the value of a known uninfected sample. Disease incidence was monitored in 1999 by ranking plots in terms of number of plants with no TSWV symptoms, slight leaf symptoms, slight stunting, severe stunting and dead plants at preharvest on 2 June. Also, leaf samples for an ELISA for TSWV were taken on 13 and 19 May and 2 and 10 June from each plot ($n = 60$ per date). In 2000, samples were randomly collected and tested from each plot on 6, 12, 20, and 25 April, 8, 17, and 26 May, and 2 and 6 June from each plot ($n = 90$ per date). In 2001, samples were taken from individual plots on 22 and 29 May and 7 and 13 June for an ELISA for TSWV. In 2002, TSWV incidence was rated as described above at harvest.

For all 4 yr, the total number of thrips by species was determined using a sample of 10 blossoms per plot, one blossom per plant, which was randomly collected and placed into a vial with a 50% ethanol solution per plot on a weekly basis. Adult thrips in the blossom samples were identified using identification keys (Stannard 1968, Oetting et al. 1993) under 70–140× magnification by using a SZH10 Olympus (Olympus America, Lake Success, NY) stereomicroscope. In the 1999 blossom samples, only *F. occidentallis* and *F. fusca* were individually counted and all other thrips, including *Frankliniella tritici* (Fitch), *Frankliniella bispinosa* (Morgan), and others were placed into an "other" category. In 2000 and 2001, *F. tritici* and *F. bispinosa* also were counted from slide mounts. From all samples a subset of thrips was slide mounted for voucher specimens. Key characters were used to verify species, including the anteromarginal and anteroangular setae, postocular setae, the pedicel of the third antennal segment, comb on abdominal tergite VIII, and other features (Stannard 1968). Other insects were monitored in the trial, but the incidence of other insect pest species was low.

Yield was assessed on the center 10 plants per subplot by quantifying fruit in various damage categories and marketable categories by size at the time of harvest by using USDA standards for fresh market tomato (http://www.ams.usda.gov/standards/tomatfrh.pdf). The exception to this was the 2002 evaluation of Roma-type tomatoes where the fruit were rated only as marketable (good shape, size and no apparent damage) or unmarketable (insect or disease damaged). Insect damage to the fruit consisted of thrips dimpling of fruit, which was considered still marketable if the fruit had acceptable shape and color, and lepdidopteran-damaged fruit, which was negligible in these tests. Physiological fruit damage, blotchy colored fruit,

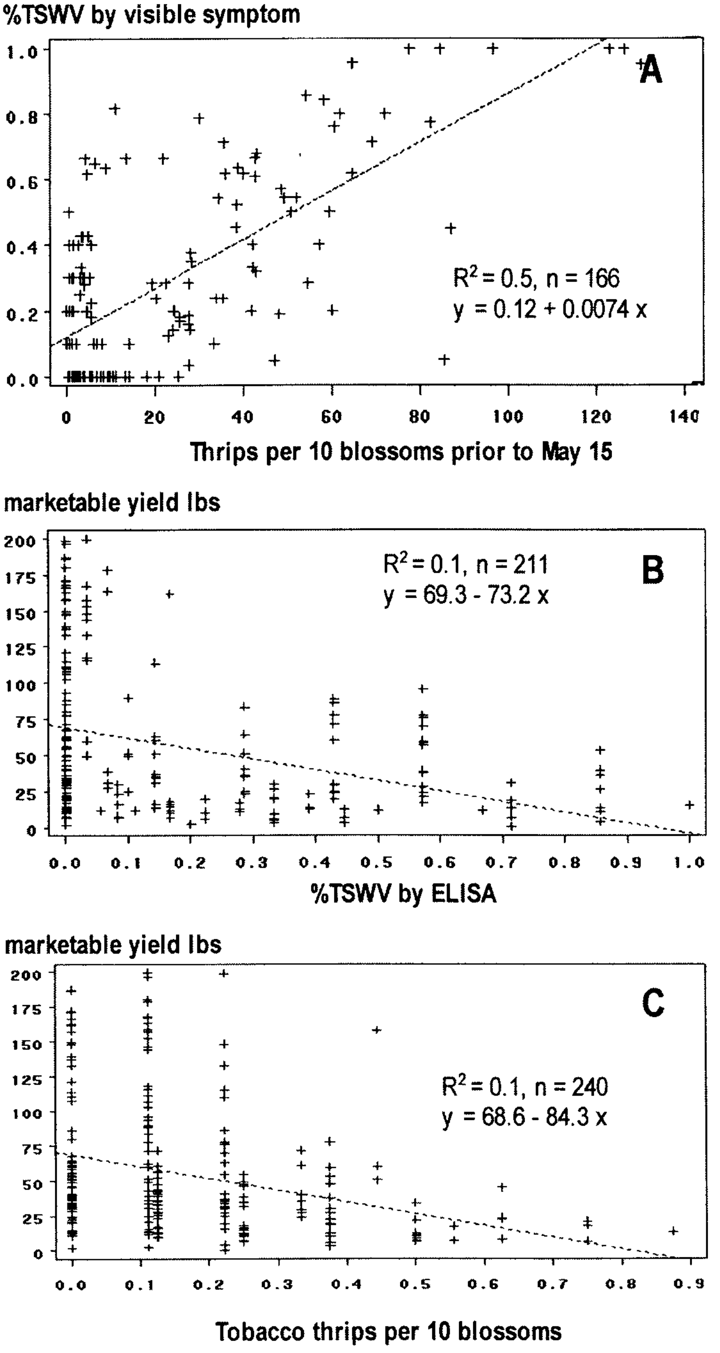

Fig. 2. Regressions based on seasonal averages of percentage of TSWV as determined by ELISA to total thrips per 10 blossoms (A) marketable tomato yield to percentage of TSWV (B), and marketable tomato yield to tobacco thrips per 10 blossoms (C) across all data from 1999 to 2002.

and blossom end rot resulted in fruit being culled (counted as unmarketable). Irregularly ripened or blotchy colored fruit at the time of harvest were assumed to be due to TSWV because the other potential causes, such as whiteflies (Bullock et al. 1998), were virtually absent (no adults observed on foliage) in the spring growing seasons during these tests. Also, most of the irregular ripening exhibited some ring-spot patterns that were associated with TSWV (Riley 2001b). Damaged or unmarketable yield was based on the condition of all fruit at the time of harvest. Data for TSWV irregular-ripened fruit assessed at the time of

Table 1. Main plot (cultivar-mulch) and subplot (insecticide) treatment effects on the average number of thrips per 10 blossoms and per sticky trap in a spring 1999 tomato test at Tifton, GA

Treatment	*F. occidentalis*/ 10 blossoms	*F. fusca*/ 10 blossoms	Other adult thrips/ 10 blossoms	Immature thrips/ 10 blossoms	Mean total thrips/ 10 blossoms
Main plot					
'Sunny Hybrid'-black	15.08a	0.17a	42.5a	5.82a	63.62a
'Sunny Hybrid'-silver	11.31b	0.18a	31.8b	5.65a	48.94b
'BHN 444'-silver	10.05b	0.18a	32.1b	4.58b	46.89b
Subplot					
Untreated	16.26b	0.18a	48.2a	8.42a	73.09a
Admire + 1 wk	18.75a	0.19a	44.1ab	7.02b	70.09a
Admire + 2 wk	10.56c	0.21a	40.6b	5.29c	56.63b
Admire + 4 wk	10.25c	0.21a	38.1b	4.83c	53.42b
Admire + 8 wk	4.91d	0.10a	6.3c	1.19d	12.51c

Means in columns followed by different letters are significantly different using least significant difference tests ($P < 0.05$) within significant mainplot and suplot treatment effects ($P < 0.05$).

harvest was not included in marketable fruit. However, in 2000 a subsample of marketable fruit was gassed with 100 ppm of ethylene for 24 h and then held for 1 wk to assess the potential for irregular ripening in the marketable fruit. For marketable yield, the approximate value of the crop was estimated per acre by using $7/11.3 kg (25 lb) carton of marketable fruit and a tomato plant population of 4,356 plants per 0.4 ha. Analysis of variance (ANOVA) was conducted using PROC GLM (SAS Institute 1990), and separation of means at the subplot level was determined using least significant difference (LSD) tests and contrast analysis for early versus late-planted tomato, insecticide-treated versus untreated tomato, and silver versus black plastic mulched beds. Correlations between thrips per blossoms, TSWV incidence, and yield over all years were conducted with PROC CORR and PROC REG procedures (SAS Institute 1990).

Results and Discussion

The overall average (±SD) levels of TSWV occurring each year reported as the percentage of infected plants based on ELISA samples were 44.5 ± 26.4% in 1999, 1.6 ± 3.6% in 2000, 19.2 ± 15.4% (replicates 1–3 only) in 2001, and 16.7 ± 21.1% in 2002 (n = 60, 90, 45, and 16, respectively). In comparison, the overall average (±SD) levels of TSWV occurring each year reported as the percentage of infected plants based on plant symptoms were 53.9 ± 27.3% in 1999, 1–2% observed late season in 2000, 18.9 ± 13.2% (replicates 1–3), and 1.0 ± 2.5% (replicates 4–6) in 2001, and 31.9 ± 23.8% in 2002. Thus, the incidence of TSWV, although fairly consistent between detection methods, was variable for this location depending on the year, which is a common observation at many farm sites in Georgia. This makes it difficult to plan before the growing season for the level of thrips/TSWV management tactics needed on a year-by-year basis.

The years that thrips in blossoms peaked earlier (1999 and 2002, Fig. 1A and D, respectively) were associated with greater incidence of TSWV (Tables 4 and 8). This association was quantified by correlating various time ranges of thrips counts on blossoms to TSWV incidence (plants with TSWV) by subplot. The one range that provided the highest correlation across all the test years was thrips counts before 15 May of each year (R = 0.70, n = 166, P < 0.0001), which corresponds to the first 6–8 wk after transplant. In comparison, this same correlation to all-season thrips averages was R = 0.55 (n = 166, P < 0.0001), which was similar to the correlation with TSWV based on ELISA determination (R = 0.52, n = 211, P > 0.0001). The regression of disease incidence based on plant symptoms to pre-15 May thrips counts by plot means was $y = 0.1206 + 0.0074\ (x)$, where y is proportion of

Table 2. Main plot (cultivar-mulch) and subplot (insecticide) treatment effects on the average number of thrips per blossom by species in a spring 2000 tomato test at Tifton, GA

Treatment	*F. occidentalis*/ 10 blossoms	*F. fusca*/ 10 blossoms	*F. bispinosa*/ 10 blossoms	*F. tritici*/ 10 blossoms	Immature thrips/ 10 blossoms	Mean total thrips/ 10 blossoms
Main plot						
'Sunny Hybrid'-black	10.68a	0.09a	0.23a	12.67a	1.40a	27.56a
'Sunny Hybrid'-silver	10.52a	0.08a	0.13a	7.53b	1.47a	21.47b
'BHN 444'-silver	8.60b	0.04a	0.11a	7.29b	1.41a	19.20b
Subplot						
Untreated	10.70a	0.07a	0.25a	10.48a	1.76a	25.32a
Admire + 1 wk	10.52a	0.06a	0.17b	9.91a	1.86a	24.40a
Admire + 2 wk	11.34a	0.06a	0.18ab	10.77a	1.60a	26.21a
Admire + 4 wk	10.58a	0.09a	0.15b	10.29a	1.35a	24.46a
Admire + 8 wk	6.52b	0.08a	0.04c	4.38b	0.55b	13.32b

Means in columns followed by different letters are significantly different using least significant difference tests ($P < 0.05$) within significant mainplot and suplot treatment effects ($P < 0.05$).

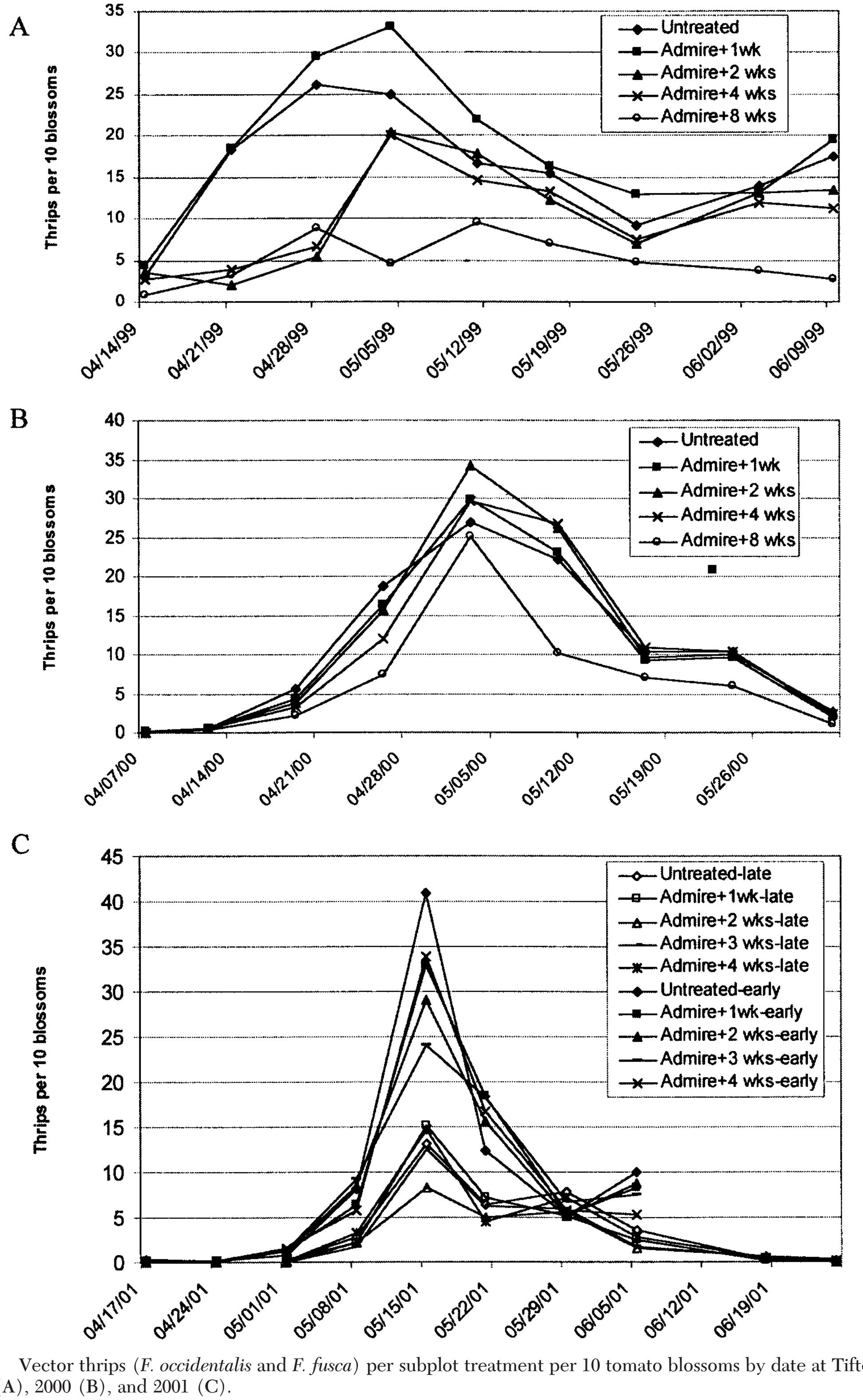

Fig. 3. Vector thrips (*F. occidentalis* and *F. fusca*) per subplot treatment per 10 tomato blossoms by date at Tifton, GA, in 1999 (A), 2000 (B), and 2001 (C).

Table 3. Main plot (cultivar-mulch) and subplot (insecticide) treatment effects on the average number of thrips per blossom by species in a spring 2001 tomato test at Tifton, GA

Treatment	*F. occidentalis*/ 10 blossoms	*F. fusca*/ 10 blossoms	*F. bispinosa*/ 10 blossoms	*F. tritici*/ 10 blossoms	Immature thrips/ 10 blossoms	Mean total thrips/ 10 blossoms
Main plot						
'Sunny Hybrid'-black	6.81a	0.33a	0.02a	9.51a	12.82a	19.97a
'Sunny Hybrid'-silver	5.68a	0.20b	0.01a	5.38a	8.19ab	14.08ab
'BHN 444'-silver	5.80a	0.23ab	0.01a	4.41a	6.98b	13.01b
Subplots						
Untreated	6.67a	0.35a	0.01a	6.30a	9.24a	16.26a
Admire + 1 wk	6.38a	0.23b	0.01a	6.02a	9.13a	15.74a
Admire + 2 wk	5.44a	0.27ab	0.02a	6.81a	9.49a	15.21a
Admire + 3 wk	5.80a	0.22b	0.01a	6.08a	8.77a	14.79a
Admire + 4 wk	6.19a	0.22b	0.03a	6.95a	10.02a	16.44a

Means in columns followed by different letters are significantly different using least significant difference tests ($P < 0.05$) within significant mainplot and suplot treatment effects ($P < 0.05$).

TSWV symptomatic plants and x is the average thrips per 10 blossom (Fig. 2). The pre-15 May thrips averages of only two thrips per blossom were associated with an average of 27% TSWV symptomatic plants under these conditions. We did not force the regression through the origin, so the regression is not accurate at very low thrips counts (<1). Given that marketable tomato yield tended to be very compromised above 20% TSWV incidence (Fig. 2B), an economic threshold for thrips vectors of TSWV would be very low.

Relative to thrips species, two interesting correlations were observed. Over all four years, *F. occidentalis* numbers in blossoms correlated better with percentage of TSWV as detected by ELISA than did *F. fusca* ($R = 0.31$, $n = 195$, $P < 0.0001$ and $R = 0.20$, $n = 195$, $P < 0.01$, respectively) and correlated well with percentage of TSWV based on plant symptoms ($R = 0.49$, $n = 150$, $P < 0.0001$). However, only *F. fusca* had a significant negative-correlation with marketable tomato yield ($R = -0.30$, $n = 240$, $P < 0.0001$; Fig. 2C) and positive correlation with TSWV-affected fruit ($R = 0.18$, $n = 240$, $P < 0.01$).

Of the thrips insecticide control treatments evaluated, the imidacloprid plus 8 wk of foliar insecticide provided the greatest observed reduction (70% in 1999 and 39% in 2000) of the main thrips vectors (*F. occidentalis* and *F. fusca*) per blossom of any test (Tables 1 and 2, respectively, and Fig. 3). Even so, the percentage of reduction of thrips vector species with insecticide was not very high in any year and even less so for the imidacloprid + 2-wk foliar treatment in 1999 (34% reduction of the same thrips vectors) where significant yield response also was observed. The cost of foliar treatments per week was approximately $60 per acre, so the additional $120 of the 4-wk spray program could be justified based on the estimated return (Table 4), but not the 8-wk spray program. Insecticide treatment did result in improved yield over the untreated check in 1999 (Table 4), but not in 2000 and 2001 (Tables 5 and 6, respectively) because of the low TSWV pressure during those years. No significant increase in marketable yield was observed between 4 and 8 wk of foliar sprays in any year (Table 7). The only year that insecticide treatments significantly improved yields over other treatments was 1999 and 2002 tended to have greater yields. These years also had the greatest incidence of TSWV in the field. This lead us to two conclusions about insecticide treatment for thrips–TSWV control. First, early season foliar sprays of an effective insecticide applied for a minimum of two consecutive weeks after transplant in combination with a imidacloprid soil treatment was an effective treatment in terms of tomato yield response,

Table 4. Main plot (cultivar-mulch) and subplot (insecticide) treatment effects on the avg tomato yield per treatment in a spring 1999 field test at Tifton, GA

Treatment	Marketable fruit		Tomato spotted wilt virus		
	Total wt (kg/10 plants)	Tomato yield value ($)/ha	% positive by rating	% ELISA positive	% irregular ripe fruit
Main plots					
'Sunny Hybrid'-black	13.4b	8,900b	27.45a	60.7a	29.1a
'Sunny Hybrid'-silver	17.6ab	11,700ab	17.45b	47.9ab	32.3a
'BHN 444'-silver	26.9a	17,900a	4.60c	25.0b	28.6a
Subplot					
Untreated	13.3b	8,800b	20.58a	56.0a	27.6a
Admire + 1 wk	14.1b	9,300b	21.25a	47.6ab	19.9a
Admire + 2 wk	22.7a	15,100a	13.50b	45.2abc	32.5a
Admire + 4 wk	24.9a	16,500a	12.17b	34.5c	32.9a
Admire + 8 wk	21.5a	14,300a	15.00b	39.3bc	36.6a

Means in columns followed by different letters are significantly different using least significant difference tests ($P < 0.05$) within significant mainplot and suplot treatment effects ($P < 0.05$).

Table 5. Main plot (cultivar-mulch) and subplot (insecticide) treatment effects on the average tomato yield per treatment in a spring 2000 field test at Tifton, GA

Treatment	Marketable fruit		Tomato spotted wilt virus		
	Total wt (kg/10 plants)	Tomato yield value ($)/ha	% ELISA positive	% irregular ripe fruit no.	% irregular ripe gassed fruit no.
Main plot					
'Sunny Hybrid'-black	39.0a	25,900a	3.1a	0.7a	0.4a
'Sunny Hybrid'-silver	42.2a	28,000a	1.4a	0.1b	3.6a
'BHN 444'-silver	44.5a	29,600a	0.3a	0.1b	1.9a
Subplot					
Untreated	43.1a	28,600a	1.1a	0.3a	1.5a
Admire + 1 wk	45.5a	30,200a	1.9a	0.2a	1.5a
Admire + 2 wk	39.7a	26,400a	1.9a	0.2a	3.5a
Admire + 4 wk	35.8a	23,800a	2.0a	0.4a	2.0a
Admire + 8 wk	45.4a	30,200a	1.3a	0.4a	1.3a

Means in columns followed by different letters are significantly different using Least Significant Difference tests ($P < 0.05$) within significant mainplot and suplot treatment effects ($P < 0.05$).

but only in years when higher incidence of TSWV (>17%) occurs. Second, continued applications later in the season, although significantly reducing thrips in blossoms, did not seem to significantly improve yields. This last observation has one caveat: the relationship of mid- to late-season TSWV inoculation to the incidence of TSWV irregular-ripened fruit has not been clarified. Fruit is not harvested from TSWV symptomatic plants at third string, but slightly symptomatic or asymptomatic plants are likely to be included in the commercial harvest. The data from 1999 clearly indicate the importance of thrips control early in the tomato-growing season, if insecticides are to be used at all. Additionally, the lack of significant thrips control in 2002 (Table 8) with just the lambda-cyhalothrin plus methamidophos treatment (Riley and Pappu 2000) suggested that chemical resistance could be important factor in this early season spray program. Imidacloprid is an important component of this program because it has been associated with reduced feeding by thrips (Chaisuekul and Riley 2001), which is needed in addition to insecticide activity to reduce virus transmission by *F. fusca* (Groves et al. 2001a).

The other control tactics reduced thrips and/or TSWV in at least one of the seasons tested. Reflective mulch tended to reduce thrips (Tables 1–3) by delaying infestations (Fig. 1). The TSWV-resistant 'BHN444' reduced the incidence of TSWV in 1999 when TSWV incidence was high based on rating (Table 4). The 'BHN444' treatment significantly reduced thrips number compared with 'Sunny Hybrid' in 2000 (Table 7), but not other years. The reflective mulch treatment significantly reduced thrips in 1999 (Table 7). In addition, the combination of 'BHN444′ and reflective mulch yielded the greatest amount of marketable tomato each year that it was tested (Tables 4–6), even though the difference was statistically significant only in the year 1999 with the highest incidence of TSWV. When we tested for main plot–subplot interactions (Table 7), no significant interactions were found. In 1999–2001, the lowest yield and highest percentage of TSWV based on ELISA was with the untreated 'Sunny Hybrid' on black plastic (22.8 ± 22.4 kg/10 plants, n = 16 and 29.0 ± 36.3%, n = 13, respectively), and the highest yield and lowest TSWV was with the 8-wk-treated 'BHN444' on reflective

Table 6. Main plot (cultivar-mulch) and subplot (insecticide) treatment effects on the average tomato yield per treatment in a spring 2001 field test at Tifton, GA

Treatment	Marketable fruit		Tomato spotted wilt virus		
	Total wt (kg/10 plants)	Tomato yield value ($)/ha	% positive by rating overall	% ELISA positive (reps. 1–3 only)	% irregular ripe fruit no.
Main plot					
'Sunny Hybrid'-black	21.0a	13,900a	12.7a	18.1a	8.2a
'Sunny Hybrid'-silver	26.0a	17,300a	9.7ab	22.4a	5.9a
'BHN 444'-silver	27.5a	18,300a	7.0b	17.0a	4.4a
Subplot					
Untreated	26.1a	17,400a	6.7a	18.2a	4.8a
Admire + 1 wk	25.6a	17,000a	10.6a	21.0a	8.0a
Admire + 2 wk	24.0a	15,900a	10.6a	14.8a	5.3a
Admire + 3 wk	22.6a	15,000a	12.2a	20.7a	7.6a
Admire + 4 wk	26.0a	17,200a	8.9a	21.3a	5.2a

Means in columns followed by different letters are significantly different using least significant difference tests ($P < 0.05$) within significant mainplot and suplot treatment effects ($P < 0.05$).

Table 7. Main plot and subplot interactions and contrast analysis (*F* values) in 1999, 2000, and 2001 for thrips and tomato yield parameters in tomato trials at Tifton, GA

Treatment	1999		2000		2001	
	Vector thrips	Market yield	Vector thrips	Market yield	Vector thrips	Market yield
Main plot * subplot	0.56	1.01	0.65	1.33	0.81	1.42
Contrast						
Black vs. silver	14.39**	0.83	0.04	0.85	2.83	1.76
'Sunny' vs. 'BHN444'	1.61	4.19	5.58*	0.44	0.04	0.15
Untreated vs. all treatments	46.44**	11.74**	2.93	0.14	1.58	0.55
Untreated vs, late treatments[a]	97.64**	17.11**	12.06**	0.33	1.23	0.62
Untreated vs. 4 wk	13.91**	17.58**	0.02	2.13	1.44	1.68
4 wk vs. 8 wk	93.24**	1.49	32.72**	3.71		

Significant differences indicated by $*P < 0.05$ or $**P < 0.01$.

[a] Early treatments were 1 and 2 wk after transplant; later treatments were 4 and 8 wk after transplant in 1999 and 2000 and 3 and 4 wk after transplant in 2001.

mulch (42.2 ± 25.5 kg/10 plants, n = 10 and 9.2 ± 11.6%, n = 10, respectively). Thus, with increased yields and reduced TSWV with combinations of tactics, we concluded that the management tactics have economically positive, additive effects. The level of economic benefit per ha is substantial with the best combination yielding $28,040/ha versus the poorest treatment yielding $15,150/ha, which is a $12,890 difference averaged over all 3 yr. The estimated additional treatment cost of $500/ha metallic reflective mulch + $1000/ha 8-wk intensive insecticide treatment + $50/ha 'BHN444' over a standard cost per year resulted in a >8:1 return on cost. With no insecticide, but the 'BHN444' and reflective mulch treatments, the yield was still quite good (33.7 ± 21.6, n = 16) with a difference in yield of $7,240/ha, or a 13:1 return on cost. In 1999–2001, reflective mulch alone with the susceptible 'Sunny Hybrid' yielded 31.3 ± 22.0 kg (n = 16) per 10 plants for a yield difference of $5,647 compared with the check. In 2002, the Repel Gro Heat Trap I doubled tomato yield over the black plastic mulch check (Table 8). The lack of yield response in Repel Gro Full Reflective in the 2002 test was a result of delayed fruit maturity as reflected in fruit weight (Table 8), but it was just as effective in reducing TSWV. Highly reflective plastic mulches can reduce soil heat accumulation (Diaz-Perez and Batal 2002), which can delay crop maturity.

In summary, all three tactics, i.e., early season insecticides, the TSWV-resistant tomato, and reflective mulch, reduced the incidence of TSWV and improved tomato yields in at least 1 yr when the level of TSWV exceeded 17%. Averaged over 3 yr, there was considerable economic incentive for using all three tactics in a preventative manner. Obviously, when TSWV incidence is low, e.g., 2% as in 2000, none of the tactics show a yield response. Unfortunately, a preseason prediction of TSWV severity is not currently available, although some overwintering host plant surveys show promise in this area (Groves et al. 2001b). Based on these studies, control tactics should be implemented in regions where TSWV is a problem to mitigate long-term risks to production. We recommend a cautious approach to using insecticide because of the threat of insecticide resistance in thrips (Kontsedalov et al. 1998). TSWV inoculation of young vegetative tomato plants has been associated with significant negative effects on tomato yield (Chaisuekul et al. 2003). Also, later the appearance of TSWV symptoms has been associated with less impact on yield (Moriones et al. 1998). So, the control of early invading *F. fusca* with insecticide could have an important impact on tomato yield. As a standard integrated pest management practice, it is important to focus treatments when needed and not season-long. The reflective metallic mulch is an effective tactic that seems to be cost-effective as

Table 8. Effects of early insecticide treatment and two metallic reflective mulches based on a single harvest of Roma tomato in a trial at Tifton, GA, in spring 2002

Treatment	Tomato spotted wilt virus			Yield by significant categories		
	Thrips/ 10 blossoms	% positive by rating	Intensity rating[a]	No. irregular ripen fruit	Avg fruit wt	Marketable wt (kg)
Black plastic with no thrips insecticide treatment	40.3a	51.0a	2.75a	59.75a	0.15ab*	10.7bc
Black plastic with a thrips insecticide treatment first 4 wk	46.5a	41.4ab	2.25b	41.25ab	0.15ab	17.8ab
RepelGro Full Reflective	18.0a	15.2b	1.75c	18.50bc	0.13b	8.2c
RepelGro Heat Trap I	25.0a	20.1b	1.75c	5.75c	0.22a	20.0a

Means in columns followed by different letters are significantly different using least significant difference tests ($P < 0.05$) within significant treatment effects ($P < 0.05$).

* Means in columns followed by different letters are significantly different using least significant difference tests ($P < 0.05$) within marginally significant treatment effects ($P < 0.15$).

[a] Intensity rating 1, low; 2, medium; 3, high incidence and severity of TSWV.

long as possible harvest delays from soil cooling are not a concern. Also, the commercial acceptability of the fruit of the 'BHN444' globe type is not as high as standard deep globe, blocky type tomato hybrids and may not be acceptable to some growers if the TSWV risk to production does not warrant sacrificing fruit marketability. If a risk index can be developed for TSWV in tomato such as has been done in peanut (Brown et al. 1999), then the selection of tactics can be based on the severity of predicted TSWV incidence, with high risk involving all available tactics and moderate risk using some selection of one or two tactics. This would help to preserve the efficacy of the existing tactics for thrips vector control and mitigate the negative economic impact of TSWV on tomato.

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