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Research

Distribution Pattern of Thrips (Thysanoptera: Thripidae) and Tomato Chlorotic Spot Virus in South Florida Tomato Fields

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Abstract

Tomato chlorotic spot virus (TCSV) is an orthotospovirus that causes a devastating disease in tomato (*Lycopersicon esculentum* Miller). TCSV emerged recently in South Florida. Studies were conducted in three commercial tomato fields in Miami-Dade County, Florida during the vegetable-growing seasons from October to April in 2015 through 2017. Each year, data were collected at 3, 6, and 9 wk after transplanting at various distances from the edges of each fields. Based on 3 yr total samples, three species of thrips were commonly observed melon thrips, *Thrips palmi* Karny (62.16 ± 0.79%), being the most abundant species followed by common blossom thrips, *Frankliniella schultzei* Trybom (21.55 ± 0.66%), and western flower thrips, *Frankliniella occidentalis* (Pergande) (16.26 ± 0.61%). Abundance of all thrips and TCSV infected plants was high at the edge of a tomato field 3 wk after transplanting with significantly fewer infected plants toward the center of the field. The distribution patterns of thrips and TCSV in various fields were mostly regular and aggregated across the sampling dates during the study period. Abundance of TCSV symptomatic plants and thrips species was high at the edge of the field and increased over time. The number of samples required to accurately determine population density of thrips was calculated by using three precision levels (0.10, 0.20, 0.30) at three predetermined densities of thrips (0.10, 0.20, and 0.40 per sample). This information will provide guidelines to growers, crop protection personnel, agricultural scouts, and researchers to develop a sustainable thrips and tospovirus management program.

Key words: thrips, tomato chlorotic spot virus, edge effect, spatial distribution, optimum sample size

The United States is one of the top tomato producing countries, and harvested 1.3 million tons of fresh tomatoes in 2015 (Guan et al. 2017). Florida ranks second in the nation growing 11,741 ha tomatoes in 2017 (USDA, NAAS 2017). However, tomato production is seriously threatened primarily due to an increased competition from Mexico. Secondly, the recent introduction of an orthotospovirus, tomato chlorotic spot virus (TCSV; genus Tospovirus, family Peribunyaviridae), has increased the threat to the Florida tomato industry valued at multi-million dollars. This virus was first reported in Florida in 2012 (Londoño et al. 2012), and has been infesting 30–40% tomato plants across all tomato plantings in Miami-Dade County, Florida (Poudel et al. 2019).

TCSV is transmitted by thrips that commonly infest tomato (Bauske 1998). *Frankliniella occidentalis* and *Frankliniella schultzei* are reported widely as vectors of TCSV and other tospoviruses, including groundnut ring spot virus (GRSV) and tomato spotted wilt virus (TSWV) in tomatoes (de Borbón et al. 2006). Other thrips, when available, can also transmit tospoviruses (TCSV) which include tobacco thrips (*Frankliniella fusca* Hinds), flower thrips (*Frankliniella intonsa* Trybom), Florida flower thrips (*F. bispinosa* Morgan), melon thrips (*Thrips palmi* Karny), onion thrips (*T. tabaci* Linderman), and chilli thrips (*Scirtothrips dorsalis* Hood) (Sakimura 1962, 1963; Webb et al. 1997; Mound 2002).

Various environmental and biological factors play important roles in the vector spread and virus transmission process (Mound 2002). The virus must be acquired by the first instar or at very early part of the second instar after which virus propagation takes place at the second instar and the developing adult (Wijkampt et al. 1993). The entire virus particle then passes through various receptor-mediated insect tissues (Nagata et al. 2002) to reach the salivary gland via gut muscles before the larva goes into pupation (Nagata et al. 1999).

Knowledge about the factors, that play an important role in population dynamics of a thrips species and virus transmission efficiency, help in developing management strategy in most reliable and cost-effective way. For example, different thrips species can transmit the same virus with different levels of efficiency (Wijcamp et al. 1995). In addition, different populations of the same species vary in transmitting efficiency of the same virus (Roca et al. 1997, Chatzivassiliou et al. 1999). This can happen due to the variation in their biological attributes, such as, phenology, behavior, population dynamics, and host plant use (Cho et al. 2000, Hansen 2000, Ramachandran 2001). Nitrogen fertilization (Schuch et al. 1998), microhabitat (Salguero-Navas et al. 1991) and vertical distribution (Atakan et al. 1996, Pearsall and Myers 2000) also play important role in population dynamics of thrips and their virus transmission capability. Males of western flower thrips are more efficient transmitter of TSWV than the females (van de Wetering et al. 1999). The dark morph of common blossom thrips occurs in southern Florida and is virulent in transmitting TCSV (Kakkar 2010). It also transmits TSWV and groundnut ringspot virus (Nagata and de Avila 2000). Most *Frankliniella* species are commonly known as flower thrips and are anthophilous in nature, whereas, common blossom thrips has demonstrated to feed on both tomato and apple leaves (Jacobson 1997; Pinent and Carvalho 1998, Leite et al. 2002) and flowers of its host plants (Milne et al. 2002).

Presence of vector thrips and their weed hosts plays an important role in the spread of tospoviruses (Abad et al. 2005). In our other project, we studied the influence of ornamental, weed, and vegetable hosts near tomato crops and found them responsible for the emigration of vector thrips and transmission of TCSV in tomatoes. In a study, Chamberlin et al. (1992) reported that western flower thrips and tobacco thrips can reproduce on many plant species near the crop production area. Similarly, other researchers studied infectious reservoirs from which TSWV spread to the susceptible hosts including nearby plantings of infected crops, volunteer crops, and weeds (Cho et al. 1989; Latham and Jones 1996, 1997; Gitaitis et al. 1998; Wilson 1998; Groves et al. 2002, 2003).

Management of thrips and TCSV in field-grown tomato is a serious concern to South Florida growers. The use of insecticides from various classes is considered the principal tool to combat thrips in tomato fields (Seal and Zhang 2015). The results from using insecticidal tactics can be inconsistent as is reflected by TCSV incidence. In our recent study, we evaluated effectiveness of various reduced risk and conventional insecticides alone or in combination with nonionic surfactants in managing thrips and TCSV in small plots. Results indicated inconsistent reduction in the number of thrips and TCSV. In most instances, applications of insecticides failed to effectively suppress thrips populations and virus incidence.

Considering the fact that various environmental and biological factors can influence occurrence, abundance, emigration, distribution, and management of thrips and their transmitted viruses, the specific objectives of this study were to determine distribution pattern of three common species of thrips (melon thrips, common blossom thrips, and western flower thrips) and TCSV in tomato, spatial distribution pattern of these thrips species and TCSV symptomatic plants in tomato fields over time and space. We also studied abundance of thrips and TCSV at different distances from the edge of the fields. By understanding the spatial pattern of distribution, more precise sampling methods can be developed to reliably sample crop fields and to use management tools selectively in a cost-effective and timely manner. Most importantly, the information will help to develop an effective, long-lasting, environmentally friendly, and sustainable management program.

Materials and Methods

Study Area and Crop Management

This study was conducted in 2015, 2016, and 2017, each year in three commercial tomato fields (field 1, field 2, and field 3) located within 22 km diameter in Miami-Dade County. All commercial fields ranged from 8.09 (20 acres) to 16.19 (40 acres) ha each. The beds in each field were running north to south. The tomato variety used in these studies was 'Sanibel'. All fields were planted following standard commercial practices, including planting, irrigation, and crop management, as mentioned in the Vegetable Production Handbook of Florida, 2015.

'Sanibel' tomato transplants were provided by Mobley Plant World, LLC, Labelle, FL and were transplanted into raised beds of Krome gravelly loam soil classified as a loamy-skeletal, carbonatic hyperthermia lithic rendoll, which consists of 67% limestone pebbles (>2 mm) and 33% finer particles (Noble et al. 1996). Beds were 243.84 meters (800 feet) long,1.83 m (6 feet) wide, and 20.32 cm (8 inches) high. Beds were covered with white-on-black plastic mulch (Can-Grow XSB, 0.9 mil, Canslit, Inc., Victoriaville, Quebec, Canada, and supplied by Imaflex, Inc., Thomasville, NC). Each bed was provided with two drip lines (Ro-Drip, United States) with emitter space 30 cm apart running parallel on both sides of a plant row at the center of a bed with 20.32 cm (8 inches) spacing. In each field, tomato plants were transplanted in October, spaced 0.46 m (18 inches) within the beds and 1.83 m (6 feet) in-between beds. Plants were irrigated two times each day delivering 182 l (48 G) per hour per 55.72 m^2 (100 × 6 feet) to maintain soil moisture at field capacity level. Chlorothalonil (Bravo Weather Silk, Syngenta Crop Protection LLC, 1752 ml/ha or 1.5 lb/acre), mancozeb (Manzate Pro-Stick, United Phosphorus, Inc., 1752 ml/ha or 1.5 lb/acre), pyrimethanil (Scala, Bayer CropScience, 511 ml/ha or 7 fl oz/acre), penthiopyrad (Fontelis, 1022 ml/ha or 24 fl oz/acre) were used in weekly rotation to prevent fungal and bacterial diseases (target spot, Rhizoctonia root rot, leaf spot, late blight). *Bacillus thuringiensis* subspp. *kurstaki,* strain ABTS-351 (Dipel DF, Valent bioscience Corporation, 1682 g/ha or 1.5 lb/acre), *Bacillus thuringiensis*, subsp. *aizawai*, Valent bioSciences Corporation, 1682 g/ha or 1.5 lb/acre), Azadirachtin (Azadirachtin 1.2% EC, 28.37 ml/9.29 sq. m or 0.96 fl. oz/100 sq. feet) were used as needed basis to control foliage damaging insect pests (beet armyworm, pinworm, silverleaf whitefly, cucumber beetle, broad mites and leafminers).

Field 1 was located at 25°32′18″ N and 80°31′37″W. There was an ornamental nursery on the west side 61 m (200 feet) away from the field. South and north sides of the field were planted with beans and other vegetable crops 300–500 feet away from the field. The edge of the field was covered with volunteer weeds of 22 species (RAK, personal observation). Some of those weeds are alternate hosts of various thrips (RAK, personal observation). The field was planted on 5, 7, and 10 October in 2016, 2017, and 2018, respectively. Wind was blowing eastward to the field.

Field 2 was located at 25°25′21″ N and 80°31′33″ W, which was bordered by a bean field on the north and residential houses on the other three sides. Most of these houses had backyards with ornamental plants and various flowering weeds belonging to approximately 15 species. Some of the weed flowers were hosting melon thrips, common blossom thrips, and western flower thrips. The field was planted on 9, 11, and 16 October in 2016, 2017, and 2018, respectively. Wind was blowing north-west and eastward to the field.

Field 3 was at the corner of two main roads at 25°29′36″ N and 80°27′54″ W. There was an eggplant field on the south side of the field, and an ornamental nursery and avocado grove on the east and

north sides of the field, respectively. Eggplants were planted near the field in all 3 yr of this study. Twenty different weed species were recorded in the grove area. The field was planted on 11, 16, and 22 October in 2016, 2017, and 2018, respectively. In this location, wind was blowing westward to the field.

In all commercial fields, the study area was selected on one side of the field, which was within 30.48–152.4 m (100–500 feet) of potential thrips reservoirs, including fallow weed patch, vegetable crops, nurseries, fruits, and palm orchards. To facilitate proper sampling, the study area in each field consisted of 12 beds, each 243.84 m (800 feet) long. Each bed was divided into eight, 30.48 m (100 feet) long plots per sections that was 1.83 m (6 feet) wide and was used for collecting samples in all studies.

Sampling for Thrips

Three weeks after planting (WAP), each field was sampled for melon thrips (not ESA-accepted common name), common blossom thrips, western flower thrips, and TCSV symptomatic plants in each section. Sampling was accomplished between 10:00 a.m. and 1:00 p.m. (EST) by randomly collecting 10 full-grown young leaves, one leaf per plant, from the top stratum of the plants in each plot. Leaves were placed in 500 ml plastic cups with lids and labeled according to the field, row, and plot numbers along with the sampling date. Thus, 96 (8 × 12) samples were collected from each field on each sampling date. A total of 288 (96 × 3 sampling dates) samples were collected from each field each year. Samples were transported to the Insect Integrated pest management (IPM) laboratory at the Tropical Research and Education Center (TREC), UF-IFAS and soaked with 70% alcohol for 20 min to dislodge thrips (Seal and Baranowski 1992). Leaves were removed carefully to leave thrips in the alcohol. The alcohol residue was passed through a sieve (USA Standard Testing Sieve, No. 60, opening 250 micrometers, Fisher Scientific Company) to separate thrips from the alcohol. Thrips left in the sieve were transferred to a Petri dish (10 cm diam) by gentle flush of 70% alcohol. Thrips in alcohol were identified to species using a digital microscope, VHX-6000, Keyence at 50X. Thrips species were separated using important taxonomic characters including antennal segments, position of post ocellar setae in ocellar triangle, and microtrichial comb on the 8th abdominal segment (Nakahara 1984). In each study year, each field was sampled three times at 3-wk intervals to record thrips species and number, and number of TCSV infected plants. TCSV was recognized based on the necrosis on leaves, chlorotic, and necrotic ring spots, followed by dwarfing and wilting of the part or entire plant (Polston et al. 2013). At fruiting stage, fruits show characteristic necrotic ring spots. TCSV was confirmed by using a quick immunostrip test for orthotospovirus and further by reverse-transcription polymerase chain reaction (RT–PCR) (Poudel et al. 2019).

Statistical Analysis

Data on the abundance of thrips and TCSV symptomatic plants were analyzed by using a linear mixed effect model Analysis of Variance (PROC Mixed, SAS version 9.3, SAS Institute Inc., Cary, NC). A linear mixed model was used to account for experimental design, a split block; to account for difference variances in time; and correlation between observations over time (an AR 1 correlation structure). The repeated statement is used to specify an AR1 covariance structure of the error term. In the model statement TCSV, common blossom thrips, western flower thrips, and melon thrips were used as dependent variables, and year, date and row were used as fixed effects. The Kenward-Roger's method was used for computing the denominator degrees of freedom for the tests of fixed effect. All data were transformed using square root ($x + 0.25$) before performing analysis. Means were separated by Tukey's honesty significant difference (HSD) Test when significant ($P < 0.05$) values were found. For ease of interpretation, means of the original data are presented in all tables.

Analysis of Spatial Distribution

In studying the distribution of an insect, multiple indices should be used. Because there is no single index that perfectly satisfies all requirements of aggregation studies (Green 1966, Rabinovich 1980, Rózsa et al. 2000). All available statistical tools used to compare distribution are based on the presumption that data consists of statistically independent events, whereas crowding data almost never meet this assumption. Data on within-field distribution pattern of melon thrips, common blossom thrips, western flower thrips and TCSV infected plants were collected on three dates 3, 6, and 9 WAP annually for three years (2015, 2016, 2017) from three tomato fields (field 1, field 2, and field 3) each year. All data from a field-collected on a same date (WAP) in different years were combined and subjected to various statistical indices to determine within-field distribution of each parameter (thrips and TCSV symptomatic plants). Taylor's Power law' (Taylor 1961) and Iwao's Patchiness (Iwao 1968) regression models are commonly used to calculate dispersion of insects (Southwood 1978). Taylor's Power Law (b) and Iwao's Patchiness regression (β) indicate the type of dispersion. In both models, when the slope (b and β) is not significantly different from 1, it indicates a random distribution pattern, slope value significantly > 1.0 indicates an aggregated distribution pattern, and slope value significantly less < 1.0 ($P < 0.05$) indicates a uniform or regular distribution pattern. Taylor's power law (equation 1) and Iwao's patchiness regression (equation 2) were calculated using the general linear regression models (Southwood 1978, SAS Institute 2004). Taylor's power law determines the relationship between mean density of adults (log $\bar{x}$) and variance (log s^2) and sampling factor (log a) (equation 1).

$$b = \left(\log s^2 - \log a\right) / \log \bar{x} \quad (1)$$

Iwao's patchiness regression relates the Lloyd (1967) mean crowding index

$$[(\mathbf{s^2}/^{x}\bar{x}) - 1] + ^{xx}\bar{x} - \alpha \quad (2)$$

To determine the within field distributions for melon thrips, common blossom thrips, western flower thrips, and TCSV infected plants using Taylor (b) and Iwao's (β), we first determined the goodness of fit of data to both linear models using regression coefficients (r^2) from each study. Then a student t-test ($P < 0.05$) was used to determine whether the slopes b and β were significantly different from 1.0. Taylor (b) and Iwao's (β) tests can be checked to determine correlation values (r^2), which indicates the reliability of the test value.

Index of Dispersion

It is commonly used to understand the dispersion index for counts. The index is also known as coefficient of dispersion, relative variance or variance to mean ratio (VMR) (Cox and Lewis 1966). VMR is a good measure of degree of randomness of a given phenomenon. When the VMR is larger than 1, the dispersion is considered clumped; VMR < 1 indicates regular distribution; and VMR = 1 indicates random spatial distribution (Rabinovich 1980). The index (I) is estimated by the equation:

$$I = \frac{s^2}{\hat{m}} = \frac{\sum_{i=1}^{n} (x_1 - \hat{m})^2}{\hat{m}(n-1)}$$

Where:

s^2 = sample variance;

$\hat{m}$ = sample mean;

X_1 = number of thrips found in the sample units;

n = number of sample units.

Green's Index or Green's Coefficient (C_x)

This index ranges from a negative value indicating uniform distribution; 0 indicating random distribution; 0 to 1 indicating aggregation (Green 1966). It is estimated by the equation:

$$C_x = (\sigma^2/m - 1)/(\Sigma x - 1)$$

Mean Crowding (mx)

It is estimated by the equation: mx = mean + (variance/mean) – 1;

Lloyd's Index of Patchiness or Lloyd's Mean Crowding

This index defines the mean number per individual of one species in relation to other species in the defined area (Lloyd 1967). It is expressed by m^*, which is calculated by the formula: $m^* = m + [(\sigma^2/m) - 1]$, where m is the mean density and σ^2 is the variance. When this index is >1, it indicates aggregation; values = 1 indicate random distribution and < 1 indicate uniform or regular distribution.

Determination of Optimum Sample Size

In developing an effective IPM program, it is important to estimate population density at a given level of reliability, the number of samples (n) required for a particular plot size can be determined by the following equation developed by Wilson and Room (1982):

$$N = c^2 t a x^{b-2}$$

Where, c is the reliability (half of the width of the confidence interval as a percentage of the mean), a and b are the coefficients of regression equation derived from Taylor's power law or Iwao's patchiness regression, x is the theoretical mean density based on experience, t is student's t value determined with n–1 degrees of freedom. This t value is approximately 2.0 when n is large. In the present study, sample size was determined at three levels of precision (0.10, 0.20, and 0.40) for predetermined densities of 0.10, 0.20, and 0.40 adults of melon thrips, common blossom thrips and western flower thrips in a 10-leaf sample of tomato per 55.78 sq. m. section (each plot) 3, 6, and 9 WAP.

Results

Field Edge Effect on the Abundance of Thrips in Tomato Fields

We recorded three species of thrips, including melon thrips, common blossom thrips and western flower thrips in all fields (fields 1, 2, and 3) during the study period. Melon thrips, common blossom thrips, western flower thrips and TCSV abundance was impacted by date, distance, and date × distance interaction irrespective of the fields (Table 1). Regardless of the fields, date × year interaction significantly affected populations of all dependent variables. In field 1, mean numbers of melon thrips were significantly higher at 1.83 m (2.50 per sample) and 3.66 m (1.75 per sample) away from the edge of the field than the rest of the area on the first sampling date (3 WAP) in 2015 (Fig. 1). Melon thrips population decreased with increase in distance from the edge. Population decreased sharply after 3.66 m (12 feet) away from the edge. Similar

Table 1. Analysis of variance of year, date, distance and their interactions for the number of adult melon thrips, common blossom thrips, western flower thrips and TCSV in tomato fields

Variables	Effect	df	*F*	*P*
Melon thrips	Year	2,4.33	13.58	0.013
	Distance	11,71.8	61.11	0.001
	Distance × year	22,71.8	1.20	0.278
	Date	2,101.0	93.15	0.001
	Date × year	4,113.0	5.19	0.0001
	Distance × Date	22,128	3.41	0.0001
	Distance × Date × Year	44,121	0.92	0.6173
Common blossom thrips	Year	2,6.09	13.58	0.013
	Distance	11,71.8	61.11	0.001
	Distance × year	22,71.8	1.20	0.278
	Date	2,101.0	93.15	0.001
	Date × year	4,113.0	5.19	0.0001
	Distance × Date	22,128	3.41	0.0001
	Distance × Date × Year	44,121	0.92	0.6173
Western flower thrips	Year	2,3.92	3.35	0.1416
	Distance	11,61.5	51.18	0.001
	Distance × year	22,81.7	3.20	0.208
	Date	2,201.0	85.17	0.001
	Date × year	4,213.0	6.29	0.0001
	Distance × Date	22,128	5.47	0.0001
	Distance × Date × Year	44,121	0.88	0.5624
TCSV	Year	2,14.2	1.31	0.300
	Distance	11,65.09	84.34	0.001
	Distance × year	22,65.9	0.17	1.001
	Date	2,97.3	175.85	0.001
	Date × year	4,109.0	1.77	0.140
	Distance × Date	22,125	16.81	0.0001
	Distance × Date × Year	44,119	0.66	0.942

pattern of melon thrips abundance was observed 6 and 9 WAP in tomato field in 2015 (Fig. 1a). Adult population density increased at the edge with increasing age of the tomato plants. We repeated this study in the same field per location in 2016 (Fig. 1b) and 2017 (Fig. 1c). The same pattern of melon thrips abundance on tomato was found on different sampling dates (3, 6, and 9 WAP). We studied the abundance of melon thrips in two additional tomato fields designated as field 2 and field 3 and separated from field 1 by 1.61 and 3.22 km, respectively. Density of melon thrips in these two fields showed similar trend on different sampling dates (field 2, Fig. 1d–f and field 3, Fig. 1g–i).

Common blossom thrips population abundance was low (0–0.88/10 leaf sample) on the first sampling date (3 WAP) in field 1 in 2015 (Fig. 2a). Population abundance of common blossom thrips remained low on tomato during this study in all fields. However, the pattern of abundance observed was similar as melon thrips (Fig. 2a–i). More common blossom thrips adults was observed at the edge on the first bed at 1.83 m of edge on different sampling dates (3 WAP: 0.88 per sample; 6 WAP: 2.63 per sample; 9 WAP: 2.62 per sample) and decreased sharply with the increase of distance on all three sampling dates. On all sampling dates, common blossom thrips population ranged from 0 to 0.13 per sample in 2015 in field 1 at 10.97 m (36 feet) away from the edge (Fig. 2a–c). Common blossom thrips abundance also followed the same trend on all sampling dates in field 2 (Fig. 2d–f) and field 3 (Fig. 2g–i).

Western flower thrips adult abundance was low in field 1 in 2015 (Fig. 3a). Higher abundance of adults was recorded at 1.83 to 7.32 m (6 to 24 feet) away from the edge. The abundance of adult western flower thrips was zero on all sampling dates at a distance > 7.32 m (24 feet) from the edge in 2015 (Fig. 3a). Population of western flower thrips in 2016 was similar as 2015 on the first two sampling dates 3 and 6 WAP (Fig. 3b). Population abundance increased on the third sampling date 9 WAP and was recorded up to 21.95 m (72 feet) away from the edge. In 2017, western flower thrips adults occurred up to 21.95 m (72 feet) from the edge on all sampling dates (Fig. 3c). However, significantly higher number of adults was recorded at the edge of the field on all sampling dates. In field 2, western flower thrips population abundance did not differ among distances in 2015 on the first two sampling dates (3 and 6 WAP). Population abundance varied significantly among various distances from the edge 9 WAP (Fig. 3d). In 2016, western flower thrips abundance among different distances did not vary on different sampling dates as in 2015 (Fig. 3e). In 2017, higher thrips abundance was recorded at the edge on all sampling dates (Fig. 3f). Adult abundance decreased with the increase of distance from the edge on all three sampling dates. In field 3, abundance of western flower thrips adults differed among various distances with the highest numbers at the edge on all sampling dates in 2015 (Fig. 3g). In 2016 (Fig. 3h) and 2017 (Fig. 3i), western flower thrips adult abundance did not differ among various distances on the first two sampling dates, 3 and 6 WAP. On the last sampling date, 9 WAP, western flower thrips adult density increased at the edge showing significant differences in the abundance among various samples.

TCSV Abundance

Mirroring the thrips occurrence, mean numbers of TCSV symptomatic plants were significantly higher in density at the edge of the field and decreased away from the edge (Fig. 4a–i). This pattern was consistent on all sampling dates in all fields (F1, F2, and F3) during 2015, 2016, and 2017. In 2015, mean numbers of TCSV infected plants were 3.0, 4.63, and 6.0 per 30.48 m (100 feet) linear bed at the edge of the field on the 3rd, 6th, and 9th WAP, respectively, in field 1 (Fig. 4a). In the same field, the corresponding numbers were 5.05, 7.13, and 10.13, respectively, in 2016 (Fig. 4b); and 3.63, 6.38, and 10.63, respectively in 2017 (Fig. 4c). In field 2, mean numbers of TCSV infected plants were significantly higher at the edge (up to 3.66 m away from the edge) 3 (3.28 plants), 6 (9.00 plants), and 9 WAP (12.25 plants) (Fig. 4d). In the same field (field 2), mean numbers of infected plants per 30.48 m (100 feet) linear bed at the edge

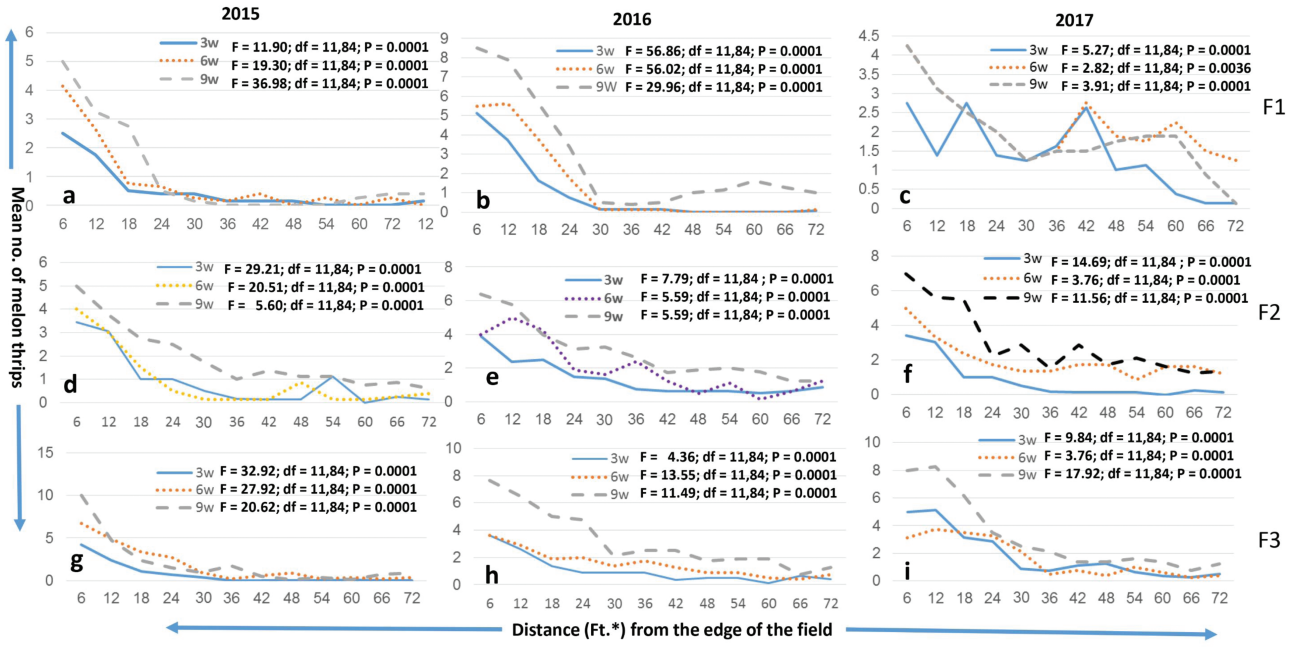

Fig. 1. Edge effect on the abundance of common blossom thrips in three fields during 2015, 2016, and 2017; a–c = Tomato field #1 (Fl), d–f = Tomato field #2 (F2), a–c = Tomato field #3 (B). *6 feet = 1.83 m, 12 feet = 3.66 m, 18 feet = 5.49 m, 24 feet = 7.32, 30 feet = 9.14 m, 36 feet = 10.97 m, 42 feet = 12.80 m, 48 feet = 14.63 m, 54 feet = 16.46 m, 60 feet = 18.29 m, 66 feet = 20.12 m, 72 feet = 21.95 m.

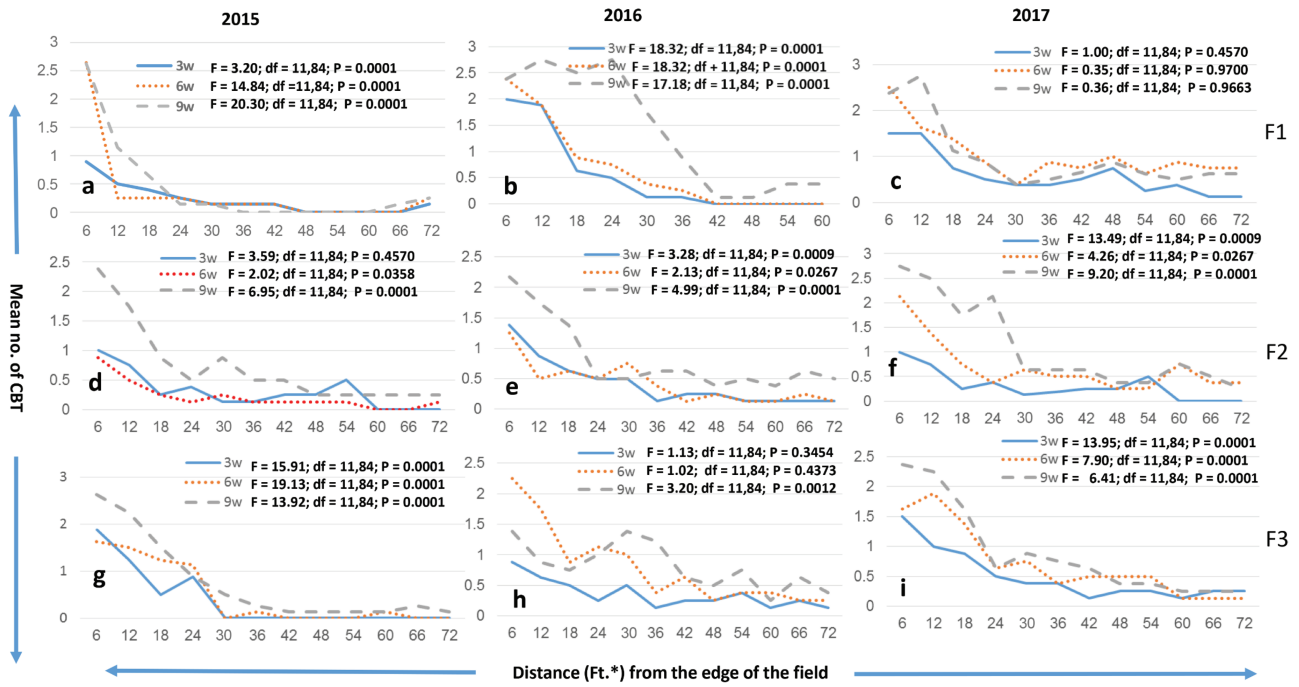

Fig. 2. Edge effect on the abundance of common blossom thrips in three fields during 2015, 2016, and 2017; a–c = Tomato field #1 (FI), d–f = Tomato field #2 (F2), a–c = Tomato field #3 (B). m, m, m, m, 54 feet = 16.46 m, 60 feet = 18.29 m, 66 feet = 20.12 m, 72 feet = 21.95 m.

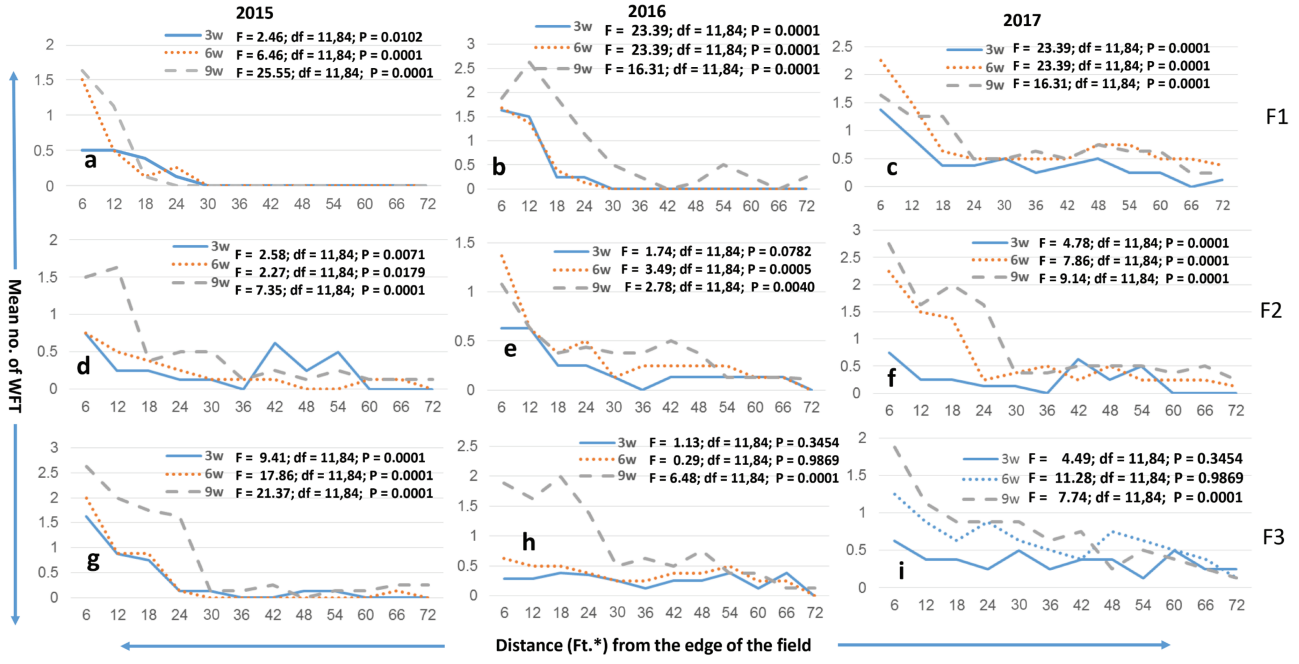

Fig. 3. Edge effect on the abundance of western flower thrips in three fields during 2015, 2016, and 2017; a–c = Tomato field #1 (FI), d–f = Tomato field #2 (F2), a–c = Tomato field #3 (B). m, m, m, m, 54 feet = 16.46 m, 60 feet = 18.29 m, 66 feet = 20.12 m, 72 feet = 21.95 m.

of the field were 3.00, 5.50, and 7.42 in 2016 (Fig. 4e); and 3.63, 6.25, and 9.50 in 2017 (Fig. 4f) 3, 6, and 9 WAP, respectively. In field 3, mean numbers of infested plants at the edge of the field were 2.88, 7.88, and 11.88 per 30.48 m (100 feet) linear bed length 3, 6, and 9 WAP, respectively in 2015 (Fig. 4g). These numbers of infected plants at the edge of the field were significantly greater than the numbers observed in locations away from the edge. In the same field, the numbers of infected plants were 2.25, 5.38, and 10.75 in 2016 (Fig. 4h); and 3.88, 8.63, and 15.12 per 30.48 m (100 feet) linear bed length 3, 6 and 9 WAP, respectively in 2017 (Fig. 4i).

When fields and dates of all 3 yr are combined together, percentage of melon thrips was higher at the edge than common blossom thrips and western flower thrips (Table 2). Percentages of all thrips species decreased as distance from the edge increased. With the decrease in the percentages of vector thrips, mean number of TCSB symptomatic plants decreased as distance increased from the edge.

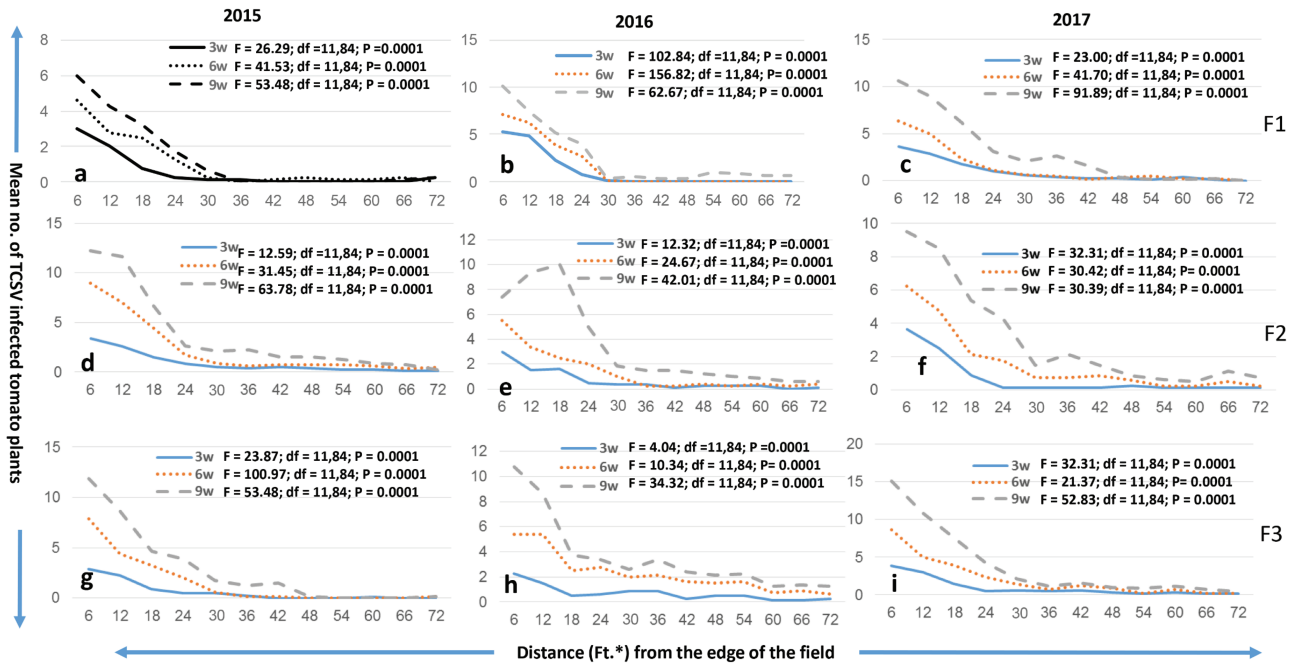

Fig. 4. Edge effect on the abundance of TCSV infected tomato plants in three fields during 2015, 2016, and 2017; a–c = Tomato field #1 (Fl), d–f = Tomato field #2 (F2), a–c = Tomato field #3 m, m, m, m, 54 feet = 16.46 m, 60 feet = 18.29 m, 66 feet = 20.12 m, 72 feet = 21.95 m.

Table 2. Mean percentage ± SEM of TCSV symptomatic plants and percentages ± SEM of common blossom thrips, western flower thrips and melon thrips in tomato fields

Distance (m)	TCSV	Common blossom thrips	Western flower thrips	Melon thrips
1.83	6.74 ± 0.24a	5.50 ± 0.23a	4.30 ± 0.21a	15.73 ± 0.51a
3.66	5.28 ± 0.22b	3.77 ± 0.22b	3.13 ± 0.21b	11.72 ± 0.43b
5.49	3.18 ± 0.16c	2.43 ± 0.18c	2.24 ± 0.18c	8.11 ± 0.37c
7.32	2.00 ± 0.12d	2.14 ± 0.18c	1.51 ± 0.15d	5.44 ± 0.32d
9.14	0.92 ± 0.07e	1.41 ± 0.14d	0.81 ± 00.11e	3.42 ± 0.28e
10.97	0.87 ± 0.08e	1.07 ± 0.13de	0.65 ± 0.09eg	2.99 ± 0.27eg
12.80	0.66 ± 0.06f	0.87 ± 0.11ef	0.77 ± 0.09ef	3.23 ± 0.29ef
14.63	0.50 ± 0.05g	0.78 ± 0.11ef	0.78 ± 0.11ef	2.46 ± 0.24fh
16.46	0.44 ± 0.05gh	0.72 ± 0.11f	0.71 ± 0.11eg	2.46 ± 0.24gi
18.29	0.33 ± 0.04hi	0.77 ± 0.11f	0.54 ± 0.09eg	2.25 ± 0.24hi
20.12	0.36 ± 0.05hi	0.75 ± 0.10ef	0.47 ± 0.08g	2.52 ± 0.26i
21.95	0.29 ± 0.04i	0.88 ± 0.13ef	0.54 ± 0.10fg	2.52 ± 0.26gi

Percentage is based on all thrips.
TCSV, tomato chlorotic spot virus; CBT, common blossom thrips; WFT, western flower thrips.
(a–i)Means within the same column followed by the same letter are not significantly different according to Tukey's Honestly Significant Difference test (P = 0.05).

Spatial Distribution Pattern of Thrips

Melon thrips, common blossom thrips, western flower thrips, and their transmitted TCSV symptomatic plants were distributed in a regular pattern in field 1 on the first sampling date, 3 WAP (Table 3). Both Taylor's Power Law and Iwao's Patchiness regression models were in agreement in the distribution of various parameters in the tomato field. Both models fit well to the data sets based on strong r^2 values. r^2 values ranged from 0.63 to 0.97 for Taylor's power law, and 0.64–0.98 for Iwao's patchiness regression representing strong fit to data irrespective of sampling dates. The slope (b) values in all instances were significantly smaller than 1 ($P > 0.05$) indicating a regular distribution of thrips and TCSV symptomatic plants. Intercept values (a) for Taylor's power law are mostly negative and those of Iwao's patchiness regression are mostly positive. Similar pattern of regular distribution was observed when data collected 6 and 9 WAP were subjected to Taylor's Power Law and Iwao's Patchiness Regression Models.

Among other statistical indices, Index of dispersion, Mean crowding, Lloyd's Mean Crowding and Green's Index provided closely related values for various parametes in field 1 (Table 4). All indices stated aggregated pattern of melon thrips on all sampling dates. Green's index showed a tendency (values between 0.1 and 0.99) towards aggregation (TA).

TCSV distribution was regular 3 WAP with indices values significantly less than 1 in Index of dispersion, Mean crowding and Lloyd's Mean Crowding, and a negative value of Green's index (Table 3). On the same sampling date (3 WAP), these four indices showed similar pattern of 'Regular' distribution for common blossom thrips. Western flower thrips distribution was regular in Index of dispersion, Mean crowding and Lloyd's Mean Crowding, and random in Green's index.

All three indices were in agreement in showing aggregated distribution of melon thrips with values significantly greater than '1', whereas Green's index showed a value approaching to aggregation.

In field 1, 6 WAP, Taylor's Power Law and Iwao's Patchiness regression model showed regular pattern of distribution of all parameters (common blossom thrips, western flower thrips, and TCSV) having slope value less than 1.00 (Table 3). Both models fit well to the data sets having r^2 values ranging from 0.50 to 0.93 in Taylor's Power Law and 0.64 to 0.98 in Iwao's Patchiness regression. Mean crowding value (1.42) showed aggregated distribution of TCSV, whereas index of dispersion, Lloyd's mean crowding and Green's index showed 'Regular' distribution (Table 4). All three indices showed aggregated distribution of melon thrips with Green's index showing a weak trend toward aggregation. Common blossom thrips and western flower thrips distribution was aggregated based on `Index of dispersion' and 'Lloyd's Mean Crowding'.

In the same field (field 1), 9 WAP, Taylor's Power Law, and Iwao's Patchiness regression model showed similar pattern of distribution of all parameters as the samples 6 WAP having slope values less than 1.00 (Table 3). All three indices (Index of dispersion, Mean crowding, and Lloyd's mean crowding) showed aggregated distribution of TCSV and melon thrips (Table 4). On the contrary, all three indices indicated regular distribution of common blossom thrips. However, 'Index of dispersion' and 'Lloyd's Mean Crowding' indicated aggregated distribution of western flower thrips.

In field 2, Taylor's Power Law and Iwao's Patchiness Regression (Table 5) showed similar pattern of distribution (regular distribution) of all parameters on all sampling dates (3, 6, and 9 WAP) as in the instance of field 1 in Table 3. All other indices showed regular distribution of all parameters in 75% occasions 3 WAP (Table 6). Melon thrips distribution was aggregated in Lloyd's mean crowding and showed weak aggregation in Green's index. At 6 WAP, TCSV

Table 3. Taylor's Power Law and Iwao's Patchiness regression equations pertaining to general distribution patterns of thrips and TCSV based on cumulative data collected from field 1 during 3 yr of tomato growing seasons

	Taylor's power law				Iwao's patchiness regression		
Parameters	*n*	r^2	*a*	*b*	r^2	*a*	β
TCSV	288	0.97	−0.13	0.86 REG	0.98	−0.02	0.89 REG
Melon thrips	288	0.81	0.13	0.94 REG	0.33	0.92	0.71 REG
Common blossom thrips	288	0.91	−0.19	0.78 REG	0.69	0.05	0.64 REG
Western flower thrips	288	0.95	−0.13	0.86 REG	0.74	0.05	0.68 REG
				6 WAP			
TCSV	288	0.93	−0.17	0.79 REG	0.98	−0.003	0.89 REG
Melon thrips	288	0.50	0.17	0.47 REG	0.64	1.31	0.58 REG
Common blossom thrips	288	0.76	−0.11	0.66 REG	0.71	0.33	0.62 REG
Western flower thrips	288	0.79	−0.11	0.77 REG	0.71	0.36	0.52 REG
				9 WAP			
TCSV	288	0.91	0.01	0.86 REG	0.98	0.32	0.92 REG
Melon thrips	288	0.88	0.11	0.85 REG	0.96	0.42	0.92 REG
Common blossom thrips	288	0.63	−0.12	0.77 REG	0.77	0.13	0.80 REG
Western flower thrips	288	0.67	−0.19	0.66 REG	0.40	0.29	0.52 REG

Means within a column followed by the same letter do not differ significantly according to Tukey's HSD ($P = 0.05$).

Table 4. Various statistical indices pertaining to the general pattern of distribution ofTCSV and three species of thrips based on cumulative data collected in three tomato growing seasons in field 1

Parameters	*n*	Index of dispersion	Mean crowding	Green's index	Lloyd's mean crowding
			3 WAP		
TCSV	288	0.87 REG	0.95 REG	−0.03 REG	0.84 REG
Melon thrips	288	1.62 AGG	1.63 AGG	0.17 TA	2.32 AGG
Common blossom thrips	288	0.88 REG	0.35 REG	−0.02 REG	0.84 REG
Western flower thrips	288	0.94 REG	0.29 REG	0.02 RAN	0.93 REG
			6 WAP		
TCSV	288	0.83 REG	1.42 AGG	−0.02 REG	0.90 REG
Melon thrips	288	1.69 AGG	2.17 AGG	0.12 TA	2.24 AGG
Common blossom thrips	288	1.10 AGG	0.70 REG	−0.06 REG	1.53 AGG
Western flower thrips	288	1.15 AGG	0.58 REG	0.17 TA	1.91 AGG
			9 WAP		
TCSV	288	1.12 AGG	2.46 AGG	0.03 TA	1.31 AGG
Melon thrips	288	1.28 AGG	2.21 AGG	0.04 TA	1.45 AGG
Common blossom thrips	288	0.96 REG	0.83 REG	−0.01 REG	0.97 REG
Western flower thrips	288	1.01 AGG	0.60 REG	0.09 TA	1.49 AGG

Index of dispersion, Mean crowding, Lloyd's mean crowding: AGG, aggregated distribution, value significantly > 1; RAN, random distribution, value not significantly different from 1; REG, regular distribution, value significantly < 1. Green's index: AGG, Aggreated distribution, Value = 1; RAN, Random distribution, Value = 0; REG, Regular distribution, Value negative.

distribution was clumped as per Mean Crowding and Lloyd's Mean Crowding. All four indices showed aggregated distribution of melon thrips (except Green's Index) and regular distribution of common blossom thrips and western flower thrips. At 9 WAP, only Mean crowding showed aggregated distribution and the other indices showed regular and random distribution of TCSV. Three indices showed aggregated distribution of melon thrips with very weak aggregation in Green's index. Index of dispersion and Lloyd's mean crowding showed aggregated distribution of common blossom thrips and only Lloyd's mean crowding showed aggregated distribution of western flower thrips.

In field 3, all parameters, 3 WAP, showed regular distribution according to Taylor's power law (r^2 = 0.79–0.94) and Iwao's patchiness regression (r^2 = 0.20–0.93) (Table 7). Both models showed aggregated distribution of western flower thrips 6 WAP. On the same sampling date, melon thrips distribution was regular (b < 1.0) (Taylor's Power Law) and random (b = 1) Iwao's Patchiness regression). Both models showed regular distribution of TCSV and common blossom thrips. At 9 WAP, distribution of all parameters was regular as shown by the two models (Taylor's power law: r^2 = 0.79–0.94; Iwao's patchiness regression: r^2 = 0.40–0.99). All indices showed regular distribution of all parameters 3 WAP, except melon thrips having aggregated distribution (Table 8). At 6 WAP, all indices showed aggregated distribution of all parameters with very weak aggregation in Green's index. TCSV distribution was strongly aggregated 9 WAP as shown by Mean crowding value (3.21). Other indices showed regular or random distribution of TCSV. All indices, except Green's Index, showed weak to strong aggregated distribution of melon thrips. According to Lloyd's mean crowding, western flower thrips distribution was aggregated 9 WAP. Other indices showed regular distribution of common blossom thrips and western flower thrips.

Table 5. Taylor's Power Law and Iwao's Patchiness regression equations pertaining to general distribution patterns of thrips and TCSV based on cumulative data collected from field 2 during 3 yr of tomato growing seasons

		Taylor's power law			Iwao's patchiness regression		
Parameters	n	r^2	a	b	r^2	a	β
				3 WAP			
TCSV	288	0.89	−0.28	0.67 REG	0.97	−0.04	0.77 REG
Melon thrips	288	0.69	−0.19	0.65 REG	0.75	0.26	0.68 REG
Common blossom thrips	288	0.90	−0.22	0.77 REG	0.64	0.00	0.65 REG
Western flower thrips	288	0.77	−0.14	0.82 REG	0.19	0.12	0.57 REG
				6 WAP			
TCSV	288	0.89	−0.09	0.82 REG	0.94	−0.06	0.92 REG
Melon thrips	288	0.52	−0.07	0.68 REG	0.83	0.38	0.77 REG
Common blossom thrips	288	0.88	−0.15	0.83 REG	0.65	0.02	0.71 REG
Western flower thrips	288	0.88	−0.18	0.82 REG	0.63	−0.02	0.71 REG
				9 WAP			
TCSV	288	0.91	−0.05	0.87 REG	0.99	0.001	0.96 REG
Melon thrips	288	0.61	0.19	0.68 REG	0.91	0.80	0.84 REG
Common blossom thrips	288	0.81	−0.03	0.90 REG	0.70	0.16	0.84 REG
Western flower thrips	288	0.67	−0.19	0.66 REG	0.40	0.29	0.52 REG

AGG, aggregated distribution, b/ β significantly > 1; RAN, random distribution, b/ β not significantly different from 1; REG, regular distribution, b/ β significantly <1.

Table 6. Various statistical indices pertaining to the general patter of distribution of TCSV and three species of thrips based on cumulative data collected in three tomato growing seasons in field 2

Parameters	n	Index of dispersion	Mean crowding	Green's index	Lloyd's mean crowding
			3 WAP		
TCSV	288	0.78 REG	0.58 REG	−0.04 REG	0.69 REG
Melon thrips	288	0.96 REG	0.89 AGG	0.03 RAN	1.23 AGG
Common blossom thrips	288	0.85 REG	0.27 REG	−0.04 REG	0.72 REG
Western flower thrips	288	0.96 RAN	0.34 REG	−0.01 REG	0.98 RAN
			6WAP		
TCSV	288	0.93 REG	1.66 AGG	0.02 RAN	1.15 AGG
Melon thrips	288	1.04 AGG	1.48 AGG	0.01 RAN	1.16 AGG
Common blossom thrips	288	0.89 REG	0.34 REG	−0.03 REG	0.77 REG
Western flower thrips	288	0.86 REG	0.27 REG	−0.06 REG	0.64 REG
			9WAP		
TCSV	288	0.89 REG	2.81 AGG	−0.001 REG	0.99 RAN
Melon thrips	288	1.43 AGG	2.75 AGG	0.04 RAN	1.41 AGG
Common blossom thrips	288	1.04 AGG	0.77 REG	0.01 RAN	1.11 AGG
Western flower thrips	288	0.96 RAN	0.52 REG	0.05 RAN	1.18 AGG

Index of dispersion, Mean crowding, Lloyd's mean crowding: AGG, aggregated distribution, value significantly > 1; RAN, random distribution, value not significantly different from 1; REG, regular distribution, value significantly <1. Green's index: AGG, Aggreated distribution, Value = 1; RAN, Random distribution, Value = 0; REG, Regular distribution, Value negative.

Table 7. Taylor's Power Law and Iwao's Patchiness regression equations pertaining to general distribution patters of thrips and TCSV based on cumulative data collected from field 3 during 3 yr of tomato growing seasons

Parameters	Taylor's power law				Iwao's patchiness regression		
	n	r^2	*a*	*b*	r^2	*a*	*β*
				3 WAP			
TCSV	288	0.91	−0.18	0.80 REG	0.93	−0.05	0.84 REG
Melon thrips	288	0.79	0.11	0.89 REG	0.78	0.78	0.79 REG
Common blossom thrips	288	0.94	−0.07	0.93 REG	0.79	0.02	0.84 REG
Western flower thrips	288	0.79	−0.19	0.79 REG	0.20	0.15	0.55 REG
				6 WAP			
TCSV	288	0.86	−0.003	0.88 REG	0.97	0.07	0.99 REG
Melon thrips	288	0.78	−0.03	0.90 REG	0.87	0.20	1.02 REG
Common blossom thrips	288	0.94	−0.01	0.94 REG	0.64	0.17	0.85 REG
Western flower thrips	288	0.86	−0.10	1.15 REG	0.52	−0.15	1.64 REG
				9 WAP			
TCSV	288	0.68	−0.08	0.74 REG	0.99	−0.07	0.96 REG
Melon thrips	288	0.73	0.04	0.77 REG	0.98	0.14	0.95 REG
Common blossom thrips	288	0.70	−0.15	0.71 REG	0.85	0.08	0.76 REG
Western flower thrips	288	0.67	−0.19	0.66 REG	0.40	0.29	0.52 REG

AGG, aggregated distribution, b/ β significantly > 1; RAN, random distribution, b/ β not significantly different from 1; REG, regular distribution, b/ β significantly < 1.

Table 8. Various statistical indices pertaining to the general pattern of distribution of TCSV and three species of thrips based on cumulative data collected in three tomato growing seasons in field 3

Parameters	n	Index of dispersion	Mean crowding	Green's index	Lloyd's mean crowding
			3 WAP		
TCSV	288	0.83 REG	0.59 REG	−0.03 REG	0.75 REG
Melon thrips	288	1.50 AGG	1.81 AGG	0.11 TA	1.89 AGG
Common blossom thrips	288	0.95 REG	0.40 REG	−0.02 REG	0.88 REG
Western flower thrips	288	0.92 REG	0.23 REG	−0.04REG	0.78 REG
			6 WAP		
TCSV	288	1.05 AGG	2.33 AGG	0.05 TA	1.31 AGG
Melon thrips	288	1.23 AGG	2.07 AGG	0.03 TA	1.32 AGG
Common blossom thrips	288	1.08 AGG	0.68 REG	0.08 TA	1.43 AGG
Western flower thrips	288	1.22 AGG	0.80 REG	0.02 TA	1.22 AGG
			9 WAP		
TCSV	288	0.80 REG	3.21 AGG	−0.001 REG	0.97 RAN
Melon thrips	288	1.00 AGG	2.71 AGG	0.01 REG	1.08 AGG
Common blossom thrips	288	0.87 REG	0.72 REG	−0.02 REG	0.88 REG
Western flower thrips	288	0.93 REG	0.73 REG	0.05 TA	1.25 AGG

Index of dispersion, Mean crowding, Lloyd's mean crowding: AGG, aggregated distribution, value significantly > 1; RAN, random distribution, value not significantly different from 1; REG, regular distribution, value significantly <1. Green's index: AGG, Aggreated distribution, Value = 1; RAN, Random distribution, Value = 0; REG, Regular distribution, Value negative.

Generalized Distribution Pattern of Various Parameters

Data from three distantly located fields collected on three dates in each of 3 yr during the tomato growing season were combined and were subjected to various statistical tools to determine general pattern of distribution of three thrips species and TCSV symptomatic plants in South Florida tomato agroecosystem (Table 9). The slope values of each model for various parameters on different sampling dates (3, 6, and 9 WAP) are significantly <1.00 indicating regular distribution of thrips and TCSV infected plants. The intercept (*a*) values of Taylor's power law in 67% instances are negative rendering it unsuitable to accurately determine optimum sample size for developing management programs. In the present situation, Iwao's patchiness regression is more suitable than Taylor's power law in determining distribution pattern of thrips species and TCSV symptomatic plants.

When all indices are considered, melon thrips distribution was aggregated on all sampling dates (3, 6, and 9 WAP) (Table 10). Common blossom thrips distribution was regular 3 and 9 WAP, and became aggregated 6 WAP except Mean crowding value. Western flower thrips distribution was regular 3 WAP and became aggregated 6 WAP except Mean crowding value. Western flower thrips distribution 9 WAP was aggregated according to Lloyd's mean crowding value, but was regular according to other indices. All indices indicated regular distribution of TCSV symptomatic plants 3 WAP, and almost aggregated 6 WAP. TCSV distribution was variable based on the indices (regular, random, and aggregated) 9 WAP.

Optimum Sample Size Determination

Optimum sample size was determined at three levels of precision (0.10, 0.20, and 0.40) using three predetermined density levels (0.10,

Table 9. Taylor's Power Law and Iwao's Patchiness regression equations pertaining to general distribution patterns of thrips and TCSV based on cumulative data collected from fields 1, 2, and 3 during 3 yr of tomato growing seasons (all fields all years together for 3, 6, and 9 WAP)

Parameters	Taylor's power law			Iwao's patchiness regression	
	n	r^2	Equation	r^2	Equation
			3 WAP		
TCSV	864	0.97	$\log s^2 = -0.15 + 0.85 \log x$	0.98	$x^* = -0.03 + 0.86\ x$
Melon thrips	864	0.76	$\log s^2 = 0.09 + 0.75 \log x$	0.41	$x^* = 0.98 + 0.61\ x$
Common blossom thrips	864	0.98	$\log s^2 = -0.15 + 0.86 \log x$	0.90	$x^* = 0.01 + 0.70\ x$
Western flower thrips	864	0.94	$\log s^2 = -0.12 + 0.89 \log x$	0.52	$x^* = 0.01 + 0.68\ x$
			6 WAP		
TCSV	864	0.93	$\log s^2 = -0.001 + 0.83 \log x$	0.98	$x^* = 0.19 + 0.94\ x$
Melon thrips	864	0.76	$\log s^2 = 0.14 + 0.64 \log x$	0.85	$x^* = 0.81 + 0.77\ x$
Common blossom thrips	864	0.93	$\log s^2 = -0.06 + 0.82 \log x$	0.79	$x^* = 0.21 + 0.72\ x$
Western flower thrips	864	0.86	$\log s^2 = 0.10 + 1.15 \log x$	0.52	$x^* = -0.15 + 1.64\ x$
			9 WAP		
TCSV	864	0.96	$\log s^2 = -0.01 + 0.87 \log x$	0.99	$x^* = 0.09 + 0.96\ x$
Melon thrips	864	0.89	$\log s^2 = 0.13 + 0.81 \log x$	0.98	$x^* = 0.44 + 0.92\ x$
Common blossom thrips	864	0.79	$\log s^2 = -0.09 + 0.79 \log x$	0.90	$x^* = 0.10 + 0.80\ x$
Western flower thrips	864	0.92	$\log s^2 = -0.11 + 0.82 \log x$	0.77	$x^* = 0.15 + 0.68\ x$

x*, mean crowding index.

Table 10. Various statistical indices pertaining to the general pattern of distribution of TCSV and three species of thrips based on cumulative data collected in three tomato growing seasons

Parameters	*n*	Index of dispersion	Mean crowding	Green's index	Lloyd's mean crowding
			3 WAP		
TCSV	864	0.85 REG	0.64 REG	−0.01 REG	0.70 REG
Melon thrips	864	1.56 AGG	1.62 AGG	0.06 TA	2.90 AGG
Common blossom thrips	864	0.88 REG	0.29 REG	−0.01 REG	0.68 REG
Western flower thrips	864	0.92 REG	0.22 REG	−0.01 REG	0.69 REG
			6 WAP		
TCSV	864	1.07 AGG	1.88 AGG	0.02 RAN	1.59 AGG
Melon thrips	864	1.44 AGG	2.02 AGG	0.03 RAN	1.84 AGG
Common blossom thrips	864	1.06 AGG	0.60 REG	0.02 RAN	1.48 AGG
Western flower thrips	864	1.14 AGG	0.61 REG	0.02 RAN	1.60 AGG
			9 WAP		
TCSV	864	0.99 RAN	2.88 AGG	0.004 RAN	1.11 AGG
Melon thrips	864	1.25 AGG	2.58 AGG	0.01 RAN	1.23 AGG
Common blossom thrips	864	0.94 REG	0.76 REG	−0.002 REG	0.93 REG
Western flower thrips	864	0.95 REG	0.58 REG	0.01 REG	1.17 AGG

Index of dispersion, Mean crowding, Lloyd's mean crowding: AGG, aggregated distribution, value significantly > 1; RAN, random distribution, value not significantly different from 1; REG, regular distribution, value significantly <1. Green's index: AGG, Aggreated distribution, Value = 1; RAN, Random distribution, Value = 0; REG, Regular distribution, Value negative; TA, Toward aggregation.

0.20, and 0.40 per sample) for melon thrips, common blossom thrips, and western flower thrips (Table 11). Considering predetermined density of melon thrips 0.10 per sample, one needs 1,280 samples to correctly estimate melon thrips density accepting 10% reduction in precision level; whereas, the corresponding sample number is only 80 using the same density (0.10 per sample) at 40% reduction in precision (Table 11). Further, at the same precision level of 40% by increasing the visual density of melon thrips to 0.40 instead of 0.10 per sample, one needs only 14 samples per 55.74 m^2 (600 ft^2) area. These numbers varied with the advanced sampling dates keeping the precision level and visual density same. As common blossom thrips and western flower thrips density is low with lots of zeros in the total pool of samples, sample size determination to estimate their density correctly may become faulty. At this low population level of common blossom thrips and western flower thrips, it is reasonable to use medium to low precision levels at low to medium predetermined density.

Discussion

During the 3 yr of this study (2015, 2016, and 2017) at three locations and additional one dozen locations in South Florida, we observed that TCSV infection started invariably at the edge of the fields at the beginning of tomato plantings. We also determined the distribution of vector thrips of this tospovirus. In order to determine key thrips vectors of TCSV, we conducted a detailed survey in various tomato fields at various locations. We recorded six species of thrips including melon thrips (*Thrips palmi* Karny), onion thrips (*T. tabaci* Lindeman), chilli thrips (*Scirtothrips dorsalis* Hood), common blossom thrips (*Frankliniella schultzei* Trybom), western

Table 11. Determination of optimum sample size for common blossom thrips, western flower thrips, and melon thrips at 0.10, 0.20, and 0.40 precision level using theoretical density (*x*) 0.10, 0.20, and 0.40 per sample

	Density level								
Precision level (%)	0.10	0.20	0.40	0.10	0.20	0.40	0.10	0.20	0.40
	3 WAP			6 WAP			9 WAP		
				Common blossom thrips					
0.10	1597.6	64.8	26.3	3203.8	1317.1	549.4	1265.6	551.2	240.0
0.20	39.9	16.2	6.6	800.9	329.3	137.3	316.4	137.8	60.0
0.40	9.9	4.1	1.6	200.2	82.3	34.3	79.1	34.4	15.0
				Western flower thrips					
0.10	166.9	66.9	26.8	565.6	314.4	174.4	2504.4	1004.4	402.
0.20	41.7	16.7	6.7	140.4	78.6	43.6	626.1	251.1	100.5
0.40	10.4	4.2	1.7	35.1	19.6	10.9	156.5	62.7	25.1
				Melon thrips					
0.10	1280.2	537.8	226.1	2572.6	999.0	382.6	4224.0	1999.3	946.8
0.20	320.0	134.5	56.5	643.1	249.7	97.4	1056.0	499.8	236.7
0.40	80.0	33.6	14.1	160.8	62.4	24.2	264.0	124.9	59.1

flower thrips (*F. occidentalis* (Pergande)) and Florida flower thrips (common name not approved by ESA) (*F. bispinosa* Morgan). An earlier study by Seal and Zhang (2015) also reported these thrips from South Florida tomato fields. Among these six species, melon thrips, common blossom thrips and western flower thrips were common in all TCSV infected tomato fields at higher numbers. This information led us to speculate that melon thrips, common blossom thrips and western flower thrips might be the vectors of TCSV in tomato fields. Various research studies also reported the TCSV transmission potentials of common blossom thrips (Wijkamp et al. 1995, Nagata et al. 2004, Londoño et al. 2012, Webster et al. 2015) and western flower thrips (Wijkamp et al. 1995, Nagata et al. 2004). The role of melon thrips in transmitting tospovirus is not quite clear although it is the most common thrips in the tomato fields. Several researchers also recorded it as a vector of tospoviruses (Sakimura 1962, 1963; Webb et al. 1997; Mound 2002).

During the 3 years' survey, we collected thrips adults from the TCSV infected tomato fields with a very insignificant number of larvae, thus indicating viruliferous vector adults originated from outside hosts. Tospoviruses are transmitted in a persistent propagative manner (Ullman et al. 1997, Ullman et al. 2002). Tospoviruses can only be acquired by early instars of vector thrips while feeding on infected plants, and the developing adults are considered as viruliferous adults. These adults are capable of transmitting virus through their lifetime (Moritz et al. 2004, Whitefield et al. 2005, Persley et al. 2006). Our observation on the rare abundance of thrips larvae in tomato clearly indicated that the viruliferous adults came from outside hosts near the virus affected tomato fields. Duffus (1971) accordingly stated that epidemiology of emerging viruses in any agroecosystems comprises the diversity of wild plant hosts, cultivated crops and insect complex. Duffus (1971) also indicated that the wild plants can be the hosts of virus or virus-vectors. In a study, Seal and Khan (2018) collected 26 ornamental plants from nearby nurseries. Various species of thrips adults and larvae (not all identified) were recorded on all those plants. They also collected 21 species of weeds from the tomato agroecosystem of which 67% plant species had thrips larvae, 48% had common blossom thrips adults, 52% had melon thrips adults, and none was found positive for western flower thrips. Most of these weeds voluntarily grew at the sides of the tomato fields, fallow areas, groves of avocado, palm, and on the fences of neighboring houses. Thrips generally migrate from the weeds to the younger cultivated hosts (Puche et al. 1995, Coutts et al. 2004, Fernandes and Fernandes 2015). Various factors such as temperature, precipitation, resource abundance, population density, and attacks from the natural enemies are the most probable stimuli associated with migration of vectors (Hance et al. 2007).

In the present study, we observed that abundance of thrips is decreased with the increase of distance from the edge of the field toward the center of the field. Thrips take advantage of wind direction to migrate from their original non-tomato hosts to tomato. Seal et al. (2006) reported such effect of prevailing wind in chilli thrips distribution in pepper fields. Being driven by wind, thrips land immediately at the edge of the tomato field and slowly move further inside the tomato fields. This statement is evident from our data on the abundance of thrips and TCSV in the present study fields (Figs. 1–4). High abundance of thrips and TCSV at the edge of a field was consistent on all sampling dates of 2015, 2016, and 2017 in all tomato fields sampled. Like thrips, TCSV spread in tomato fields follow the same pattern with more infected plants at the edge than away from the edge.

Spatial Distribution

Tomato is a poor host of thrips as documented from the present study. Until 2012, tomato was not considered as a host of melon thrips (Capinera 2000). Common blossom thrips and western flower thrips are considered as pests of tomato (Seal and Zhang 2015, Seal and Khan 2018) but their abundance and reproduction are very low on tomato ((Reitz 2002).

Determining thrips distribution pattern in tomato is critical due to the poor host and pest relationship. However, dispersion and spatial distribution pattern are important factors that accelerate thrips infestation and cause them to be difficult to control (Heyler and Brobyn 1992). We tested various statistical models to determine the distribution pattern of each thrips species and also of TCSV symptomatic plants. Taylor's power law and Iwao's patchiness regression fit well to the data pertaining to each thrips species and TCSV as observed from the r^2 values (r^2 = 0.63–0.97 for Taylor's power law; 0.64–0.98 for Iwao's patchiness regression in field 1). In this field, distribution of all parameters (TCSV, melon thrips, common blossom thrips, and western flower thrips), irrespective of sampling dates, followed regular pattern, which is agreed on by both models based on the b/ β (slope) values (Table 3). Compared to both models, other indices (Index of dispersion, Mean crowding, Green's index, and Lloyd's index) showed variable distribution patterns depending on parameters and sampling dates in field 1 (Table 4). In field 2,

both models showed similar pattern of distribution of all parameters irrespective of sampling dates as in field 1 (Table 5). Other indices showed (75%) regular and 6% aggregated distribution of all parameters on the first sampling date (3 WAP) (Table 6). On the following sampling dates (6 and 9 WAP), distribution pattern varied depending on indices and parameters. Based on indices, various parameters showed aggregated distribution, which increased with increasing sampling dates. In field 3, both models showed regular distribution pattern of all parameters (TCSV, melon thrips, common blossom thrips, and western flower thrips) irrespective of sampling dates (Table 7). Based on other indices (Table 8), pattern of distribution of various parameters was mostly regular (75%) on the first sampling date, but shifted to aggregation to a greater number (63%) on the second (6 WAP) and third (9 WAP) sampling dates (31%). Milne et al. (2002) and Arevalo and Liburd (2007) reported clumped distribution of common blossom thrips and western flower thrips. Several other studies also reported clumped distribution pattern of Thysanoptera species. *Frankliniella occidentalis* (Pergande) had aggregated distribution on greenhouse cucumber (Steiner 1990, Cho et al. 2001). *Frankliniella intonsa* (Trybom), *F. occidentalis*, *Thrips angusticep* (Uzel), and *T. tabaci* demonstrated aggregated distribution in cotton (Deligeorgidis et al. 2002). Seal et al. (2006) stated *Scirtothrips dorsalis* Hood distribution in pepper as mostly aggregated followed by regular. Kakkar et al. (2012) demonstrated aggregated distribution of *F. schultzei* on field-grown cucumber using Taylor's power law, Iwao's patchiness regression and Index of dispersion (ID). However, all these studies were conducted on preferred hosts of above-mentioned thrips unlike the present study. There is a paucity of information on the factors that influence thrips to aggregate. We speculate that host suitability, temperature, fertilizer, irrigation and natural enemies might play important role in this regard which should be properly investigated.

Intercept values (*a*) of Taylor's power law are mostly negative and those of Iwao's patchiness regression are for mostly positive. Negative slope values always create unfavorable situation in determining sample size, where intercept (*a*) value is an important factor. Based on this, we found that Iwao's patchiness regression is more suitable for determining within-field distribution of various parameters.

The generalized distribution pattern of each parameter conforms to the individual pattern from individual sampling date in each year in each field. Both Taylor's Power Law and Iwao's Patchiness Regression models fit well to the data as shown by high r^2 values. Iwao's patchiness distribution model fits better than the Taylor power law when the intercept values are considered. Among the various indices, Green's index is not suitable for determining distribution pattern in the present study scenarios. Lloyd's mean crowding reflects predetermined distribution pattern (aggregated distribution) more closely followed by Index of dispersion and Mean crowding.

The present study situation is unique and differs from others in relation to the vector thrips population abundance and presence of various non-tomato hosts in the tomato agroecosystem. Taylor's power law and Iwao's patchiness regression provide answers for vector and virus distribution at the beginning of the season 3 WAP. With the progression of the season, other statistical indices (Index of dispersion, Mean crowding, Green's index, and Lloyd mean crowding) reflected expected distribution (aggregated) of thrips and TCSV infected plants (Table 10). Based on the present study results, thrips and TCSV distribution were mostly regular at the beginning (3 WAP) which occurs due to the migration of thrips from a wider area of weed or non-tomato host population to a long and narrow strip of early planted tomato at the edge of the field. As tomato season progresses, more viruliferous thrips migrate to the edge of tomato fields and causes aggregation of the population of certain thrips and TCSV symptomatic plants. TCSV propagation is principally by the influx of viruliferous adults from the outside hosts.

We determined sample size using three predetermined densities per sample (0.10, 0.20, and 0.40) at three levels of precision (0.10, 0.20, and 0.40). As melon thrips density is comparatively higher than common blossom thrips and western flower thrips, these predetermined precision and density levels will be useful to determine optimum sample size. However, for common blossom thrips and western flower thrips with fairly low population density and virus transmission potentials (as observed from the present field situation), the low density (0.10 to 0.20) at medium (20%) to high (40%) precision levels will be appropriate to determine optimum sample size.

The study results demonstrated that vector thrips adults and TCSV infected tomato plants appeared first at the edge of a field shortly after planting tomato by the migration of vectors from the wild hosts. Abundance of thrips and TCSV decreased with the distance and increased with the age of tomato. Melon thrips distribution was aggregated; other thrips and TCSV distribution varied from regular to aggregated, or vice-versa. Iwao's patchiness regression, Index of dispersion, Mean crowding, Green's index and Lloyd's mean crowding should be used for understanding appropriate pattern of distribution of thrips and tospovirus. To develop a time-sensitive and economically feasible and reliable sampling plan to understand vector density, number of samples should be collected based on predetermined density of 0.40 adults per sample at 0.40 precision level, which will provide accurate information about all thrips investigated in this study. This will help growers and pest management personnel to collect minimum and adequate samples required to understand pest density accurately to initiate management program at right time.

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