Spatial distribution and temporal dynamics of *Frankliniella occidentalis* Pergande, 1895 and *Thrips palmi* Karny, 1925 (Insecta: Thysanoptera: Thripidae) in orchids in Singapore[1]

He Liansheng[2], Zuria Mohama Din[2], and Yap Mei Lai[2]

Abstract: The spatial distribution and temporal dynamics of the Western Flower Thrips, *Frankliniella occidentalis*, and of the Melon Thrips, *Thrips palmi* (both Thysanoptera: Thripidae), were studied in five orchid farms in Singapore. The population of *T. palmi* was more abundant and dominant than that of *F. occidentalis* during the study. *Frankliniella occidentalis* occurred in the farms only from February to June 2011 and *Thrips palmi* was present for the entire sampling period, January to November 2011. Blue traps trapped *T. palmi* more effectively while WFT traps were more suitable for population monitoring of *F. occidentalis.* Both *F. occidentalis and T. palmi* tend to aggregate themselves at the tested population size of 10 thrips/trap in average. Parameters "a" and "b" of the Taylor's Power Law and parameters of "α" and "β" of the Iwao's Patchiness Regression Index indicate that individuals of *F. occidentalis* and *T. palmi* tend to form aggregation patches. While *T. palmi* aggregate in patches, the patches are uniformly distributed. In contrast, for *F. occidentalis*, both individuals and patches are aggregated. Parameters to be considered for a surveillance strategy for *F. occidentalis* are also discussed.

Key Words: Thysanoptera, *Frankliniella occidentalis, Thrips palmi,* dominance, temporal dynamics, spatial distribution

Frankliniella occidentalis Pergande, Western Flower Thrips (WFT) (Figure 1a) and *Thrips palmi* Karny, Melon Thrips (MT) (Figure 1b) were among the main insect pests detected in commercial cultivation of orchids under netting in Singapore in 2011. *Frankliniella occidentalis* is a small insect native to the west coast of North America that has reported to have spread through much of Europe in the 1980's. More recently, *F. occidentalis* has been reported throughout the temperate parts of North and South America, most countries in Europe, the temperate parts of Africa, Australia, New Zealand, and Japan (Kirk and Terry 2003, Waterhouse and Norris 1989). The WFT has a broad host range of more than 500 plant species placed in 50 families, including many cultivated crops and ornamentals (Yudin et al. 1986). The host range for this insect pest include eggplants (*Solanum melongena* L., Solanaceae), peppers (*Capsicum* spp., Solanaceae), tomatoes (*Solanum lycopersicum* L., Solanaceae), cucumbers (*Cucumis sativus* L., Cucurbitaceae), watermelons [*Citrullus lanatus* (Thunb.), Cucurbitaceae], lettuces (*Lactuca sativa* L., Asteraceae), and onions (*Allium cepa* L., Amaryllidaceae). *Frankliniella occidentalis* has been reported to be a

[1] Submitted on July 4, 2013. Accepted on July 15, 2013. Final revisions received on October 30, 2013.

[2] Plant Health Laboratory Department, Laboratories Group, Agri-Food and Veterinary Authority of Singapore, Singapore 718827. E-mail: HE_Lian_Sheng@ava.gov.sg

DOI: 10.9784/LEB1(3)He.03
Electronically available on November 11, 2013. Mailed on December 28, 2013.

particularly serious pest of tomatoes, peppers, some leafy vegetables such as celery (*Apium graveolens* L var. *secalinum*, Apiaceae), spinach (*Spinacia oleracea* L., Amaranthaceae), silverbeet (*Beta vulgaris* subspecies *cicla* (L.), Amaranthaceae), and cucurbits (Kakkar et al. 2012, Rosenheim et al. 1990, Terry 1997). Ornamental crops, especially cut flowers, such as roses (*Rosa chinensis* Jacq, Rosaceae), chrysanthemum (*Chrysanthemum* spp., Asteraceae), and orchids (*Dendrobium* spp., Orchidaceae), can also be devastated by this pest (Metcalf and Flint 1962, Kakkar et al. 2012). Moreover, *F. occidentalis* is also responsible for the transmission of numerous viral diseases, such as the Tomato Spotted Wilt Virus (TSWV) and the *Impatiens Necrotic Spot Virus* (INSV), both affecting peppers and a wide range of ornamental crops (Cho et al. 1986, 1988; Welter et al. 1990; Yolanda et al. 2006; Yudin et al. 1986).

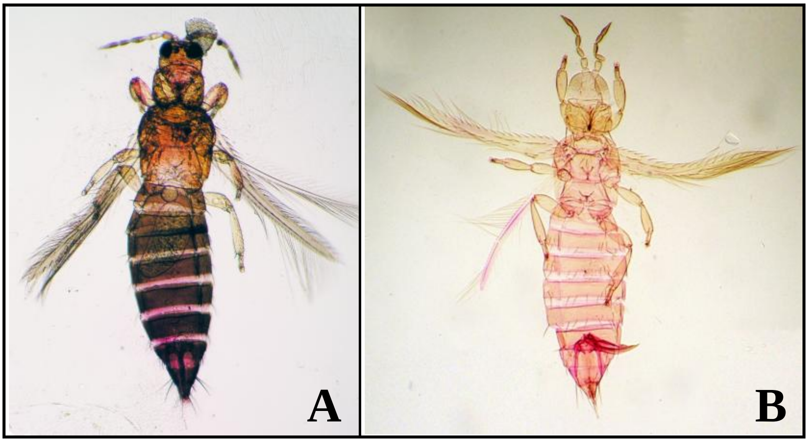

Figure 1. a. Female *Frankliniella occidentalis*, the Western Flower Thrips (WFT). b. Female *Thrips palmi*, the Melon Thrips (MT). Both *F. occidentalis* and *T. palmi*, have their wing surfaces covered with microtrichia, females have well developed saw-like ovipositor which turns downwards away from the body, and their abdominal segment X is conical (never tubular). However, the WFT is larger (1.3 – 1.7 mm long) and has 8-segmented antennae. Female WFT are usually dark brown and have transversal white bands on the posterior portion of the abdominal tergites; males are smaller and lighter in color, sometimes they are pale or light yellow depending on the host plants, season, and geographic location. In contrast, the MT is smaller (1.0–1.3 mm long), has 7-segmented antennae, and it is almost entirely yellow in different hues (specimen looks pink as it was stained for scientific study). Although thrips are bisexual insects, females reproduce with or without copulation. Unmated females produce progeny by parthenogenesis. In the field, most of thrips are females.

In orchid farms, *T. palmi*, is another important polyphagous pest. This thrips species can infest a wide range of ornamental and vegetable crops, particularly those under Cucurbitaceae and Solanaceae, such as cucumber, and sweet pepper (CABI 1998; Hirose 1991; Kawai 1990; Lewis 1973, 1997; North and Shelton

1986; Okajima et al. 1992; Rosenheim et al. 1990; Sedaratian et al. 2010). The species is capable of causing economic damage to crops both as a direct result of its feeding activity and from its ability to vector tospoviruses, such as Groundnut bud necrosis virus, Melon yellow spot virus and Watermelon silver mottle virus. *Thrips palmi* has been recorded from more than 36 plant families (Kawai and Kitamura 1987, Hirose 1991, Lewis 1997). Direct feeding damage is caused by adults and larvae sucking the cell contents from leaves, stems, flowers and the surface of fruits, thereby causing silvery scars and leaf chlorosis. Plant growth can be stunted as well as fruits deformed and heavily scarred. A severe infestation can kill an entire plant (Lewis 1973, 1997; Tsai et al. 1995; Welter et al. 1990).

Factors affecting thrips distribution

Colour and height of host plants have been reported to affect the spatial distribution of thrips (Beavers et al. 1971, Cho et al. 1995, Hoddle et al. 2002). Knowledge of pests' temporal and spatial distribution is essential in integrated pest management (IPM) efforts, including definition of monitoring procedures, damage assessment, and evaluation of control measures efficacy (Cho et al. 1995, 2001; Kirk 1984; Shipp and Zariffa 1991; Yudin et al. 1987).

To understand the temporal dynamics and the spatial distribution of thrips in orchid farms, it was necessary to have an intensive surveillance of *F. occidentalis* and *T. palmi*. Thrips tend to be trapped more by blue sticky traps than any other colour of traps. The efficacy of insect trapping is dependent on the placement height of the traps (Kirk 1984, Lewis 1959, Matteson and Terry 1992, Navás et al. 1994, Vernon and Gillespie 1995). The WFT male-produced aggregation pheromone, Neryl(S)-2-methylbutanoate and (R)-lavandulyl acetate have been identified as male-produced compounds with the former being shown to increase trap catch in glasshouse trials (Dublon 2009, Fargro Biological Control 2013). Therefore, the blue sticky traps and WFT male-produced aggregation pheromone traps were used as the basic tools for population dynamic monitoring of thrips.

In this paper, the dominant species of thrips, the effectiveness of different traps, and the population temporal dynamics, and spatial distribution of *F. occidentalis* and *T. palmi* in local orchid farms were considered to provide insights for development of possible surveillance strategy.

Methods

The study was conducted in the five local orchid farms[1], all located in northeastern Singapore, as shown in Figure 2. The experimental period was from February to October 2011.

[1] Please, feel free to contact the authors for the details of the orchid farms.

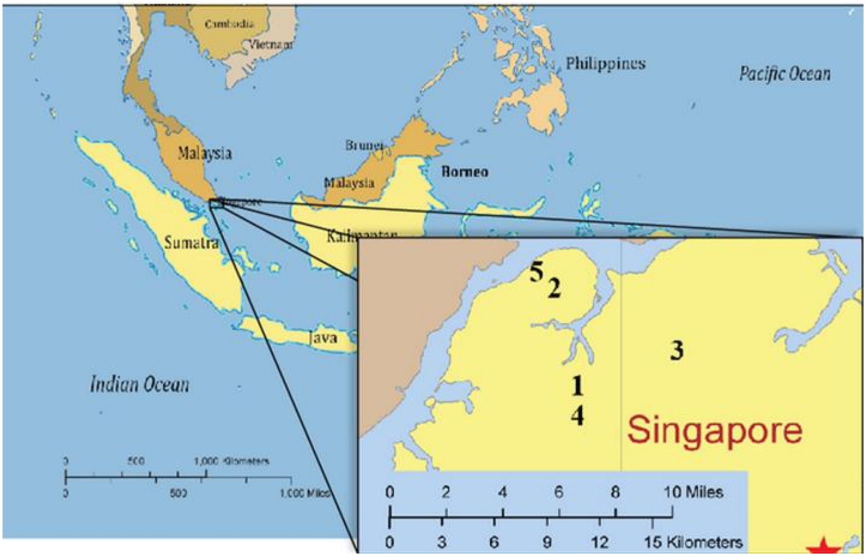

Figure 2. Singapore, showing locations of the study (1-5), and some of its southeastern Asian neighbouring countries.

Trap setting

The placement of the traps was based on the biology of the WFT and MT. Based on our preliminary results, two different heights were set for trapping *F. occidentalis* and one height was set for *T. palmi* in each orchid farm. The details of the traps setting were described below.

1. Blue sticky traps for *T. palmi*: These were used to detect and monitor temporal fluctuation of thrips population. Four such traps were deployed to each farm. The traps were placed at a height of 50 cm below the orchid florescence, some 100 cm above the ground. The distance among the traps were at least 10 meters away. Based on our preliminary experiments, which was reported in an internal technical report of Agri-Food and Veterinary Authority of Singapore (AVA), which has not been published yet, blue sticky traps caught more *T. palm* at this height than any other height in the orchid farms.

2. Blue sticky traps for *F. occidentalis*: Similarly, four blue sticky traps were set per farm at a height of 50 cm above the top of orchid flowers to catch *F. occidentalis.* Preliminary results also demonstrated that this height maximized capture of *F. occidentalis*. The traps were also set at 10 meters apart from each other.

3. WFT Pheromone traps: WFT synthetic pheromone lures were purchased from Syngenta Bioline Ltd. (Telstar Nursery, Holland Road, Little Clacton, Essex CO16 9QG, UK). The WFT Pheromone traps were consisted of two parts, the blue sticky trapping papers and the pheromone lures. Four blue sticky papers each with a synthetic WFT sexual aggregation pheromone were set at 30 cm above the top of flowers at 10 meters apart in the selected farm.

Trap collection and replacement

Both MT and WFT blue sticky traps were collected and replaced weekly. WFT pheromone traps were collected and replaced as follows: the blue sticky paper traps were collected and replaced weekly while the WFT pheromone lures were replaced every three months.

Trap assessment

The traps collected weekly were examined with a stereozoom microscope in the laboratory. The number of caught *F. occidentalis* and *T. palmi* were recorded. Where needed, trapped thrips were extracted from the traps and mounted for morphological examination and identification.

Population dominance assessment

To analyse the degree of dominance of the two species of thrips in orchid farms, the Simpson-Yule Dominance Index (SYDI) (Bakus 2007; Bakus et al. 2007) was calculated, as follows (1).

$$\text{SYDI} = n_i * (n_i - 1) / [N*(N-1)] \qquad (1)$$

In equation (1), n_i was the number of individuals of species i, N was the total number individuals of all species.

Measurement of population spatial pattern

The spatial distribution patterns of *F. occidentalis* and of *T. palmi* were determined by using four different formulae: Taylor's Power Law [Taylor 1961, equation (2), below], Iwao's Patchiness Regression Index (Iwao 1968), Index of dispersion (ID) (Elliott 1977), and mean crowding (Lloyd 1967).

Taylor's Power Law parameters were obtained by the regression of $\log_{10}$-transformed variances, "y", on $\log_{10}$-transformed mean number, "x" of *F. occidentalis* and *T. palmi* per sample, i.e., by means of the linear regression model (Taylor 1961):

$$\text{Taylor's Power Law: } \log y = \log a + b \log x \qquad (2)$$

In equation (2), y was the standard deviation; x was the individuals of thrips on traps. The value, "*a*", was a parameter relevant to the sample size while "*b*" was the parameter of population aggregation relevant to the characteristics of species. The transformation log $\sqrt{X + 0.5}$ was used in Taylor's Power Law. According to this model, a "*b*" value > 1 denoted a population with an aggregated distribution, a "*b*" value significantly < 1 denoted a regular (uniform) distribution, and a "*b*" value not significantly different from 1 (b=1) denoted a random distribution. The fit of each data set to the linear regression model was evaluated by calculating the r^2 the coefficient of determination (Pearson r-squared, R^2), which was used as an indicator of quality of the linear regression log y and log *x* (Colin et al. 1997, Flynn and Pereira 2009) The Student's t-test was used to determine if the slopes (*b* values) obtained by means of the linear regression procedure were equal to 1, significantly < 1, or significantly > 1 (Neter and Wasserman 1974).

Likewise, the Iwao's Patchiness Regression was calculated for each data set.

$$\text{Iwao's Patchiness Regression } M^* = \alpha + \beta M \qquad (3)$$

which might be seen as parallel to Taylor's Power Law, was the regression of mean crowding, M*, on the mean M (Lloyd 1967, Iwao 1968). The factor, "α", depends on the size of the sampling unit and "β" was the index of aggregation in the population. If $\beta = 1$, the population was randomly distributed, and if $\beta > 1$ or $\beta < 1$, the spatial distribution would be aggregated and uniform, respectively. The fit of each model to data from various trap types was determined based on the values of r^2, the coefficient of determination (Colin et al. 1997, Nagelkerke 1991)

Generalized linear model (GLM) procedures, which are statistical technique to conduct Analysis of Variance for experiments with two or more factors, were also used to perform analyses of variance of dependent variables of data collected from the various types of traps.

In addition, an Index of Dispersion (ID) (Elliott 1977) was calculated as follows:

$$ID = s^2/x \qquad (4)$$

In equation (4), "*x*" was the mean number of *F. occidentalis* or *T. palmi* individuals per sample and "s^2" is the sample variance. Values of ID greater than 1.0 indicated an aggregated distribution of samples, < 1 regular and = 1 random (Elliott 1977).

Finally, Mean Crowding (m*) and Lloyd's 'Patchiness' Index (m*/m) were calculated for *F. occidentalis* and *T. palmi* collected from various traps in the five farms.

$$\text{Mean Crowding, } m^* = m + [(\sigma^2/m) - 1] \qquad (5)$$

$$m = \sum_{j=1}^{Q} \frac{x_j}{Q}$$

where, m = mean density; δ^2 = the sample variance, and x_i = number of individuals/sample (Q).

Mean crowding (m^*) was proposed by Lloyd (1967) to indicate the possible effect of mutual interference or competition among individuals. Theoretically, mean crowding was the mean number of other individuals per individual in the same niche or the status of an organism within its environment and community affecting its survival as a species. As an index, mean crowding is highly dependent both upon the degree of clumping and population density. To remove the effect of changes in density, Lloyd (1967) introduced the index of patchiness, expressed as the ratio of mean crowding to the mean. As with the variance-to-mean ratio, the index of patchiness is dependent upon quadrate size: m* / m = 1 random, < 1 uniform (regular), and > 1 aggregated (Lloyd 1967). Thus, in equation (5), mean crowding equaled the difference between the ratio of the variance to mean density minus 1 plus the mean density itself. In a random distribution, the variance and mean density were equal, the quantity in parentheses disappears, and m* and m become equal. In the instance of Lloyd's Patchiness Index, the value of m* was divided by m (m*/m) (Sedaratian et al. 2010). All statistical tests were performed for a level of significance (a) equal to 0.25 to 0.01 (Steel and Torrie 1980).

Results

All results of thrips indicated in this report were referred to the species *F. occidentalis* (WFT) and *T. palmi* (MT). The analyses were based on 444 samples collected from 20 locations distributed in the five orchid farms in Singapore.

Population temporal dynamics of WFT and MT in orchid farms

The population temporal dynamics of *F. occidentalis* (Figure 3) indicated that the thrips were present in the field only from February to June 2011. They disappeared after 15 June in all of the five farms. In contrast, *T. palmi* was observed all the time during the experiment period (Figure 4).

For *F. occidentalis*, WFT traps set at a height of 50cm above the top of the orchid flowers appeared to be the most effective (Figure 3) in trapping *F. occidentalis*. On the other hand, the blue traps set at a height of 50cm below the top of the orchid flowers were found to have caught more *T. palmi* compared to the WFT traps (Figure 4).

During the observation period, the population of *F. occidentalis* peaked during February to March 2011. Thereafter, the population decreased until mid June when the species disappeared (Figure 3). On the other hand, the population of *T. palmi* showed three peaks. The first was from early March to early April 2011, which was slightly later than that of *F. occidentalis*. The second population peak was from early July to end of July while the third peak was after 19 Oct. 2011 (Figure 3).

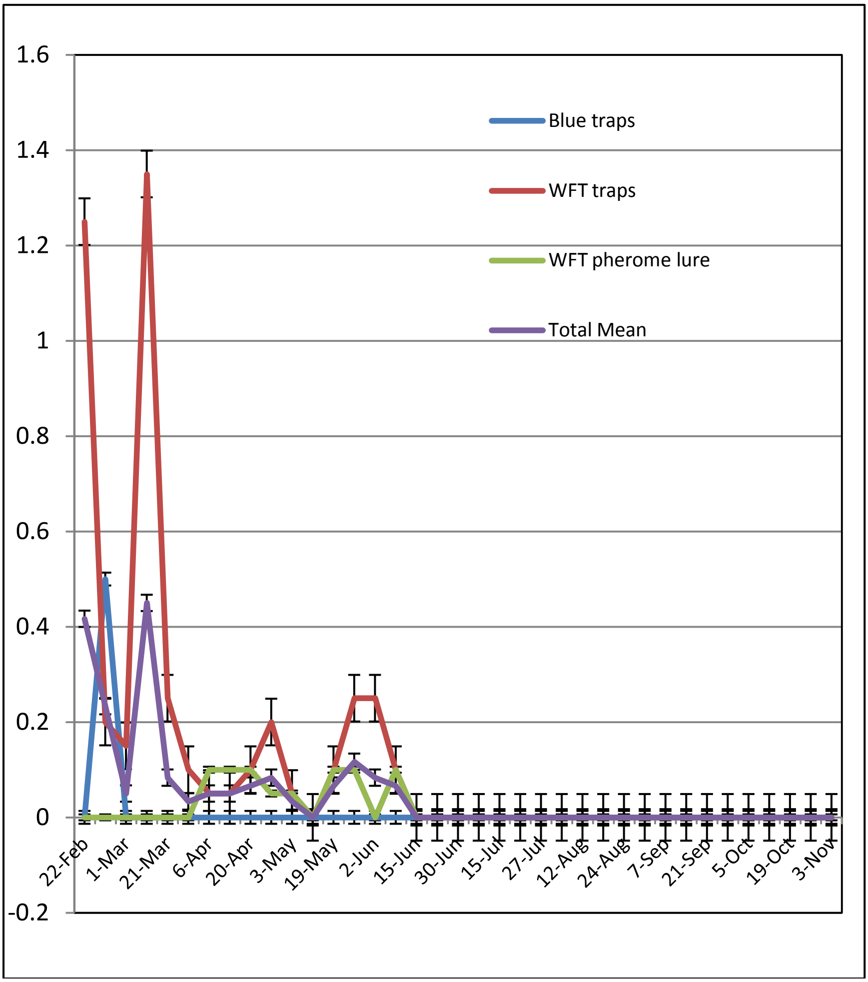

Figure 3. Population temporal dynamics of *Frankliniella occidentalis* monitored in the local orchid farms in Singapore in 2011.

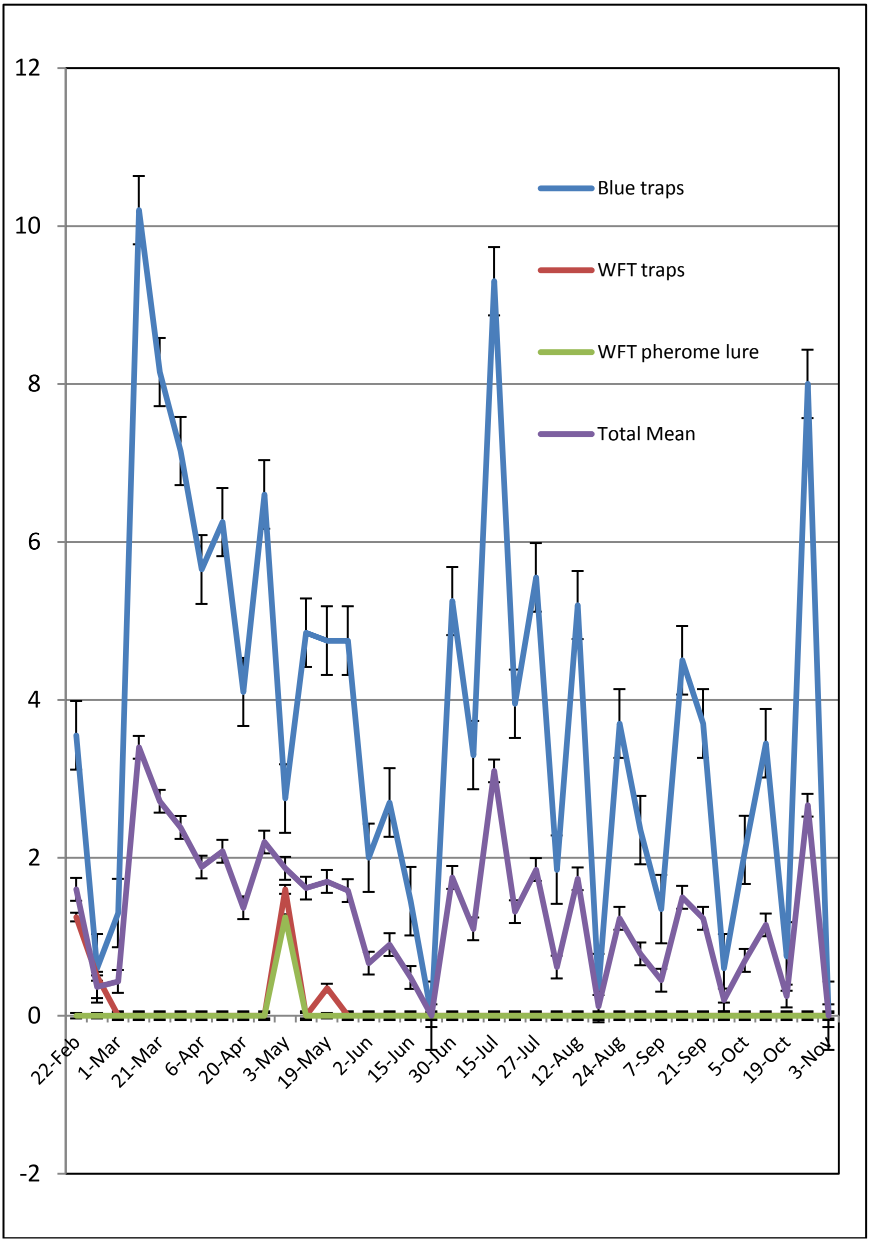

Figure 4. Population temporal dynamics of *Thrips palmi* monitored in the local orchid farms in Singapore in 2011.

Dominance of thrips on orchid in the farms

The results of the two thrips species dominance analysis are presented in Table 1. *Thrips palmi* was found to be the dominant species on orchid in the observed farms with the dominance index (DI) value of 0.9272. On the other hand, the DI value of *F. occidentalis* was 0.0131 only, 70.8 x smaller than that of *T. palmi*.

Table 1. The Simpson's dominance index (DI) of the Western Flower Thrips, *Frankliniella occidentalis*, and Melon Thrips, *Thrips palmi*.

DI	***Frankliniella occidentalis***	***Thrips palmi***
General DI	0.01311±0.056b*	0.9272±1.88a
Blue trap DI	0.004097±0.027b	0.7337315±0.53a
WFT trap DI	0.612586±0.029a	0.000570±0.045b
WFT Pheromone	0.010324±0.017a	0.000058±0.027b

* Values followed by the same letters within each column indicate no significant difference (P > 0.05), Duncan's multiple range tests.

When the DI values of both *F. occidentalis* and *T. palmi* on different types of traps were compared, not surprisingly, the WFT trap was the most significantly effective trap for *F. occidentalis* (DI = 0.61, P < 0.05). This was followed by the WFT pheromone traps (DI = 0.01). Blue traps were the least effective traps (DI = 0.004). For trapping of *T. palmi*, blue sticky traps were more effective (DI = 0.73) than the WFT pheromone traps (DI = 0.0006), and WFT traps (DI = 0.00006, Table 1).

The spatial pattern of F. occidentalis and *T. palmi*

Taylor's Power Law (section A, below), Iwao's Patchiness Regression (B), Lloyd's Patchiness Index and the Index of Dispersion (C) are given in Tables 2 and 3.

A. Taylor's Power Law

Frankliniella occidentalis. The Taylor's Power Law analyses suggested a positive significant relationship between variance and mean density of *F. occidentalis* (Table 2). When the mean density increased, the variance also increased (Figure 5). The Taylor's intercept, "*a*", was greater than zero (*a* = 0.34, t = 1.21, df = 443, P < 0.25). The slope "*b*" was significantly greater than 1 (*b* = 3.121, t = 11.1, df = 443, P < 0.01), which meant that the species *F. occidentalis* tended to have an aggregated dispersion pattern (Table 2).

Table 2. The spatial pattern of Western Flower Thrips, *Frankliniella occidentalis*, and the Melon Thrips, *Thrips palmi*, indicated by Taylor's Power Law.

Thrips Species	Taylor's Power Law Index		
	a	***b***	r^2
Frankliniella occidentalis	0.34	3.121	0.789
Thrips palmi	0.38	2.061	0.992

Thrips palmi. The parameters of Taylor's Power Law for *T. palmi* indicated a positive significant relationship between variance and mean density like that of *F. occidentalis* (Table 2). When the mean density increased, the variance also increased (Figure 6).

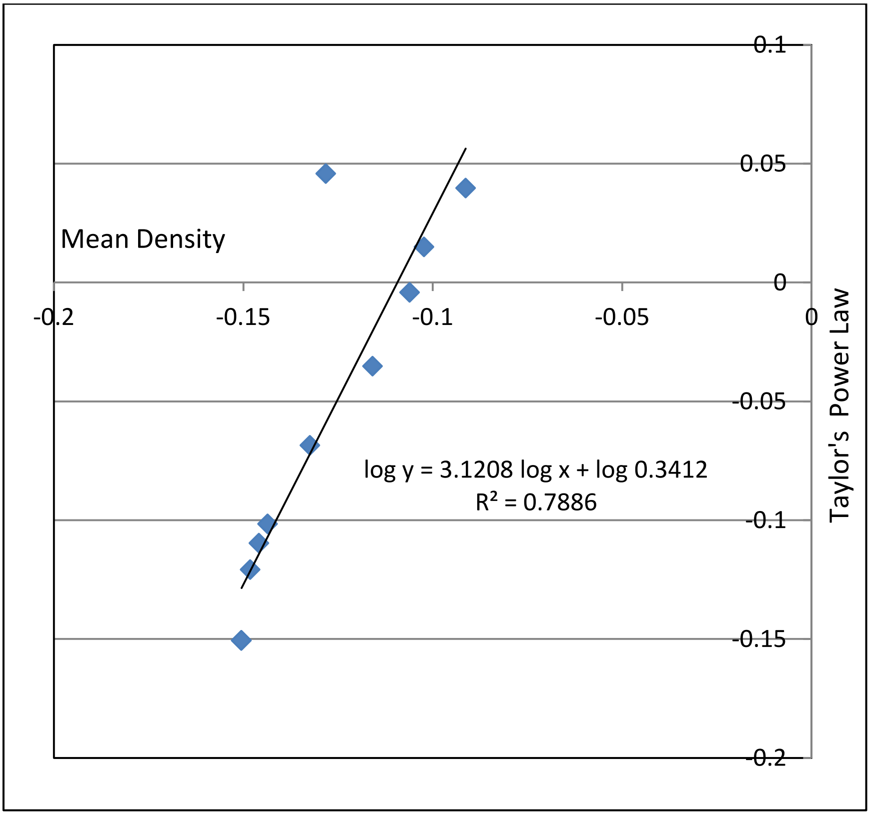

Figure 5. Regression analysis of Taylor's Power Law (log y = log *a* + *b* log *x*) for *Frankliniella occidentalis* on orchids. The diamonds represent the relationship between mean density and Taylor's Power Law.

The Taylor's intercept, "*a*", was 0.38, which was significantly larger than zero (t = 2.44, df = 443, P < 0.05). The slope, "*b*", was 2.06, which was significantly larger than 1 (t = 13.25, df = 443, P < 0.001), which means that *T. palmi* tended to have an aggregated dispersion pattern as well (Table 2).

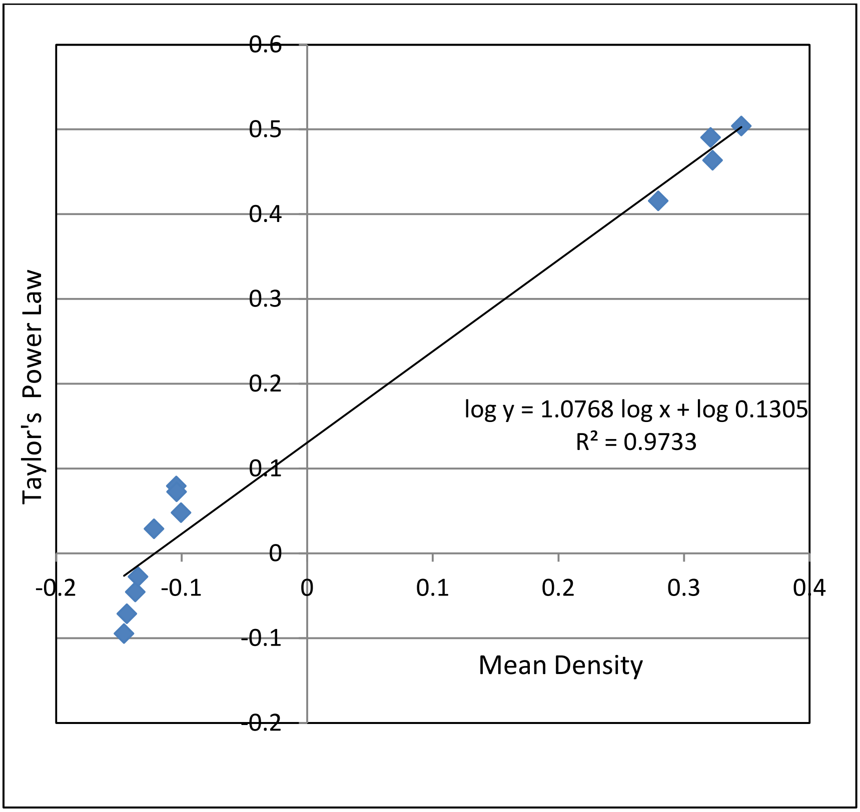

Figure 6. Regression analysis of Taylor's Power Law (log y = log *a* + *b* log *x*) for *Thrips palmi* on orchids. The diamonds represent the relationship between mean density and Taylor's Power Law.

B. Iwao's Patchiness Regression

Frankliniella occidentalis. Iwao's Patchiness Regression of *F. occidentalis* was calculated in table 3 below. The values γ^2 exhibited that Iwao's Patchiness Regression, Taylor's Power Law were more suitable to the spatial distribution of *T. palmi* than that of *F. occidentalis* (Table 3). The γ^2 values of MT were above 0.973 while those of *F. occidentalis* were below 0.741 (Table 3, column 4).

Table 3. The spatial pattern of Western Flower Thrips, *Frankliniella occidentalis*, and the Melon Thrips, *Thrips palmi*, indicated by the Iwao's Patchiness Regression.

Thrips Species	**Iwao's Patchiness Regression Index**		
	α	**β**	r^2
Frankliniella occidentalis	0.064	4.274	0.741
Thrips palmi	0.131	1.080	0.973

The parameters of Iwao's Patchiness Regression of *F. occidentalis* revealed that the intercept value (α) was > 0 ($\alpha = 0.0635$, t = 0.23, df = 443, $P > 0.05$), but it was not significant ($P > 0.05$). Estimated value of "β", the density contagiousness coefficient, was significantly bigger than 1 ($\beta = 4.274$, t = 15.19, df = 443, $P < 0.01$), which indicated that within this population size, they were aggregated (Table 3 and Figure 7).

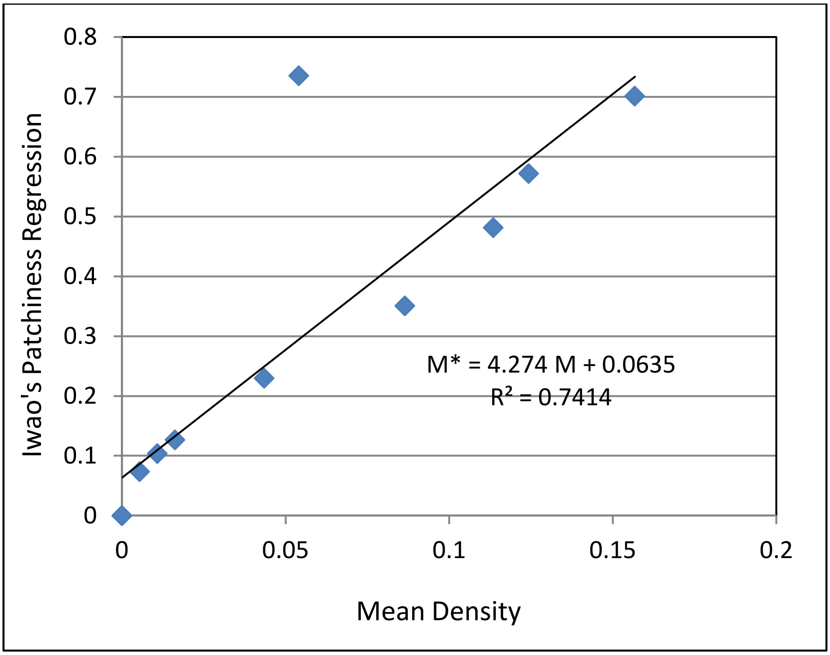

Figure 7. Regression analysis of Iwao's Patchiness Regression ($M^* = \alpha + \beta M$) for *Frankliniella occidentalis* on orchids. The diamonds represent the relationship between mean density and Iwao's Patchiness Regression.

Thrips palmi. Similarly, the Patchiness Regression Index of *T. palmi* indicated that the α was also greater than 0 ($\alpha = 0.1305$, t = 0.84, df = 443, $P < 0.25$). The value of β was significantly larger than 1 ($\beta = 1.08$, t = 6.95, df =

443, P < 0.01). The β value for *T. palmi* showed that this species at this population size aggregated too (Table 3, Figure 8).

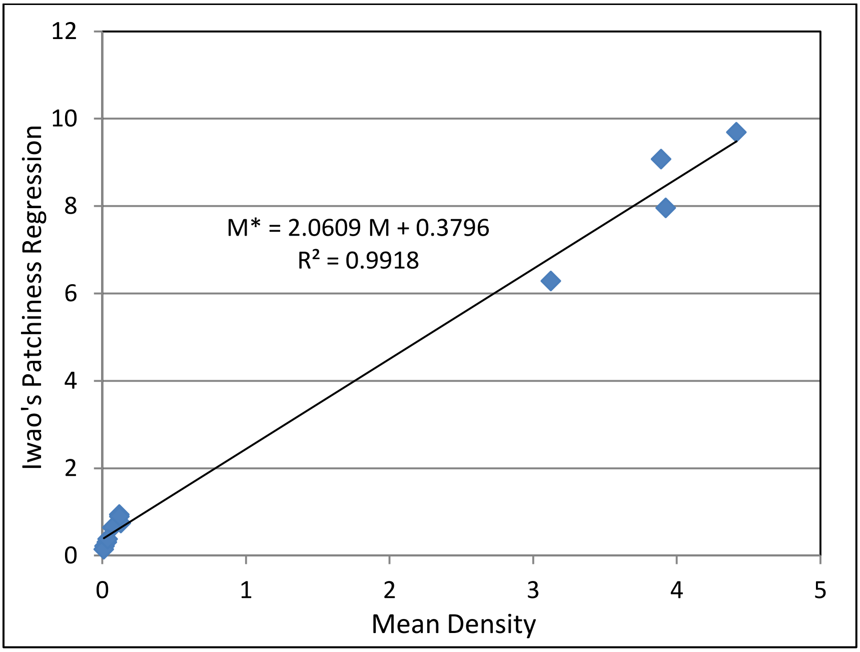

Figure 8. Regression analysis of Iwao's Patchiness Regression (M* = α + βM) for *Thrips palmi* on orchids. The diamonds represent the relationship between mean density and Iwao's Patchiness Regression Index.

C. Index of Dispersion and Lloyd's Patchiness Index

When the spatial distribution of *F. occidentalis* and *T. palmi* were measured by the index of dispersion (ID), a similar trend of mean crowding was obtained, though the difference was not as large as that obtained by calculating the mean crowding index. The individual *F. occidentalis* aggregated (ID = 2.05) while those of *T. palmi* were uniformly (regularly) distributed (ID = 0.66, Table 4).

The values of Lloyd's Patchiness Index showed that *F. occidentalis* aggregated more with the m^*/m value of 21.64. In contrast, *T. palmi* appeared to be uniformly distributed with the m^*/m value of 0.746 (Table 4).

When the spatial distribution of *F. occidentalis* and *T. palmi* were measured by the index of dispersion (ID), a similar trend of mean crowding index was obtained, though the difference was not as large as that obtained by calculating the mean crowding index. The individual *F. occidentalis* aggregated (ID = 2.05) while those of *T. palmi* were uniformly distributed (ID = 0.66, Table 4).

Table 4. The spatial pattern of Western Flower Thrips, *Frankliniella occidentalis,* and Melon Thrips, *Thrips palmi*, indicated by Lloyd Index, Mean Crowding and the Dispersion Index.

Thrips Species	Lloyd Index (m*/m)	Mean Crowding (m*)	Index of Dispersion (ID)
Frankliniella occidentalis	1.101462	21.64	2.050561
Thrips palmi	0.987406	0.746	0.663081

Discussion and Conclusions

Based on the Simpson-Yule Dominance Index, *T. palmi* was found to be more dominant by having a larger DI value as compared to the DI value for *F. occidentalis*. Thus, this study supported the fact that *T. palmi* is the major pest of orchid plants in Singapore in nurseries and population dynamics needed to be monitored.

Although all the traps used in the trial relied on the sticky paper to catch the thrips, different placement heights seemed to have affected the trapping efficacy of different species. The population temporal dynamics depicted in figures 3 and 4 indicated that a height of 50cm below the orchid flowers should be used to trap *T. palmi* as compared to the height of 50cm above the top of orchid flowers to trap *F. occidentalis.* The results obtained in this study further reinforced the preliminary findings of an unpublished report of an evaluation of the trapping efficacy of different colours and the heights of sticky traps used to trap *Thrips palmi* in local orchid farms in 2001 (i.e. traps set at 50cm below than the orchid flowers) was found to be the optimum height to trap *T. palmi* followed by the height of 50cm above the tip of the orchid spray.

Dublon (2009) reported that a synthetic version of a sexual aggregation pheromone for *F. occidentalis* was available for use as lures in *F. occidentalis* pheromone traps. No pheromone trap specific for *T. palmi* has been reported. The natural pheromone produced by the male *F. occidentalis* attracted both male and female into mating aggregations (Deligeorgidis et al. 2002). However, the use of the commercial pheromone lure for WFT in this trial was found not to be effective in trapping *F. occidentalis* in the test population in traps set at 30cm above the top of orchid flowers. However, the height of the pheromone trap i.e. 30cm could be a limiting factor in this study. Therefore, further evaluation on the efficacy of the pheromone trap and the height of trap placement in catching *F. occidentalis* would be required for more definite conclusion.

The data of *F. occidentalis* obtained from the trial (Table 5) were found to have a better fit to the Iwao's Patchiness Regression Method, as well as to the Taylor’s Power Law than that of MT. In other words, the spatial distribution pattern of *F. occidentalis* in orchid flowers is well described by both the Iwao's

Patchiness Regression Method and Taylor's Power Law while that of *T. palmi* is not as well described.

Table 5. Summary table of values obtained for *Thrips palmi* and *Frankliniella occidentalis*

Aggregation index	**Taylor (b value)**	**Iwao (β value)**	**Index of Dispersion**	**Lloyd's Patchiness index**
Thrips palmi (MT)	2.06 >1 = aggregated	1.08 >1 = aggregated	0.66 <1 = regular	0.98 <1 = regular
Frankliniella occidentalis (WFT)	3.12 >1 = aggregated	4.27 >1 = aggregated	2.05 >1 = aggregated	1.10 >1 = aggregated

Cho et al (1999) reported that in *Solanum tuberosum*, the within-field spatial patterns of adults and immature *Thrips palmi* Karny were found to be aggregated. In addition, Mateus *et* al 2005 reported the aggregation pattern of F. *occidentalis* on cucumber and green bean. In this report, parameters *a* and *b* of Taylor's Power Law and parameters of "α" and "β" of Iwao's Patchiness Regression indicated that both *F. occidentalis* and *T. palmi* were distributed at aggregation patches on orchid flowers in the farms observed, though the degree of aggregation of WFT is not as strong as MT.

The values of *a* greater than zero for the *F. occidentalis* and *T. palmi* indicated a degree of attractiveness between collected individuals, which might correspond to a "collaborative" relationship, such as mating. This was supported by the fact that the thrips caught by the three types of traps were all adults, including males and females in this study.

Mateus et al. (2005) reported that a negative value of *a* in the Taylor's Power Law for the total number of adults and immature thrips indicated a degree of repellence between individuals thrips, which might correspond to a competition for space in each flower. Hence, further study of the spatial distribution of thrips below the height of orchid should be carried out for both species of thrips.

The parameters *b* for *F. occidentalis* and *T. palmi* indicated that there was a higher tendency for aggregation in *F. occidentalis* than in *T. palmi*. This phenomenon should be considered when setting traps for the monitoring of population dynamics.

The index of dispersion (ID) and the Lloyd's patchiness index revealed a very interested phenomenon that the population of *F. occidentalis* appeared to be heavy aggregated while *T. palmi* were uniformly distributed. It appeared that the aggregation status of *T. palmi* indicated by ID values and Lloyd's

'Patchiness' Index were not consistent with those of Taylor's Power Law and Iwao's Patchiness Regression.

The Taylor's Power Law and the Iwao's Patchiness Regression actually revealed the individual aggregation behaviour (Kilpatrick and Ives 2003, Iwao 1968, Iwao 1975, Taylor 1961). They are empirical laws in ecology that relate the between-sample variance in density of individuals to the overall mean density of a sample of organisms in a study area. On the other hand, the Index of Dispersion and Lloyd's 'Patchiness' Index describe the measure of pattern intensity that is unaffected by thinning (random removal of points) (Ho 1993, Hoel 1943, Wilson and Room 1983). They are about the aggregation behavior of groups of thrips and describe "group or patch" aggregation behavior and the aggregation is about the patch's clumps. Therefore, it can be concluded that the individual *T. palmi* aggregate in patches but the patches are uniformed distributed. For *F. occidentalis*, both individuals and the patches aggregate.

The aggregation behaviour of WFT and MT individuals reflect their population succession during invasion into new areas. Benefits to aggregation in herbivorous insects have been well studied i.e. increase efficiencies in locating mates, better utilisation of resources, and as a defence or escape behaviour from predators (Turchin and Kareiva 1989, Vulinec 1990; Clark and Faeth 1997, Hunter 2000, Coster-Longman et al. 2002). The behaviour of WFTs correlated with the presence of aggregation pheromone in WFTs. When the populations aggregate, it might be more difficult to detect the insects with the same number of traps. The data collected from this study also supported that to effectively monitor *F. occidentalis* population; more traps would likely be needed.

Although Lublinkoh and Foster (1977) reported that the development of *F. occidentalis* was heavily depended on temperature variation, it is well known that the geographical distribution of an insect is determined partly by its response to temperature. For a species to establish in a new environment, the conditions must be conducive for reproduction and development to occur, and a significan proportion of the population would have to survive through periods of unfavourable conditions, such as winter (Jamie et al. 1998, McDonald et al. 1997, Wagner et al. 1985). The survival of *F. occidentalis* from eggs to adults was reported to be the highest at 20 ^{o}C with no development into adults at 35 ^{o}C (Zhang et al. 2012).

Temperature is likely not to be an important factor affecting the population dynamics of *F. occidentalis* in Singapore as the temperature fluctuation is quite minimal. The factors that led to the disappearance of *F. occidentalis* after 15 June in all of the five local farms were not clear. It was possible that the small population size precluded its detection by our trapping methods. Other weather factors, such as the amount of rainfall, might have contributed to the disappearance of *F. occidentalis* in the orchid farms studied (Deligeorgidis et al. 2002, Kakkar et al. 2012, Lublinkoh and Foster 1977).

The results obtained from this study highlighted several issues that would need to be explored further in development of a surveillance strategy for these thrips.

Literature Cited

Bakus, G. J. 2007. *Quantitative Analysis of Marine and Biological Communities. Field Biology and Environment*. John Wiley & Sons, Inc. New York, NY, USA. 435 pp. http://dx.doi.org/10.1002/0470099186

Bakus, G. J., G. Nishiyama, E. Hajdu, H. Mehta, M. Mohammad, U. Pinheiro, S. Sohn, T. Pham, Z. Yasin, T. Shau-Hwai, A. Karam, and E. Hanan. 2007. A comparison of some population density sampling techniques for biodiversity, conservation, and environmental impact studies. *Biodiversity and Conservation* 16(9):2445-2455. http://dx.doi.org/10.1007/s10531-006-9141-7

Beavers, J. B., J. G. Shaw and R. B. Hampton. 1971. Color and height preference of the citrus thrips in a naval orange grove. *Journal of Ecological Entomology* 64:1112–1113.

CABI. 1998. *Thrips palmi* Karny. *Distribution Maps of Plant Pests*. http://www.cabi.org/dmpp/FullTextPDF/2006/20066600480.pdf (15 September 2010).

Cho, J. J., R. F. L. Mau, D. Gonsalves and W. C. Mitchell. 1986. Reservoir Weed Hosts of Tomato Spotted Wilt Virus. *Plant Disease* 70(11):1014-1016. http://dx.doi.org/10.1094/PD-70-1014

Cho, J. J., R. F. L. Mau, R. T. Hamasaki, and D. Gonsalves. 1988. Detection of Tomato Spotted Wilt Virus in individual thrips by Enzyme-Linked Immunosorbent Assay. *Phytopathology* 78(10): 1348-1352. http://dx.doi.org/10.1094/Phyto-78-1348

Cho, K. J., C. S. Eckel, J. F. Walgenbatch, and G. G. Kennedy. 1995. Comparison of colored sticky traps for monitoring thrips populations (Thysanoptera, Thripidae) in staked tomato fields. *Journal of Ecological Sciences* 30:176–190.

Cho, K., S.-H. Kang, and G.-S. Lee. 1999. The spatial distribution of adult and immature *Thrips palmi* Karny on fall potato, *Solanum tuberosum* L. *Journal of Economic Entomology* 93(2):503-510. http://dx.doi.org/10.1603/0022-0493-93.2.503

Cho, K.J., J.-H. Lee, J.-J., Park, J.-K. Kim, and K. B. Uhm. 2001. Analysis of spatial pattern of *Frankliniella occidentalis* (Thysanoptera: Thripidae) on greenhouse cucumbers using dispersion index and spatial autocorrelation. *Applied Entomology and Zoology* 36(1):5-32. http://dx.doi.org/10.1303/aez.2001.25

Clark, B. R. and S. H. Faeth. 1997. The consequences of larval aggregation in the butterfly *Chlosyne lacinia*. *Ecological Entomology* 22:408–415. http://dx.doi.org/10.1046/j.1365-2311.1997.00091.x

Colin Cameron, A., F. A. G. Windmeijer, H. Gramajo, D. E. Cane, and C. Khosla. 1997. An R-squared measure of goodness of fit for some common nonlinear regression models. *Journal of Econometrics* 77(2):1790–1792. http://dx.doi.org/10.1016/S0304-4076(96)01818-0

Coster-Longman, C., M. Landi, and S. Turillazzi. 2002. The role of passive defense (selfish herd and dilution effect) in the gregarious nesting of *Liostenogaster* wasps (Vespidae, Hymenoptera, Stenogastrinae). *Journal of Insect Behavior* 15:331–350. http://dx.doi.org/10.1023/A:1016213125161

Deligeorgidis, P. N., C. G. Athanassiou, and N. G. Kavallieratos. 2002. Seasonal abundance, spatial distribution and sampling indices of thrip populations on cotton; a 4-year survey from central Greece. *Journal of Applied Entomology* 126(7-8): 343-348. http://dx.doi.org/10.1046/j.1439-0418.2002.00634.x

Dublon, I. A. N. 2009. *The aggregation pheromone of the western flower thrips*. Thesis of Bachelor of Science. Thrips Research Group, Centre for Applied Entomology and Parasitology, School of Life Sciences, Huxley Building. Keele University. Keele, Staffordshire, UK. 268 pp.

Elliott, J. M. 1977. *Some methods for the statistical analysis of samples of benthie invertebrates*. Second Edition. Scientific Publications No. 25. The Freshwater Biological Association. The Ferry Landing. Far Sawrey, Ambleside, Cumbria, England, UK. 157 pp.

Fargro Biological Control. 2013 Traps. www.fargro.co.uk/products/biologicalControl/traps.asp

Flynn, M. N. and W. R. L. S. Pereira. 2009. Estimation of Taylor's power law parameters *a* and *b* for tidal marsh macrobenthic species. *CICIMAR Oceánides* 24(2):85-90.

Hirose, Y. 1991. Pest status and biological control of *Thrips palmi* in southeast Asia. pp. 57-60. *In*, Talekar, N. S. (Editor). *Thrips in Southeast Asia*. Asian Vegetable Research and Development Center. Taipei, Taiwan. 342 pp.

Ho, C. C. 1993. Dispersion statistics and sample size estimates for *Tetranychus kanzawai* (Acari: Tetranychidae) on mulberry. *Environmental Entomology* 22: 21-25.

Hoddle, M. S., L. Robinson, and D. Morgan. 2002. Attraction of thrips (Thysanoptera: Thripidae and Aeolothripidae) to colored sticky cards in California avocado orchard. *Crop Protection* 21:383–388. http://dx.doi.org/10.1016/S0261-2194(01)00119-3

Hoel, P. 1943. On the indices of dispersion. *Annals of Mathematical Statististics* 14:155. http://dx.doi.org/10.1214/aoms/1177731457

Hunter, A. F. 2000. Gregariousness and repellent defences in the survival of phytophagous insects. *Oikos* 91:213–224. http://dx.doi.org/10.1034/j.1600-0706.2000.910202.x

Iwao, S. 1968. A new regression method for analyzing the aggregation pattern of animal population. *Research Population Ecology* 10:1-20. http://dx.doi.org/10.1007/BF02514729

Iwao, S. 1975. A new method of sequential sampling to classify populations relative to a critical density. *Research Population Ecology* 16:281-28. http://dx.doi.org/10.1007/BF02511067

McDonald, J. R., J. S. Bale, and K. F .A. Walters. 1998. Effect of temperature on development of the Western Flower Thrips, *Frankliniella occidentalis* (Thysanoptera: Thripidae). *European Journal of Entomology* 95:301-306.

Kakkar, G., D. R. Seal, P. A. Stansly, O. E. Liburd, and V. Kumar. 2012. Abundance of *Frankliniella schultzei* (Thysanoptera: Thripidae) in flowers on major vegetable crops of south Florida. *Florida Entomologist* 95:468-475. http://dx.doi.org/10.1653/024.095.0231

Kawai, A. 1990. Life cycle and population dynamics of *Thrips palmi* Karny. *Japan Agricultural Research Quarterly* 23: 282-288.

Kawai, A. and C. Kitamura. 1987. Studies on population ecology of *Thrips palmi* Karny XV. Evaluation of effectiveness of control methods using a simulation model. *Applied Entomology and Zoology* 22:292–302.

Kilpatrick, A. M. and A. R. Ives. 2003. Species interactions can explain Taylor's Power Law for ecological time series. *Nature* 422:65–68. http://dx.doi.org/10.1038/nature01471

Kirk, W. D. J. 1984. Ecologically selective color traps. *Ecological Entomology* 9:35–41. http://dx.doi.org/10.1111/j.1365-2311.1984.tb00696.x

Kirk, D. J. and I. L. Terry. 2003. The spread of the western flower thrips *Frankliniella occidentalis* (Pergande). *Agricultural and Forest Entomology* 5:301-310. http://dx.doi.org/10.1046/j.1461-9563.2003.00192.x

Lewis, T. 1959. A comparison of water trap, cylindrical sticky traps, and suction traps for sampling thysanopteran populations at different levels. *Entomologia Experimentalis et Applicata* 2:187-203. http://dx.doi.org/10.1111/j.1570-7458.1959.tb00434.x

Lewis, T. 1973. *Thrips: Their Biology, Ecology and Economic Importance*. Academic Press. London, England, UK. 349 pp.

Lewis, T. (Editor). 1997. Field and laboratory techniques. pp. 435-475. *Thrips as crop pests*. CAB International. Axon, New York, USA. 740 pp.

Lloyd, M. 1967. Mean Crowding. *Journal Animal Ecology* 36:1-30. http://dx.doi.org/10.2307/3012

Lublinkoh, J. and D. E. Foster. 1977. Development and reproductive capacity of *Frankliniella occidentalis* (Thysanoptera: Thripidae) reared at three temperatures. *Journal of the Kansas Entomological Society* 50(3):313-316.

Mateus, C., J. Araújo, and A. Mexia. 2005. *Frankliniella occidentalis* (Thysanoptera: Thripidae) in spray-type carnations: spatial distribution analysis. *Boletín de Sanidad Vegetal Plagas* 31:47-57.

Matteson, N. I. and L. A. Terry. 1992. Response to color by male and female *Frankliniella occidentalis* during swarming and non-swarming behaviour. *Entomologia Experimentalis et Applicata* 63:187–201. http://dx.doi.org/10.1111/j.1570-7458.1992.tb01573.x

McDonald, J. R., J. S. Bale, and K. F. A. Walters. 1997. Low temperature mortality and overwintering of the western flower thrips *Frankliniella occidentalis* (Thysanoptera: Thripidae). *Bulletin of Entomological Research* 87(05)497-505. http://dx.doi.org/10.1017/S0007485300041365

Metcalf, C. L. and W. P. Flint. 1962. *Destructive and Useful Insects. Their Habits and Control*. Fourth Edition (Revised by R. L. Metcalf). McGraw-Hill Book Company. New York, NY, USA. 1087 pp.

Nagelkerke, N. J. D. 1991. A note on a general definition of the coefficient of determination". *Biometrika* 78(3):691–692. http://dx.doi.org/10.1093/biomet/78.3.691

Navás, V., E. Salguero, J. E. Funderburk, T. P. Mack, R. J. Beshear, and S. M. Olson. 1994. Aggregation indices and sample size curves for binomial sampling of flower- inhabiting *Frankliniella* species (Thysanoptera, Thripidae) on tomato. *Journal of Economic Entomology* 87(6):1622-1626.

Neter, J. and W. Wasserman. 1974. *Applied Linear Statistical Models*. Richard D. Irwin, Inc. Homewood, Illinois, USA. 842 pp.

North, R. C. and A. M. Shelton. 1986. Ecology of Thysanoptera within cabbage fields. *Environmental Entomology* 15: 520–526.

Okajima, S., Y. Hirose, H. Kajita, M. Takagi, B. Napompeth, and S. Buranapanichpan. 1992. Thrips on vegetables in South East Asia. *Applied Entomology and Zoology* 27:300–303.

Rosenheim, J. A., S. C. Welter, M. W. Johnson, R. F. L. Mau, and L. R. Gusukuma-Minuto. 1990. Direct feeding damage on cucumber by mixed-species infestations of *Thrips palmi* and *Frankliniella occidentalis* (Thysanoptera: Thripidae). *Journal of Economic Entomology* 83(4):1519-1525.

Sedaratian, A., Y. Fathipour, A. A. Talebi, and S. Farahani. 2010. Population density and spatial distribution pattern of *Thrips tabaci* (Thysanoptera: Thripidae) on different soybean varieties. *Journal of Agricultural Science and Technology* 12:275-288.

Shipp, J. L. and N. Zariffa. 1991. Spatial patterns of and sampling methods for Western Flower Thrips (Thysanoptera: Thripidae) on greenhouse sweet pepper. *Canadian Entomologist* 123(5):989-1000. http://dx.doi.org/10.4039/Ent123989-5

Steel, R. G. D. and J. H. Torrie. 1980. *Principles and Procedures of Statistics: A biometrical approach*. Second Edition. McGraw-Hill Book Company. New York, NY, USA. 672 pp.

Taylor, L. R. 1961. Aggregation, variance and the mean. *Nature* 189:732-735. http://dx.doi.org/10.1038/189732a0

Terry, L. I. 1997. Host selection, communication and reproductive behavior. pp. 435–475. Lewis, T. (Editor). *Thrips as Crop Pests.* CABI International. Oxon, England, UK. 736 pp.

Tsai J. H, B. Yue, S. E. Webb, J. E. Funderburk, and H. T. Hsu. 1995. Effects of host plant and temperature on growth and reproduction of *Thrips palmi* (Thysanoptera: Thripidae). *Environmental Entomology* 24:1598-1603.

Turchin, P. and P. Kareiva. 1989. Aggregation in *Aphis vaians*: an effective strategy for reducing predation risk. *Ecology* 70:1008–1016. http://dx.doi.org/10.2307/1941369

Vernon, R. S. and D. R. Gillespie. 1995. Influence of trap shape, size and background color on captures of *Frankliniella occidentalis* (Thysanoptera: Thripidae) in a cucumber greenhouse. *Journal of Economic Entomology* 88(2):288-293.

Vulinec, K. 1990. Collective security: aggregation by insects as a defense. pp. 251–288. *In,* Evans D. and J. O. Schmidt (Editors). *Insect Defenses*. State University of New York Press. New York, NY, USA 482 pp.

Wagner, T. L., H. I. Wu, R. M. Feldman, P. J. H. Sharpe, and R. N. Coulson. 1985. Multiple cohort approach for simulating development of insect population under variable temperatures. *Annual Entomology Society of America* 78:691-704.

Waterhouse, D. F. and K. R. Norris. 1989. *Frankliniella occidentalis* (Pergande). Chapter 4, pp. 24-35. *In, Biological Control Pacific Prospects - Supplement 1*. Australian Centre for International Agriculture Research. Canberra, Australia. 123 pp.

Welter, S. C., J. A. Rosenheim, M. W. Johnson, R. F. L. Mau, and L. R. Gusukuma-Minuto. 1990. Effects of *Thrips palmi* and western flower thrips (Thysanoptera: Thripidae) on the yield, growth, and carbon allocation pattern in cucumbers. *Journal of Economic Entomology* 83:2092-2101.

Wilson, L. T. and P. M. Room. 1983. Clumping patterns of fruit and arthropods in cotton, with implications for binomial sampling. *Environmental Entomology* 12:50-54.

Yolanda, Y., J. Stavinsky, S. Hague, J. Funderburk, S. Reitz, and T. Momol. 2006. Evaluation of *Frankliniella bispinosa* (Thysanoptera: Thripidae) as a vector of the *Tomato spotted wilt virus* in pepper. *Florida Entomologist* 89:204-207. http://dx.doi.org/10.1653/0015-4040(2006)89[204:EOFBTT]2.0.CO;2

Yudin, L. S, J. J. Cho, and W. C. Mitchell. 1986. Host range of Western Flower Thrips, *Frankliniella occidentalis* (Thysanoptera: Thripidae), with special references to *Leucaena glauca*. *Environmental Entomology* 15(6):1292-1295.

Yudin, L. S., W. C. Mitchell, and J. J. Cho. 1987. Color preference of thrips (Thysanoptera: Thripidae) with reference to aphids (Homoptera: Aphidae) and leaf miners in Hawaiian lettuce farms. *Journal of Ecological Entomology* 80:51–55.

Zhang Z.-J., Zhang Y.-J., B.-Y. Xu, G.-R. Zhu, and Q.-J. Wu. 2012. Effects of temperature on development, reproduction and population growth of the western flower thrips, *Frankliniella occidentalis* (Thysanoptera: Thripidae). *Acta Entomologica Sinica* 55(10):1168-1177.