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Geostatistical analysis of the attractive distance of two different sizes of yellow sticky traps for greenhouse whitefly, *Trialeurodes vaporariorum* (Westwood) (Homoptera: Aleyrodidae), in cherry tomato greenhouses

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Abstract Variogram analysis was used to estimate and compare the attractive distances of two different sizes of yellow sticky traps (small trap: 9.6 × 8.0 cm; large trap: 9.6 × 16 cm) for sampling greenhouse whitefly, *Trialeurodes vaporariorum* (Westwood), adults in four commercial cherry tomato greenhouses, during 2002–2003. The patch size of *T. vaporariorum* immatures between plants was also estimated using visual counts. Within each greenhouse, 64 permanent sampling stations were established on an 8 × 8 grid, with one yellow sticky trap or one tomato plant per location. Standardised exponential and Gaussian variogram models were fitted to the empirical variograms developed from the data collected by each sampling method. All the variograms reached the sill indicating the presence of spatial dependence among the spatial data obtained by the two sampling methods. For *T. vaporariorum* adults on sticky traps the range of variogram (a measure of attractive distance) was not considerably different between the two trap sizes: 15.40 and 15.95 m for the large and small traps, respectively. This result indicated that the attractive distances of the two different yellow sticky traps were very similar. The ranges of the variograms for the visual count of immatures on plants were always less (7.49–10.00 m) than those for adults, indicating that the attractive distance of the traps for *T. vaporariorum* adults extends beyond the patch size for immatures on cherry tomato plants. These data have implications for developing sampling plans for the management of *T. vaporariorum* in tomato greenhouses.

Key words range, spatial autocorrelation, *Trialeurodes vaporariorum*, variogram, visual count.

INTRODUCTION

The use of sticky traps to monitor populations of *Trialeurodes vaporariorum* (Westwood) is commonly advocated as a key component of IPM programs in cherry tomato greenhouses (Steiner *et al*. 1999; Kim *et al*. 2001). Yellow sticky traps have advantages over conventional sampling methods (e.g. foliage samples) primarily in the area of survey and rapid assessment of adult populations (Parrella & Jones 1985). These advantages diminish quickly as the numbers of *T. vaporariorum* on the trap increase, as the time involved in counting and recording data is related to the trap size. More whiteflies are usually trapped on larger traps than on smaller traps (Parrella & Jones 1985). Therefore, a small-sized trap is preferred to estimate the mean density of *T. vaporariorum* if there is a strong relationship between trap catches and whitefly densities on the plants. This necessitates evaluating the effect of sticky trap sizes on the monitoring of *T. vaporariorum* populations in greenhouses.

The effective distance of a yellow sticky trap which is measured according to its attractive range for adult *T. vaporariorum* is an important factor that determines the effectiveness and accuracy of sequential sampling plans for managing *T. vaporariorum*, because sampling plans are developed under the assumption that individual trap catches are spatially independent (Midgarden *et al*. 1993; Kim *et al*. 2001). It is obvious that a trap with a long attractive distance will catch *T. vaporariorum* from a farther distance than one with a short attractive distance. Therefore, the trap density or spacing in a sequential sampling plan relies strongly on the attractive distance of the trap. If the distance changes with trap sizes, the effectiveness of a trap for monitoring *T. vaporariorum* also changes. Determining the attractive distance of a trap enables an effective trap size, trap density and trap spacing to be selected for accurate mean estimates of *T. vaporariorum* in tomato greenhouses (Kim *et al*. 2001). Despite a long history of research on sticky traps for monitoring *T. vaporariorum* in greenhouses, little quantitative information has been collected on the attractive distance of these traps.

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It is practically infeasible to estimate the attractive distance between a trap and *T. vaporariorum* by only direct observation, because of the difficulty associated with tracking small flying insects in greenhouses. Recently, the utility of the spatial statistical analysis method, variography, in ecological and entomological studies was highlighted (Rossi *et al*. 1992; Liebhold *et al*. 1993; Nansen *et al*. 2003; Sciarretta *et al*. 2005). To estimate the attractive distance of sticky traps, two statistics, correlogram and variogram, could be used. Correlogram, which is a generalised version of the correlation coefficient, is a statistic that is dependent on the distance, h, between the locations of the traps. Because this statistic is a correlation, when two variables are independent, the mean of the correlogram is 0. Under the stationarity condition, the correlogram is generally a decreasing function of distance, h, and for a given value h_0, whenever $h > h_0$, the correlogram becomes 0. The value h_0 can be regarded as the attractive distance. In contrast, the variogram has been commonly used in geostatistical analysis due to the several available mathematical variogram functions and stationarity condition. The variograms are more commonly employed in descriptive geostatistics, while the correlograms are the prevalent graphical presentation in ecology (Fortin & Dale 2005).

The variogram measures the extent of dependence in the sample data by evaluating the variance as a function of the distance and direction between observations (Cressie 1993). The semivariance γ for lag distance h is given by

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2$$

where $z(x_i)$ is a measured sample point at x_i, $z(x_i + h)$ is a measured sample at point $x_i + h$ and $N(h)$ is the number of pairs separated by lag h. The variogram is described by three parameters: the sill, nugget and range (Isaaks & Srivastava 1989). The semivariance increases with increasing lag, then levels off. The lag value at which the plateau is achieved is called the range, and the semivariance value of the plateau is the sill. Empirical variograms seldom pass the origin, but rather intersect with the ordinate. This discontinuity is the nugget, and consists of two parts: the spatial variance of scales less than the minimum sampling distance (if present), and measurement and sample location error. Among these parameters, the range has biological meaning, and can be defined as a neighbourhood where all points are related to one another to some degree. Thus, the range of a variogram is an indication of the scale of the spatial pattern or patch size of living organisms at a short lag distance. Within a distance in the range or size of a patch, trap catches are spatially dependent on each other, and this reflects the attractive distance between the trap and *T. vaporariorum*. Therefore, the attractive distances of the traps can be explained through the ranges of the variograms for adult *T. vaporariorum*.

To improve the process of monitoring *T. vaporariorum* adults in cherry tomato greenhouses, a study was conducted and geostatistical analysis was used to determine the effective attractive distances of two different sizes of yellow sticky traps. The ranges of variograms for *T. vaporariorum* immatures on tomato plants were also estimated and compared with those for adults.

MATERIALS AND METHODS

Four commercial greenhouses, with the cherry tomato cultivar 'Koko' in Buyeo (36º20′N, 126º95′E), Chungcheongnam province, Korea, were monitored for *T. vaporariorum* adults and immatures during the growing seasons of 2002 and 2003. Since the greenhouse sizes surveyed varied (2500–4000 m^2 in size), a 44 × 44 m (1936 m^2) portion of each greenhouse in the middle of greenhouses was surveyed four to six times at weekly intervals.

In all the greenhouses, cherry tomato plants were grown by the modified ventral cordon system (Kim *et al*. 2001) used in about 90% of the cherry tomato acreage in Korea. Horizontal support wires were positioned directly over the row of plants, at a height of 1.8–2.0 m. Initially, each plant was trained vertically along and around a supporting plastic twine, and tied with plastic snap-on clips. As the plant reached the top supporting wire, the clips were untied, and the reserved twine released, allowing the plant to drop ≈0.3 m, with its lower section lying on the ground. The lowest foliage was removed to promote flower and fruit production. Therefore, newly expanded leaves always occurred at the top canopy and the oldest leaves at the lower canopy of the tomato plants.

In all the greenhouses, the cherry tomatoes were planted in early August in 2002 and early September in 2003. Plants were spaced ≈30 cm apart in a single row on beds (0.1 m high and 0.5 m wide) of soil and covered with black polyethylene mulch. The surveyed greenhouses consisted of 12–15 beds at a centre separation of ≈0.8 m.

Tomatoes were grown according to the agronomic practice recommend by Rural Development Administration, Suwon, Korea (RDA 2001). The drip tape was installed under the plastic mulch ≈5 cm below the soil surface for irrigation and fertigation. The total amount of fertiliser used was 36.4 g N/m^2, 20.8 g P/m^2 and 52.6 g K/m^2. Average monthly maximum and minimum temperatures ranged from 34°C and 19°C in 2002 to 33°C and 14°C in 2003.

Yellow sticky traps

Trialeurodes vaporariorum adults were sampled with yellow sticky traps (Panaplate, Kossil Products, Korea) coated with a thin application of adhesive (Tanglefoot®, The Tangle Foot Company, Grand Rapid, MI, USA). Two different sizes of flat yellow traps were used: small (9.6 × 8.0 cm) and large (9.6 × 16.0 cm). In each year, two cherry tomato greenhouses were monitored, one for the small trap trial (GST1 in 2002 and GST2 in 2003) and the other for the large trap trial (GLT1 in 2002 and GLT2 in 2003). The traps were always placed at the top plant canopy and fastened to the horizontal wire with clothespins. This placement maintained an equal trap height over the entire greenhouse, regardless of plant growth. The space between the trap and the canopy was adjusted to 0.25–0.45 m as the plants gained additional growth.

Within each greenhouse, a grid of permanent sampling stations was established with one sticky trap per location. The sampling array for each greenhouse consisted of 64 grid cells, laid out in an 8×8 pattern. Each grid cell covered ≈25 m^2 and contained ≈180 plants. The distance between traps was ≈5.0 m both across and down a row. Traps were left in the greenhouse for 1 week, and the numbers of adult *T. vaporariorum* at each sample location and for each sample week were determined using a 20× magnifier.

Visual estimates of whiteflies on tomato plants

In situ counts of immature whiteflies on the tomato plants were conducted to determine the spatial distribution of *T. vaporariorum* on the plants. Counting immatures on the plants provides more reliable data than counting adults, as their populations are the result of adult dispersal. In addition, adult dispersal between and within plants might be disturbed by sampling activity and agronomic practices such as pruning, insecticide application and harvesting. The numbers of immatures (third to mid-fourth instars) were visually inspected on the lower surfaces of the terminal three leaflets of each leaf located near the middle stratum of the plant (≈1.3 m above ground level). Because adult whiteflies prefer young plant foliage as feeding or oviposition sites (Gerling & Horowitz 1984), the third to mid-fourth instars of *T. vaporariorum* are most abundant at the middle stratum of the tomato plant in the modified ventral cordon system (Kim *et al*. 1999).

To analyse the spatial relations of *T. vaporariorum* immatures on the plants, the same sampling grid, established for the trap trials, were used. However, the sampling locations for the visual counts were different from those used in the sticky trap study. For the visual counts, one tomato plant located at the mid-point between stick trap positions was selected. The reason for changing the sample position in the visual count study was to minimise interference of the adult flight behaviour near the traps between and within tomato plants. Tomato plants that were selected for visual counts were marked at the bottom with white tape and were monitored throughout the growing seasons.

Geostatistical analysis

The spatial statistic modules in S-Plus (Mathsoft, Seattle, WA, USA) were used to analyse the spatial autocorrelation structure of *T. vaporariorum* in the greenhouses. The analysis included fitting theoretical variograms to empirical variograms for the sticky trap and visual count data, and the results obtained from the two count methods were compared. The log-transformed data were used to reduce the skewness of the distribution of the raw data. Directionality was not included into the variogram analysis because the data sets used in this study had insufficient numbers of paired observations (<30) within a given direction (Nansen *et al*. 2003). Therefore, isotropy was assumed and omnidirectional variograms were used for all the data sets throughout this paper.

The spatial autocorrelation structure of the data sets was explored by estimating empirical variograms ($\gamma(h)$) for pooled sampling dates. By pooling over time, data from different dates were treated as replicates. This process allows more precise estimates of spatial model parameters, especially in the small-scale components (Cressie 1993). The empirical variograms were calculated from the data counted, according to the following robust estimator of variogram developed by Cressie and Hawkins (1980):

$$\gamma(h) = \frac{\left[\frac{1}{|N(h)|}\sum_{N(h)} |z_i - z_j|^{1/2}\right]^4}{2(0.457 + 0.494/|N(h)|)} \tag{1}$$

where $N(h)$ is the set of all pairwise Euclidean distances $i - j = h$, $|N(h)|$ the number of distance pairs in $N(h)$, and z_i and z_j are data values at spatial locations i and j, respectively. All variograms were calculated using a lag distance of 5.0 m, with a tolerance ± 3.0 m. The most common choice for the lag tolerance is one-half the lag distance between two neighbouring classes. This results in increasing data pairs that can be used in the variogram calculation (Isaaks & Srivastava 1989). In geostatistical analysis, at least 30 data pairs per lag distance are required to adequately estimate the variance (Isaaks & Srivastava 1989) and the maximum lag distance for all variograms should be at least half the shortest dimension of the sampling space (Nansen *et al*. 2003). In this study, the area surveyed in all greenhouses was 44×44 m, which meant that the variograms ideally could not account for lag distances >22.0 m.

The pooled empirical variograms, by greenhouse, were modelled using two theoretical variograms (Cressie 1993):

$$\text{Gaussian variogram: } \gamma(h) = C_o + C_1\left[1 - \exp\left(\frac{-3h^2}{a^2}\right)\right] \tag{2}$$

$$\text{Exponential variogram: } \gamma(h) = C_o + C_1\left[1 - \exp\left(\frac{-3h}{a}\right)\right] \tag{3}$$

where h is the lag distance, C_0 the nugget effect, C_1 the structure variance and a the range. $C_0 + C_1$ is commonly referred to as the sill. The range is defined as the distance at which data are no longer autocorrelated. Lower ranges indicate that data are correlated only with data in close proximity, and the high ranges indicate that data are correlated over much larger distance. Statistical comparison between the range values estimated from two theoretical variograms or sampling methods cannot be performed because a proper statistical method for variance estimation of the ranges has not yet been developed. A theoretical variogram model was fitted to an empirical variogram by optimisation techniques, in the form of a non-linear weighted least squares regression, and the two theoretical models were evaluated based on the weighted sum of square residuals ($Q^*(\theta)$) (Cressie 1985).

A standardised variogram for each theoretical model was derived by dividing each variogram value by the overall sample variance. This allows variograms from different data sets on the same entity to be compared. The ranges were estimated from the Gaussian and exponential models for *T. vaporariorum* adults and immatures. Data of the adults or immatures with distances less than the range parameter of *a* are correlated, and thus are likely to be in the same patch or have the same attractive distance. Conversely, data of the adults or immatures more than *a* apart are no longer correlated, and are thus assumed to be in different patches.

RESULTS

Description of population dynamics

For both sizes of sticky traps, *T. vaporariorum* adult populations usually grew gradually from low levels at the inception of trapping and to high densities in all the greenhouses surveyed (Fig. 1). Changes in immature populations on the tomato leaves were moderately associated with adult densities on yellow sticky traps. Population sizes of *T. vaporariorum* adults and immatures were larger in the small-trap greenhouses (GST1 and GST2) than in the large-trap greenhouses (GLT1 and GLT2) ($P < 0.05$). The ranges of the mean (±SEM) numbers of *T. vaporariorum* adults on sticky traps and immatures on tomato plants were 30.6 (±5.7) to 305.6 (±63.4) and 0.1 (±0.1) to 0.6 (±0.3) in the small-trap greenhouses, and 44.5 (±12.5) to 1129.7 (±295.2) and 0.5 (±0.4) to 14.0 (±2.7) in the large-trap greenhouses, respectively.

Geostatistical analysis

Gaussian and exponential models were fitted to the empirical variograms generated from the trap count data (Table 1) and visual count data (Table 2). All the variograms reached an upper boundary, i.e. a sill that confirmed the presence of spatial dependence in both sampling methods. Both models fitted similarly to the empirical variogram, but the Gaussian model fitted the data slightly better than the exponential model for both counting methods evaluated as indicated by the smaller weighted sum of the square residuals, $Q^*(\theta)$.

With reference to the number of *T. vaporariorum* adults on yellow sticky traps, there were some variations in the range of spatial dependence between the trap sizes (Table 1). The model chosen to describe the variogram influenced the estimation range. The ranges estimated for data from the large and small traps varied from 13.97 m (Gaussian) to 17.00 m (exponential) and from 13.73 m (Gaussian) to 20.67 m (exponen-

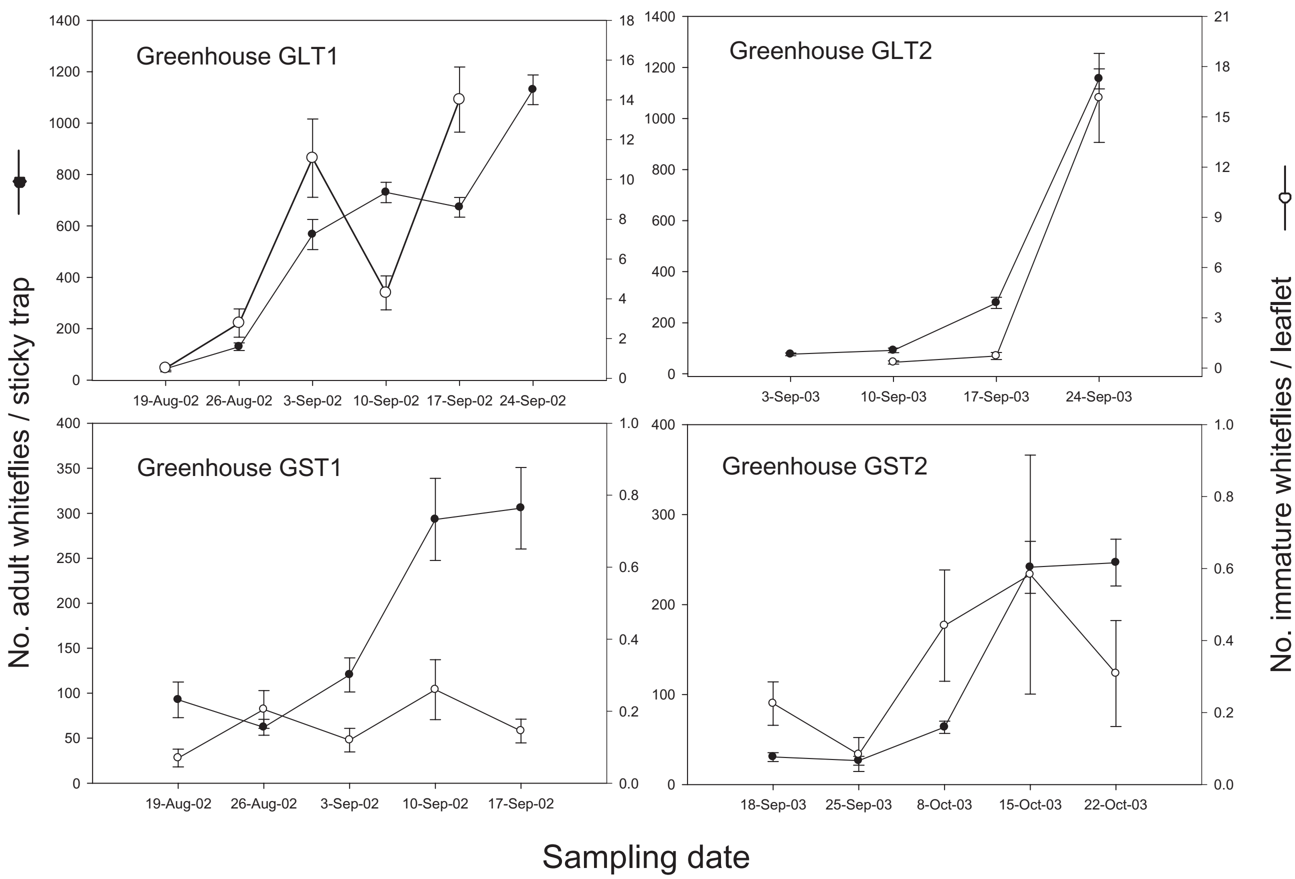

Fig. 1. Mean (±SEM) number of whitefly adults caught on yellow sticky traps and immatures on tomato leaves in four cherry-tomato greenhouses. Two different yellow trap sizes were used: small trap (9.6 × 8.0 cm) in greenhouses GST1 and GST2 and large trap (9.6 × 16 cm) in greenhouses GLT1 and GLT2.

Table 1 Comparison of variogram model parameters (±SE) of *Trialeurodes vaporariorum* adults captured on large traps (9.6 × 16.0 cm) in greenhouses GLT1 and GLT2 and small traps (9.6 × 8.0 cm) in greenhouses GST1 and GST2

Trap size	Greenhouse	Model	C_o	C	a (m)	$Q^*(\theta)$
Large	GLT1	Exponential	0.31 ± 0.01	1.00 ± 0.11	17.00 ± 0.18	0.006
		Gaussian	0.60 ± 0.07	1.00 ± 0.13	16.50 ± 2.95	0.006
	GLT2	Exponential	0.45 ± 0.03	1.05 ± 0.04	16.00 ± 1.15	0.007
		Gaussian	0.51 ± 0.13	1.04 ± 0.26	13.97 ± 2.48	0.006
Small	GST1	Exponential	0.30 ± 0.11	1.12 ± 0.19	20.67 ± 1.33	0.007
		Gaussian	0.51 ± 0.01	1.06 ± 0.03	13.73 ± 1.44	0.008
	GST2	Exponential	0.34 ± 0.10	1.04 ± 0.17	16.00 ± 7.46	0.014
		Gaussian	0.50 ± 0.06	1.05 ± 0.11	14.47 ± 2.10	0.011

C_o: nugget; C: sill; a: range; $Q^*(\theta)$: residual sum of square of weighted least square estimator.

Table 2 Variogram model parameters (± SE) of *Trialeurodes vaporariorum* immatures visually sampled from tomato plants in cherry-tomato greenhouses where large (GLT1 and GLT2) and small (GST1 and GST2) sticky traps were evaluated

Greenhouse	Model	C_o	C	a (m)	$Q^*(\theta)$
GLT1	Exponential	0.13 ± 0.08	1.03 ± 0.35	10.00 ± 2.93	0.006
	Gaussian	0.48 ± 0.02	1.03 ± 0.02	9.16 ± 0.78	0.005
GLT2	Exponential	0.10 ± 0.01	1.08 ± 0.01	12.53 ± 1.36	0.005
	Gaussian	0.45 ± 0.01	1.06 ± 0.11	10.10 ± 1.15	0.005
GST1	Exponential	0.20 ± 0.05	1.09 ± 0.10	9.81 ± 0.62	0.009
	Gaussian	0.43 ± 0.01	1.08 ± 0.13	7.38 ± 0.97	0.008
GST2	Exponential	0.24 ± 0.42	1.04 ± 0.82	10.56 ± 4.93	0.012
	Gaussian	0.39 ± 0.01	1.04 ± 0.10	7.97 ± 0.96	0.011

C_o: nugget; C: sill; α: range; $Q^*(\theta)$: residual sum of square of weighted least square estimator.

tial), respectively. However, the estimates of mean range from both models were not considerably different between the trap sizes: 15.87 m for the large traps and 16.22 m for the small traps. These results were different from those for the visual counts of immatures on plants (Table 2). The estimates of ranges of variograms for visual count data were smaller than those for trap data regardless of the greenhouses or the trap sizes. The mean ranges for immatures on the plants were 9.95 m and 8.93 m in the large- and small-trap greenhouses, respectively.

Because there were no substantial differences in the estimates of the variogram parameters among the greenhouses (Tables 1,2), the empirical variograms generated from each greenhouse were pooled by sampling method and refitted to the two theoretical models (Fig. 2). The range of spatial dependence in the trap count and visual count data varied from 15.40 to 15.95 m and from 7.49 to 10.00 m, respectively. The range for the trap data was at least 1.54 times larger than that for the visual counts, indicating that the attractive distance of yellow sticky traps to *T. vaporariorum* adults extended beyond the patch size for the immatures on the tomato plants.

DISCUSSION

To make appropriate decisions for IPM programs in tomato greenhouses, a reliable sampling scheme must be available. Currently, sequential sampling plans for monitoring *T. vaporariorum* have been developed using the information generated from yellow sticky traps in cherry tomato greenhouses (Kim *et al*. 2001). Because the sequential sampling plans are developed under the assumption that individual trap data are spatially independent, it is crucial to understand the spatial dependency between the individual trap data (Midgarden *et al*. 1993). If the spatial dependency of individual trap data changes with the trap size, trap density or spacing must be adjusted in relation to trap size to satisfy the assumption of random sampling. Thus, the change in the spatial dependency with trap sizes has to be clarified before sequential sampling plans are developed.

The spatial relationship of data in biological sciences is frequently evaluated using geostatistics, such as variograms (Liebhold *et al*. 1991; Brandhorst-Hubbard *et al*. 2001). In this study, the range of the variogram was used to determine the average extent of *T. vaporariorum* attracted distances on yellow sticky traps or plants in cherry tomato greenhouses. The range of the variogram is important for choosing the correct sampling design for *T. vaporariorum*. The sampling design that will ensure spatial independence of the samples could be any systematic random design requiring all the samples to be at least within the variogram range from each other (Flatman & Yfantis 1996). Therefore, to reliably describe the variation within a greenhouse, the sampling intensity should relate to the range (Frogbrook *et al*. 2002). Otherwise the sampling might be more intensive than necessary or too sparse to provide spatially correlated data.

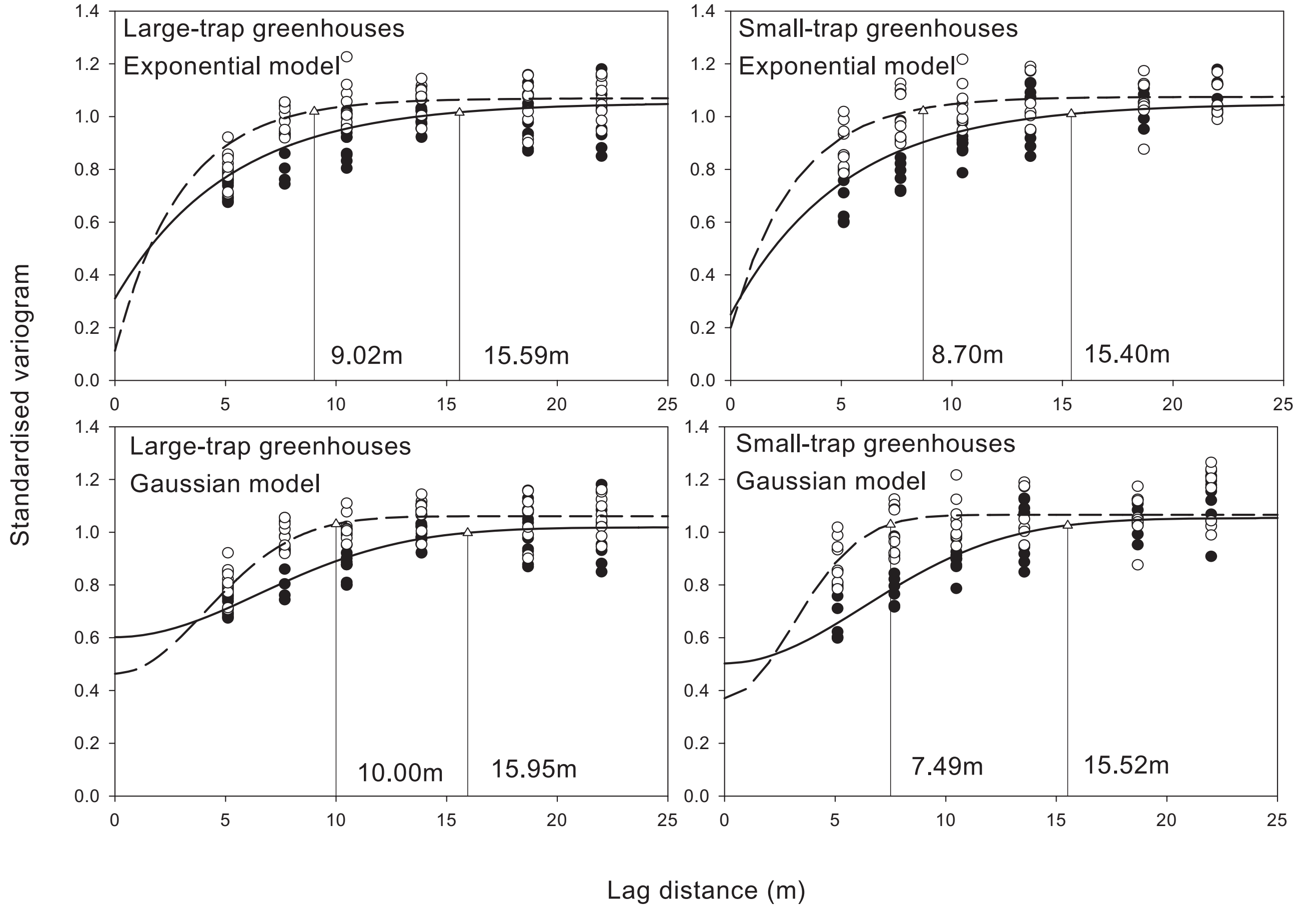

Fig. 2. Standardised Gaussian and exponential models fitted to pooled empirical variograms of visual count data (–○–) and trap count data (–●–) collected from four commercial cherry-tomato greenhouses during 2002–2003. Two different yellow trap sizes were used: small trap (9.6 × 8.0 cm) in greenhouse GST1 and GST2 and large trap (9.6 × 16 cm) in greenhouses GLT1 and GLT2. Value above the horizontal bar in each graphic panel indicates the range of variogram in exponential and Gaussian models.

Geostatistical analysis

The variograms for *T. vaporariorum* in this study showed that spatial variation occurred at different scales for the different sampling methods (Tables 1,2). For the yellow sticky trap data, the difference in the ranges between small and large sticky traps was fairly small (<0.4 m), indicating that the attractive distances for *T. vaporariorum* adults in cherry tomato greenhouses were similar (Fig. 2). These results suggest that the sticky traps can be used for monitoring programs for *T. vaporariorum* in cherry tomato greenhouses, without consideration to trap size. The ranges of the visual data were always smaller than those for the trap data, varying from 7.49 to 10.00 m (Fig. 2). These results suggest that the attractive distance of *T. vaporariorum* on yellow sticky traps is larger than the patch size of immatures on plants.

Also, variogram range parameter has been used to quantify aggregation patterns over various spatial scales (Mello & Rose 2005). Variograms of dispersed and low-density aggregated populations have large range values, whereas when populations are aggregated in a small portion, the range is low. This indicates that *T. vaporariorum* immatures on tomato plants are more aggregated than the adults on yellow sticky traps (Fig. 2).

Sampling strategy for *T. vaporariorum* in greenhouses

Yellow sticky traps and leaf inspection are the most commonly used sampling methods for monitoring *T. vaporariorum* densities in tomato greenhouses in Korea (Kim *et al*. 1999, 2001). The reliability of yellow sticky traps, however, has not been statistically examined in relation to the trap sizes in vegetable greenhouses. To date, most sequential sampling plans with sticky traps have been developed based on a dispersion index such as Taylor's power law (Taylor 1961) which is calculated under the assumption that the individual sample values are spatially independent (Midgarden *et al*. 1993). Samples should be independent of one another to be unbiased estimators of population parameters. Therefore, all samples should be placed at least the range apart to obtain samples that are less likely to be spatially related (Flatman & Yfantis 1996). Kim *et al*. (2001) demonstrated that the spatial dependency of count for sticky trap data for *T. vaporariorum* adults could negatively influence the performance of an enumerative sampling plan. Because the two different trap sizes used in this study had similar ranges (Table 1) and similar Taylor's parameters (Mun 2003), the small and large traps were supposed to have similar sampling performance for the same sample size. The cost of constructing and monitoring the small trap should be appreciably less than that of the large trap, confirming the reduced sampling cost of the small trap while maintaining the precision. Therefore, we can conclude that the small sticky (9.6×8.0 cm) traps are more efficient than the larger traps (9.6×16.0 cm) for determining the mean density of *T. vaporariorum* adults in cherry tomato greenhouses.

Most studies on sampling design for monitoring *T. vaporariorum* populations in greenhouses are conducted without considering the sample locations. The choice of sample location is based mainly on the assumption that the samples at short distance apart are related to each other, even though no statistical analysis is performed. This study clearly demonstrated that the spatial dependence and structure of *T. vaporariorum* populations are quite different when assessed using yellow sticky trap and visual counts of adults and immatures, respectively. These differences may produce poor spatial relations between the two sampling methods used in this study. If the goal of a sampling program is to obtain classical statistics, such as the mean or variance, then the leaf and trap samples should be taken at locations >9.0 m and >15.9 m apart, respectively, to obtain a more precise inference of the mean density of *T. vaporariorum*. If map generation or variance interpolation is desired, then the sample locations should not be >9.0 m for the leaf samples and >15.9 m for the trap samples in order to decrease the local interpolation error (Flatman & Yfantis 1996). It is evident that although traps are used for the benefit of growers and scientists, their utilisation could be further increased through greater understanding and correct analysis of spatial relations relative to the trap size and leaf sampling distribution within cherry tomato greenhouses.

The application of the sampling plan for mean estimates of adult *T. vaporariorum* may vary with the size of the cherry tomato greenhouse and *T. vaporariorum* density. Kim *et al*. (2001) developed sequential sampling methods to estimate the mean density of adult *T. vaporariorum* in tomato greenhouses. They reported that the required number of sticky traps at the precision 0.25 was 10 and 6 when the *T. vaporariorum* density per trap was <100 and >200, respectively. In general, two types of commercial greenhouses are used for vegetable production in Korea: a connected greenhouse (≈40 m × ≈80 m in size) for medium- to large-scale production and a single unit greenhouse (≈20 m × ≈40 m in size) for small-scale production. For the connected greenhouse, when the density was less than 100 per trap, the use of two parallel lines of five traps placed on each side of a greenhouse ≈12.5 m from the greenhouse edge should cover the greenhouse adequately to provide unbiased estimates of mean density. At high densities (>200 *T. vaporariorum* per trap), two parallel lines of three traps spaced ≈16 m apart could be placed in the greenhouse. For the single unit greenhouse, the use of two diagonal lines crossing each other (an X pattern) provides enough space for only five traps to generate spatially independent data. Therefore, unbiased estimates of mean density could be rarely obtained from the single unit greenhouse, irrespective of the adult *T. vaporariorum* density on the sticky traps. Because of this, it is recommended that five to six traps spaced ≈16 m apart be deployed for early detection or mean density estimation of *T. vaporariorum* throughout the tomato growing season in a single unit greenhouse.

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