Spatial Distribution of Eggs of *Bactericera cockerelli* (Hemiptera: Trizoidae) in Tomatillo Using Geostatistical Techniques[1]

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Abstract The tomatillo, *Physalis ixocarpa* Brotero, is an important vegetable in central Mexico but production is limited by the psyllid pest *Bactericera cockerelli* (Sulc) (Hemiptera: Trizoidae). This study was undertaken in 2016 to generate maps of the spatial distribution of *B. cockerelli* in the municipalities of Luvianos, Jocotitlán, and Ixtlahuaca in the State of Mexico to support implementation of integrated pest management strategies to improve tomatillo production. Geostatistical analysis was performed to estimate the experimental semivariogram and fitted to a theoretical model with the program Variowin 2.2. All generated models were validated. It was determined that for the three municipalities evaluated, 29 semivariograms were the adjusted spherical model, four were the Gaussian model, and three were the exponential model. Aggregation maps of the pest were evaluated in all plots, and areas were identified with the highest incidence of the pest, thus allowing initiation of control measures at selected sites while decreasing environmental impact and improving cost effectiveness.

Key Words *Bactericera cockerelli*, geostatistic, tomatillo

Tomatillo, *Physalis ixocarpa* Brotero, is an important vegetable in Central Mexico and is used in foods as well as for medicinal and ceremonial purposes. Production in Mexico in 2015 totaled 563,306.12 tons. Baja California has the greatest production followed by Sinaloa, Nayarit, Michoacán, Jalisco, Sonora, and the State of Mexico. In the State of Mexico, 804 ha produced 12,885 tons in 2015 (Servicio de Información Agroalimentaria y Pesquera [SIAP] 2015).

Recently, economic losses in tomatillo have been attributed to the psyllid, *Bactericera cockerelli* (Sulc) (Hemiptera: Trizoidae), in South Central Mexico. Other cultivated Solanaceae crops, like tomato (*Solanum lycopersicum* L.), chili (*Capsicum frutescens* L.), and potato (*S. tuberosum* L.) are also impacted by the pest (Almeyda et al. 2008; Plesch 1947). The psyllid directly damages host plants by sucking plant fluids (Munyaneza et al. 2007) and causes indirect damage by

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transmitting plant diseases (Garzón et al. 2004), including the phloem-limiting bacterium *Candidatus* Liberibacter *solanacearum* (Lso) (Liefting et al. 2008).

Integrated pest management (IPM) programs rely on knowledge of the spatial distribution of insect pests in cropping systems. Geostatistical and other newly-introduced technologies are increasing in usage with this aspect of IPM. Geostatistical analysis provides a direct measure of the precise spatial localization and mapping of organisms and their distribution (Blom and Fleischer 2001; Ramírez et al. 2011; Sciarretta and Trematerra 2006, 2011; Sciarretta et al. 2011), thus providing a degree of knowledge of the infestation and spatial distribution of an insect. Currently, the presence of eggs is overlooked because most chemical control is focused on nymphs and adults. Yet the presence of eggs indicates the initial degree of infestation in the plot. The objective of this study was to identify the spatial distribution of *B. cockerelli* eggs by geostatistical techniques in tomatillo production in the State of Mexico.

Materials and Methods

The study was conducted in three localities of major tomatillo production in the State of Mexico during 2016. The study was limited to 1 yr because growers will rotate tomatillo with corn and bean crops and will plant according to anticipated market demand and price. We, therefore, conducted the study at three locations and at sites where severe direct and indirect damage by the psyllid occurs. Agronomic management (i.e., fertilizer, irrigation, weed management) were similar at the three sites.

Sampling and analyses were conducted for the fall–winter cycle in Luvianos (1,130 m elevation) and for the spring–summer cycle in Ixtlahuaca (2,540 m elevation) and Jocotitlán (2,650 m elevation). Samples were taken at three phenological stages of crop growth: (1) 30 d after transplant (DAT) when the plant was flowering, (2) 40 DAT when fruiting began, and (3) 60 DAT as plant senescence begins. For each sample, a 100-m transect was established and sampling points were marked every 10 m along the transect. Numbers of *B. cockerelli* eggs on plant foliage were recorded at each of the 121 sample points.

The geostatistical analysis for determining the spatial distribution of *B. cockerelli* eggs consisted of an estimation of the (a) semivariogram, (b) parameters of the semivariogram model, and (c) surface (maps) using points (estimates) from Ordinary Kriging. The estimation of the semivariogram was made with the data collected from the sample sites. The experimental value of the semivariogram was calculated as described by Journel and Huijbregts (1978) and Isaaks and Srivastava (1989), where $\gamma^{*}(h)$ is the experimental value of the semivariogram for the distance interval h, $N(h)$ is the number of paired sample points separated by the distance interval h, $z(x_i)$ is the value of the variable of interest in the sample point x_i, and $z(x_i+h)$ is the value of the variable of interest in the sample point x_i+h. This semivariogram is called experimental and it is fitted to a predetermined theoretical semivariogram, which is then validated. The validation of the models fitted to the experimental semivariograms was made by the validation procedure described by Isaaks and Srivastava (1989) and Hevesi et al. (1992). The parameters to be validated are the Nugget effect, the plateau, and the range or scope, which are modified by trial and error until the following statistical cross-validation is obtained: average estimation errors (MEE), mean square error (ECM), dimensionless mean square error (ECMA), and an additional statistical estimation for validating the model fit so that the variance value of the errors is lower than the sample variance. The level of spatial dependence was calculated to determine the strength of the relation among the data obtained in the samples. This value obtained, expressed in a percentage, is classified as high if $<$25%, moderate if between 26 and 75%, and low if $>$75% (Cambardella et al. 1994; López et al. 2002).

Calculation of the infested surface area was based on a density map where Ordinary Kriging was used after the validation of the semivariograms models in order to estimate the unbiased values for points that were not sampled using the software VarioWin 2.2 (Software for Spatial Data Analysis in 2D, Springer-Verlag, New York, NY, USA), thus allowing for creation of egg density spatial distribution maps. Real surface area infested with the *B. cockerelli* eggs was estimated using Surfer 9.0 (Surface Mapping System, Golden Software Inc., Golden, CO 80401-1866 USA).

Results

All three localities sampled in this study were confirmed to have infestations of *B. cockerelli* eggs with Jocotitlán having the highest density (0–70 eggs per plant in the fruiting stage) and the lowest was found in Ixtlahuaca (0–6 eggs per plant) (Table 1). It was further determined that 29 semivariograms were fitted to the spherical model, four were fitted to the Gaussian model, and three were fitted to the exponential model (Table 1). An aggregated spatial distribution was obtained in the three localities on every sampling. Nugget effect values equaled 0 in all semivariograms of the models obtained; thus, 100% of the variation of the psyllid egg distribution was explained by the established spatial structure of the respective semivariograms and also indicated that the sample error was minimal and that the scale for each locality was adequate. The values in the ranges of the theoretical models fitted to the semivariograms were 9–25 m in Ixtlahuaca, between 6–29 m in Luvianos, and 18–30 m in Jocotitlán (Table 1), and the level of spatial dependence found in the three municipalities under study was high (Table 1).

Aggregation maps were determined in all the models and are visualized in Figures 1, 2, and 3. Maps of the egg-infested surface area in the samples indicated that the *B. cockerelli* eggs were aggregated. In Luvianos and Ixtlahuaca, aggregation foci were located in the center of plot 2 and along plot borders in plots 1, 3, and 4 (Figs. 1, 2). On the other hand, aggregation foci are seen in the center of the plots at Jocotitlán, with only a slight tendency toward the borders (Fig. 3). At Ixtlahuaca and Luvianos, the aggregation centers were located along the borders of the plots during plant flowering, the center of the plots during fruiting, and throughout most of the plot at harvest. At Jocotitlán, aggregations were observed in the center of the plot (Fig. 3), but tended toward the borders of the plot during flowering, while the entire plot was infested during fruiting and harvest. Regardless of location, the highest percentage of infested surface area was observed during the fruiting stage of development (Table 2).

Table 1. Theoretical model parameters adjusted to semivariograms of plot eggs for *B. cockerelli* in the State of Mexico, in 2016.*

Date	Plots	Model	Nugget	Sill	Range	Nugget/Sill (%)	Level of Space Dependence	Variance	Population Density (E×P)
25 Jul	P1S1	Spherical	0	0.35	25	0	High	0.58	0–6
4 Aug	P1S2	Spherical	0	5.71	23	0	High	10.39	0–21
24 Aug	P1S3	Exponential	0	0.41	24	0	High	0.42	0–6
25 Jul	P2S1	Spherical	0	12.32	36	0	High	13.88	0–19
4 Aug	P2S2	Spherical	0	14.14	38	0	High	16.14	0–20
24 Aug	P2S3	Gaussian	0	11.91	24	0	High	12.61	0–15
25 Jul	P3S1	Spherical	0	1.56	38	0	High	1.71	0–10
4 Aug	P3S2	Spherical	0	1.08	42	0	High	1.40	0–7
24 Aug	P3S3	Exponential	0	1.47	34	0	High	1.67	0–7
25 Jul	P4S1	Spherical	0	3.33	16	0	High	4.60	0–10
4 Aug	P4S2	Spherical	0	10.89	9	0	High	3.45	0–8
24 Aug	P4S3	Gaussian	0	3.20	13	0	High	12.47	0–15
13 Jan	P1S1	Gaussian	0	21.08	12	0	High	4.18	0–35
23 Jan	P1S2	Gaussian	0	2.17	12	0	High	2.50	0–7
15 Feb	P1S3	Exponential	0	3.42	15	0	High	3.88	0–8

Table 1. Continued.

Date	Plots	Model	Nugget	Sill	Range	Nugget/Sill (%)	Level of Space Dependence	Variance	Population Density (E×P)
13 Jan	P2S1	Spherical	0	9.29	18	0	High	48.61	0–28
23 Jan	P2S2	Spherical	0	4.62	20	0	High	6.25	0–15
15 Feb	P2S3	Spherical	0	38.56	11	0	High	10.80	0–15
13 Jan	P3S1	Spherical	0	9.36	29	0	High	3.92	0–7
23 Jan	P3S2	Spherical	0	5.35	18	0	High	6.85	0–12
15 Feb	P3S3	Spherical	0	3.77	22	0	High	9.42	0–11
13 Jan	P4S1	Spherical	0	9.58	17	0	High	9.04	0–26
23 Jan	P4S2	Spherical	0	8.75	6	0	High	10.70	0–11
15 Feb	P4S3	Spherical	0	5.70	6	0	High	11.57	0–16
31 Jul	P1S1	Spherical	0	0.93	24	0	High	0.98	0–5
10 Aug	P1S2	Spherical	0	11.11	30	0	High	12.83	0–13
30 Aug	P1S3	Spherical	0	57.75	27	0	High	66.52	0–50
31 Jul	P2S1	Spherical	0	12.47	25	0	High	14.07	0–29
10 Aug	P2S2	Spherical	0	1.46	27	0	High	1.58	0–8
30 Aug	P2S3	Spherical	0	141.81	25	0	High	156.25	0–48
31 Jul	P3S1	Spherical	0	4.17	27	0	High	4.49	0–8

Table 1. Continued.

Date	Plots	Model	Nugget	Sill	Range	Nugget/Sill (%)	Level of Space Dependence	Variance	Population Density (E×P)
10 Aug	P3S2	Spherical	0	2.15	23	0	High	2.37	0–8
30 Aug	P3S3	Spherical	0	64.22	20	0	High	75.51	0–34
31 Jul	P4S1	Spherical	0	12.39	26	0	High	13.96	0–15
10 Aug	P4S2	Spherical	0	14.62	18	0	High	15.69	0–18
30 Aug	P4S3	Spherical	0	245.79	28	0	High	282.90	0–70

* P = plot; S = sample; E×P = eggs × plant.

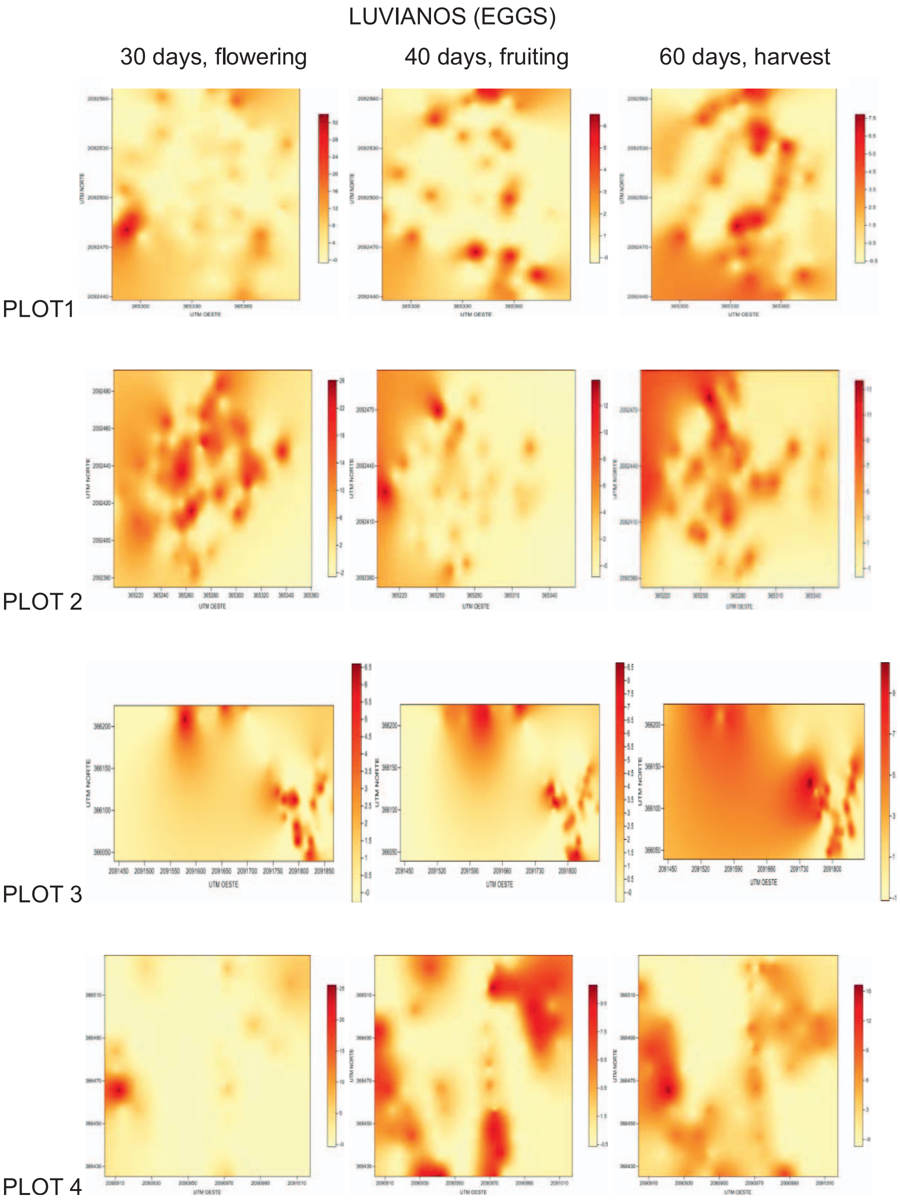

Fig. 1. **Density maps of eggs of *B. cockerelli* in tomatillo in plot 4 of the municipality of Luvianos in 2016.**

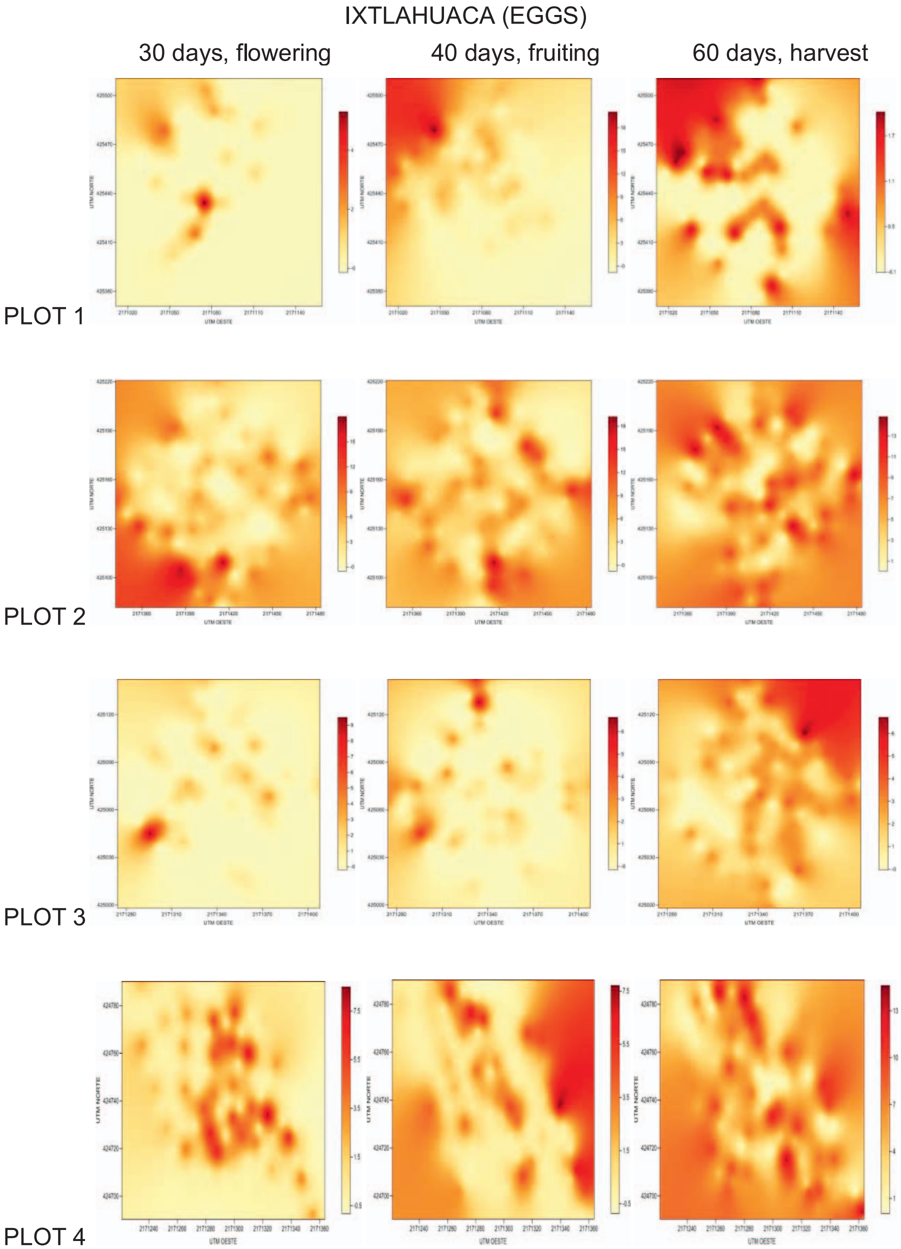

Fig. 2. Density maps of eggs of *B. cockerelli* in tomatillo in plot 4 of the municipality of Ixtlahuaca in 2016.

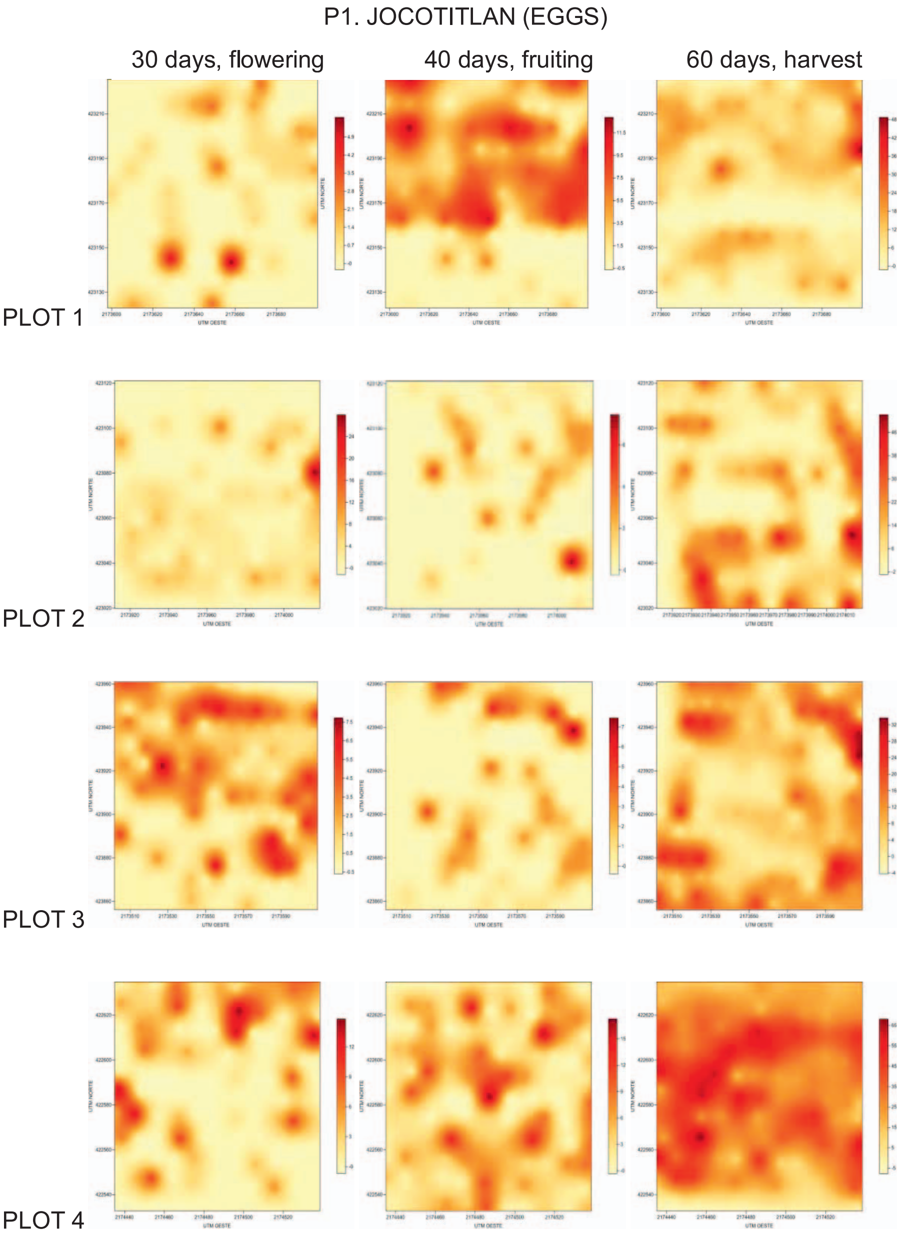

Fig. 3. Density maps of eggs of *B. cockerelli* in tomato in plot 4 of the municipality of Jocotitlán in 2016.

Table 2. Estimating the percentage of infested and uninfested surface, obtained in the sample *B. cockerelli*, by municipality and plot in the State of Mexico in 2016.*

Plot	Luvianos (%) Infested	Luvianos (%) Uninfested	Ixtlahuaca (%) Infested	Ixtlahuaca (%) Uninfested	Jocotitlán (%) Infested	Jocotitlán (%) Uninfested
P1S1	15	85	26	74	65	35
P1S2	54	46	65	35	26	74
P1S3	83	17	77	23	50	50
P2S1	79	21	47	53	58	42
P2S2	88	12	24	76	28	72
P2S3	89	11	64	36	47	53
P3S1	26	74	55	45	44	56
P3S2	33	67	32	68	48	52
P3S3	87	13	71	29	55	45
P4S1	39	61	39	61	36	64
P4S2	45	55	83	17	42	58
P4S3	89	11	91	9	56	44

* P = plot; S = sample.

Discussion

The higher density of *B. cockerelli* eggs observed during the phenological stage of harvest is likely due to the practice of halting efforts to control the psyllid pest during harvest. At that point, the eggs were generally more-evenly distributed across plots than at other phenonological development stages. The spread of eggs over phenological development (and time) from plot borders to centers is postulated to be due to insect movement and spread as population density and activity increased (Figs. 1–3), including the possibility of unchecked population growth on plant flora surrounding crop plots (Garzón 2002).

The geostatistical technology provided density maps showing aggregations or clusters of *B. cockerelli* eggs which, according to Fleischer et al. (1999a), demonstrates the relationship between average egg density and the location and degree of aggregation centers observed with the density maps. Such information allows focusing psyllid control on those areas of infestations (Fleischer et al. 1997), thus reducing inputs of insecticides, fuel used in applications, and negative environmental impacts (Fleischer et al. 1999b).

Furthermore, the statistical functions of cross-validation allowed validating the spherical models, Gaussian models, and exponential models which were fitted for the three regions. Confirmation of the spherical model suggests that the aggregation foci of infestations are more-randomly distributed across the plot (Samper and Carrera 1996). The exponential model, identified in two plots at Ixtlahuaca and one plot at Luvianos during harvest, indicates a continuous distribution across the plots while the Gaussian model shows a uniform distribution (Samper and Carrera 1996).

The level of spatial dependence at the three municipalities was high, which demonstrates an aggregated distribution of the infestation of *B. cockerelli* eggs (Cambardella et al. 1994; López et al. 2002). This was confirmed with the estimation models created with kriging (Figs. 1–3). Knowledge of locations of aggregation centers within the field, as well as the occurrence relative to crop phenology, provides for more effective and efficient management of the pest while making assumptions as to the source of infestations, e.g., neighboring plantations and fallowed areas containing solanaceous weed flora. Identification of free-of-damaging levels of *B. cockerelli* may also be identified, as was done by Ramírez et al. (2011) using geostatistical techniques in potato crops in Donato Guerra, Mexico.

The spatial distribution results obtained in this study with *B. cockerelli* eggs corroborate previous reports showing aggregation foci and centers of *Diaphorina citri* Kuwayama (Moreno et al. 2008), *Trialeurodes vaporariorum* (Westwood) on tomato (Basso et al. 2001) on *Leucaena leucocephala* (Valenciaga et al. 2005), and *Bemisia tabaci* (Gennadius) in sesame (Laurentin and Pereira 2002). Our results further show that geostatistical techniques allow for the determination of the spatial distribution of *B. cockerelli* eggs in tomatillo with the geostatistical semivariograms. Maps offer the possibility of identifying aggregation centers in fields to improve management efficiency; thus further leading to the application of precision farming methods to provide an economical return on investment and reduction of negative environmental impacts.

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