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Spatial Distribution of Nymphs Populations *Bactericera cockerelli* Sulc in Tomato Crops (*Physalis ixocarpa* Brot)

Roberto Rivera-Martínez[1], Agustín David Acosta-Guadarrama[1], José Francisco Ramírez-Dávila[2,*], Fidel Lara Vazquez[1] and Dulce Karen Figueroa Figueroa[1]

[1]Autonomous University of the State of Mexico, Cerrillo Piedras Blancas n/n km 15, Toluca, 50200, Mexico.

[2]Laboratory of Entomology Research and Technology in Precision Farming, UAEM, Cerrillo Piedras Blancas n/n km 15, Toluca, 50200, México.

[*]Corresponding Author: José Francisco Ramírez-Dávila. Email: jframirezd@uaemex.mx.

Abstract: Tomato crops (*Physalis ixocarpa* Brot.) are produced in almost all Mexico, part of the United States and Central America. Recently the tomato production has suffered economic losses of 70% to 80% due the presence of yellowing and floral abortion, whose causal agent has been attributed to the presence of phytoplasma; an insect vector of these phytoplasma is *Bactericera cockerrelli* Sulc. Alternative control of this psyllid has lacked effectiveness because their spatial distribution is unknown within tomato plots. This study aimed to determine the spatial distribution of populations of nymphs of *B. cockerelli* in four tomato plots, the determination of the spatial distribution was performed by means of geostatistics. The experimental semivariogram was determined to adjust to a theoretical model (spherical, exponential or Gaussian) through the program Variowin 2.2, the adjustment was validated with the method of cross-validation and aggregation maps of the pest were obtained through Kriging with Surfer 9.0 program. The short-term time-space stability of the pest was determined through the tests Crámer-von Mises. The results showed that populations of nymphs of *B. cockerelli* have a distribution of aggregate type, which was corroborated by density maps. Infestations are not present in 100% of the surface of the experimental plots, which helps to direct control measures on specific areas of infestation.

Keywords: Geostatistics; *Bactericera cockerelli* Sulc; Kriging

1 Introduction

The tomato (*Physalis ixocarpa* Brot.) belongs to the *Solanaceae* family, *Solanoideae* subfamily, *Solaneae* tribe (includes 18 genus). It is associated with the Pacific basin species, where it is still possible to find it wild in a strip which runs from Central America (Guatemala) to California [1].

It has been estimated that there are about 80 species from the genus *Physalis*, mostly confined to temperate and tropical zones in America, and very few species in East Asia, India, Australia, Europe and tropical Africa. Of all the species of this genus, about 70 are in Mexico [2].

Within vegetables, tomato production ranks fourth in terms of area cultivated in Mexico, only surpassed by potato, tomato and chilli. The main tomato producers are: Sinaloa, Michoacan, Puebla, Morelos, Jalisco, Hidalgo, Guanajuato, Mexico [3].

The production of green tomato represents 4.25% of the total area of vegetables nationwide, with an average annual growth of 4.4%. About 81% of the tomato is produced under irrigation, the rest 19% is temporary. The state with the largest harvested area and production volume is Sinaloa, followed by Michoacan, Jalisco, Mexico State, Sonora and Puebla [4].

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One of the main problems tomato growers face are the diseases that occur each cycle, one of which is characterized by the presence of plants that age prematurely decreasing yields 60% compared to the expected performance. Recently found that these symptoms are associated with a new bacterium which they called "Candidatus Liberibacter solanacearum" which seems to be the same bacterium that causes yellowing of the psyllids in tomato (*Lycopersicon esculentum* Mill.) and chilli (*Capsicum annuum* L.). According to these researchers, this new bacterium is transmitted by the psyllid *Bactericera cockerelli* Sulc, which is an insect widely present in most agricultural areas of Mexico.

Monitoring populations of *B. cockerelli* is very important in managing this problem as this procedure can give an overview of how it is distributed within the study plots. In order to use adequately the information derived from monitoring, it is necessary to establish sampling points that generate reliable data which allows to visualize the spatial behavior of *B. cockerelli*. The infestation of this insect pest emphasizes the importance of implementing strategies to know their location within the plots of tomato; therefore, the objective of this study was to determine the spatial behavior of populations of nymphs *Bactericera cockerelli* Sulc. in tomato crops (*Physalis ixocarpa* Brot.).

2 Materials and Methods

The study was conducted in the municipality of Luvianos, a leading producer town of tomato in the State of Mexico [3], which is located in the southern part of the State of Mexico, it is between parallels 18° 55' 30" north latitude and 100° 18" west longitude from Greenwich Mean Time; it is at a height of 1300 meters above sea level. For the study of spatial behavior of populations of nymphs of *B. cockerelli*, 4 experimental plots were established, the sample used was the transects, in which a rectangular grid of 100 meters was established and sampled every 10 meters in both directions, thus 121 plants were sampled in each plot. In each sampled plant, pest insect nymphs were recorded taking into account five leaves of the plant in its different layers, each plant was properly labeled to know its exact position. The samplings were conducted every month, the first sampling was performed when the crop was in the flowering stage and the following samplings were conducted when the crop was in the production stage.

A statistical exploration of the original data of the population of nymphs of *B. cockerelli* was performed in the corresponding samplings to each of the plots. Using the curtosis test it was determined that there was normality in the data collected, so it was not necessary to perform a logarithmic transformation of the data [log10 (n + 1)] to normalize them.

2.1 Geostatistical Analysis

An experimental semivariogram of nymphs counted in each sample is obtained, using the variowin 2.2 program. The value of the experimental semivariogram is calculated with the following formula [5,6]:

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

where γ *(h) is the experimental value of the semivariogram for the distance interval h, N (h) is the number of pairs of sampling points separated by the distance interval h, z (xi) is the value of the variable of interest in the sampling point xi, and z (xi + h) is the value of the variable of interest in the sampling point xi + h.

When the experimental semivariogram is obtained, an adjustment is made to a theoretical semivariogram (Gaussian, spherical, exponential, etc.) and a cross-validation procedure is used in which the parameters of the model are adjusted to a trial and error setting until the best values of the statisticians. The parameters that are adjusted are Co (nugget effect), plateau (C + Co) and range [6,7].

a) Mean estimation errors (MEE):

$$\text{MEE}\frac{1}{n}\sum_{i=1}^{n}\left[z^*(x_i)-z(x_i)\ \right]$$

where z* (xi) is the estimated value of the variable of interest in the point xi, z (xi) is the value measured from the value of interest in the point xi, and n is the number of sampling points used in the interpolation. The MEE should not be significantly different from 0 (*t*-Test), which would indicate that the semivariogram model allows for the calculation of unbiased estimates values.

b) Mean squared error (ECM):

$$\mathrm{ECM}\frac{1}{n}\sum_{i=1}^{n}\left[z^{*}(x_i)-z(x_i)\ \right]^{2}$$

A semivariogram model is considered appropriate if, as a rule of thumb, the statistical value is close to zero [7].

c) Dimensionless mean square error (DMSE):

$$\mathrm{ECMA}\frac{1}{n}\sum_{i=1}^{n}\frac{\left[z^{*}(x_i)-z(x_i)\ \right]^{2}}{\sigma_k}$$

where k is the standard deviation of the error expected in the estimation by kriging. The model is valid if ECMA is between the values 12(2/N) 0.5 [7].

d) Another statistical value for validation of model fit consisted of a variance value lower than the sampling variance.

The level of spatial dependence is determined to see how strong the aggregation of the pest is within the crop. This value is obtained by dividing the effect between the month and the result is expressed in the percentage, the values are high if high 25%, moderate if they are between 26 and 75% and low if they are greater than 76% [8,9].

The infested surface was calculated based on the infestation maps that were obtained using the krigeado technique, which is an interpolator that will estimate and give values associated with the points that were not sampled and the results are expressed as a map, this is done using the program Surfer 9 (Surface Mapping System, Golden Software Inc. 809, 14th Street. Golden, Colorado 80401-1866. USA).

2.2 Long-Term Spatiotemporal Stability

The maps developed with the Ordinary Kriging method for different years were compared to determine the spatiotemporal stability of nymphs Bactericera cockerelli populations by the non-parametric test of Cramér-von Mises (Ψ), modified by Syrjala [10] as advised by Liebhold et al. [11].

3 Results

3.1 Geostatistical Analysis

With the data collected in the samples it was possible to generate spatial modeling and mapping of nymphs of *B. cockerelli* populations within tomato plots. The estimated percentage of infestation was established in each sampling date allowing to determine the spatio-temporal stability of this insect in the short term.

The spatial distribution that was obtained in the populations of *B. cockerelli* nymphs was of an aggregate type, in all the samplings and adjusted models there was a nugget effect equal to 0, an exception of the date of February 18 of plot four in the one that obtained a nugget effect equal to 1.26 (Tab. 1). The low value of the nugget found in all cases indicates that the sampling error was minimal and that the sampling scale used in the present work was adequate [12].

For all models a high spatial dependence was presented, except for the date of December 17th, on the plot one in which an average spatial dependence was obtained. The values obtained were in the range of 13.4 and 30.7 m for one plot, 14.3 and 15.4 m in plot two, while the values for plots three and four ranged between 26 and 36.4m and 10.4 and 12 m respectively (Tab. 1). This distance between the ranges of each sampling shows where there is spatial dependence of the sampled data given that beyond the maximum distance value the spatial dependence is zero. The distribution of nymphs presented a high level of spatial dependence in all adjusted models, this is indicative of the existence of a strong spatial relationship of the pest in the sampled points.

Table 1: Parameters (nugget, sill and range) models adjusted to the semivariograms of nymphs *B. cockerelli*

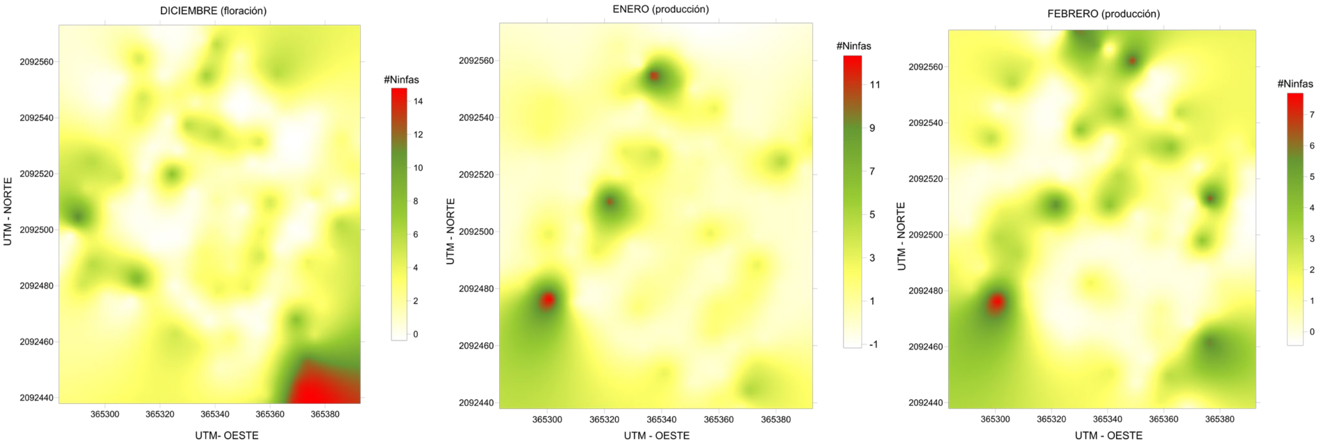
Plot	Date	Model	Nugget	Sill	Range	Nugget/Sill	Level of spatial dependence
	17-Dec-15	Spherical	0	6.863	14.4	0	Medium
1	14-Jan-16	Spherical	0	3.948	14.4	0	High
	18-Feb-16	Spherical	0	2.294	13.44	0	High
	17-Dec-15	Spherical	0	36.4	16.5	0	High
2	14-Jan-16	Spherical	0	3.192	15.4	0	High
	18-Feb-16	Spherical	0	2.88	15.4	0	High
	17-Dec-15	Spherical	0	3.264	39	0	High
3	14-Jan-16	Spherical	0	5.45579	33.791	0	High
	18-Feb-16	Spherical	0	10.64	18.6	0	High
	17-Dec-15	Spherical	0	4.355	12	0	High
4	14-Jan-16	Spherical	0	8.96	11.2	0	High
	18-Feb-16	Spherical	1.26	17.01	12	7.40	High

The models of the spatial distribution of *B. cockerelli* in the plots studied were validated through statistical parameters to be within the allowable range [6]. As for the average population of nymphs of *B. cockerelli* the month which showed a higher degree of infestation was December with 2.4876 nymphs per plant and the month with the lowest infestation was January with 1.1570 nymphs per plant for the plot one; in the plot two, the month which showed a higher degree of infestation was December with an average of 4.3057 and the month with the lowest infestation was January given that it had a sample mean of 0.9917 nymphs per plant; for the plot 3, February was the month in which major infestation was obtained with a value of 3.4793 nymphs and the lowest month was December with a value of 1.1983 individuals per plant; and finally in the plot four, the highest value was 4.3140 nymphs in February and 1.6083 nymphs per plant in December (Tab. 2).

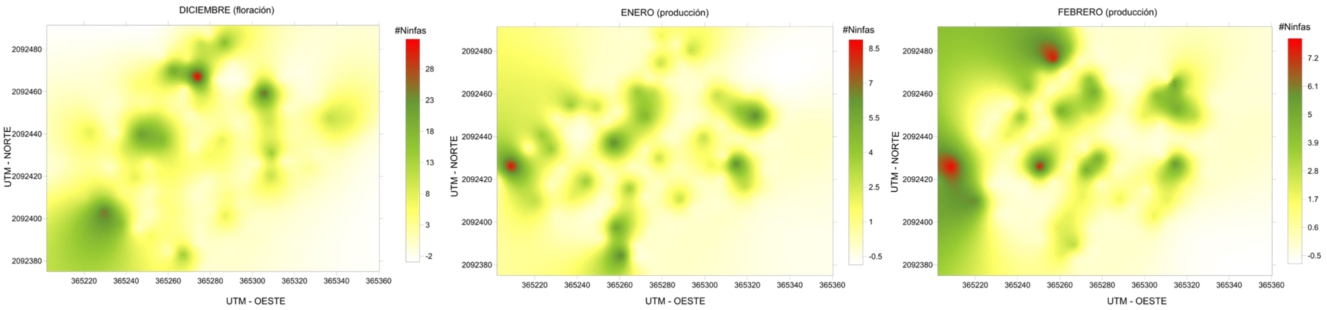
Table 2: Values of the cross validation statistics: means of estimation errors (MEE), mean square error (ECM) and non-dimensional mean square error (ECMA) of *B. cockerelli* nymphs

Plot	Date	Sample size	Sample Average	Variance Sample	MEE	Variance of the errors	MSE	DMSE
	17-Dec-15	121	2.4876	8.7852	0.11^{ns}	5.52	0.11	1.09
1	14-Jan-16	121	1.1570	4.7001	0.10^{ns}	3.03	0.09	1.12
	18-Feb-16	121	1.3471	3.0785	0.13^{ns}	2.16	0.12	1.08
	17-Dec-15	121	4.3057	39.9973	0.10^{ns}	35.22	0.10	1.10
2	14-Jan-16	121	0.9917	3.8249	0.11^{ns}	2.17	0.12	1.07
	18-Feb-16	121	1.1570	3.9501	0.12^{ns}	2.35	0.08	1.10
	17-Dec-15	121	1.1983	3.4103	0.12^{ns}	1.99	0.11	1.12
3	14-Jan-16	121	1.7603	6.2170	0.10^{ns}	4.72	0.10	1.11
	18-Feb-16	121	3.4793	13.5183	0.13^{ns}	11.25	0.13	1.09
	17-Dec-15	121	1.6083	6.5595	0.10^{ns}	4.96	0.13	1.13
4	14-Jan-16	121	3.0578	13.9216	0.13^{ns}	11.51	0.11	1.08
	18-Feb-16	121	4.3140	20.2505	0.11^{ns}	17.05	0.06	1.12

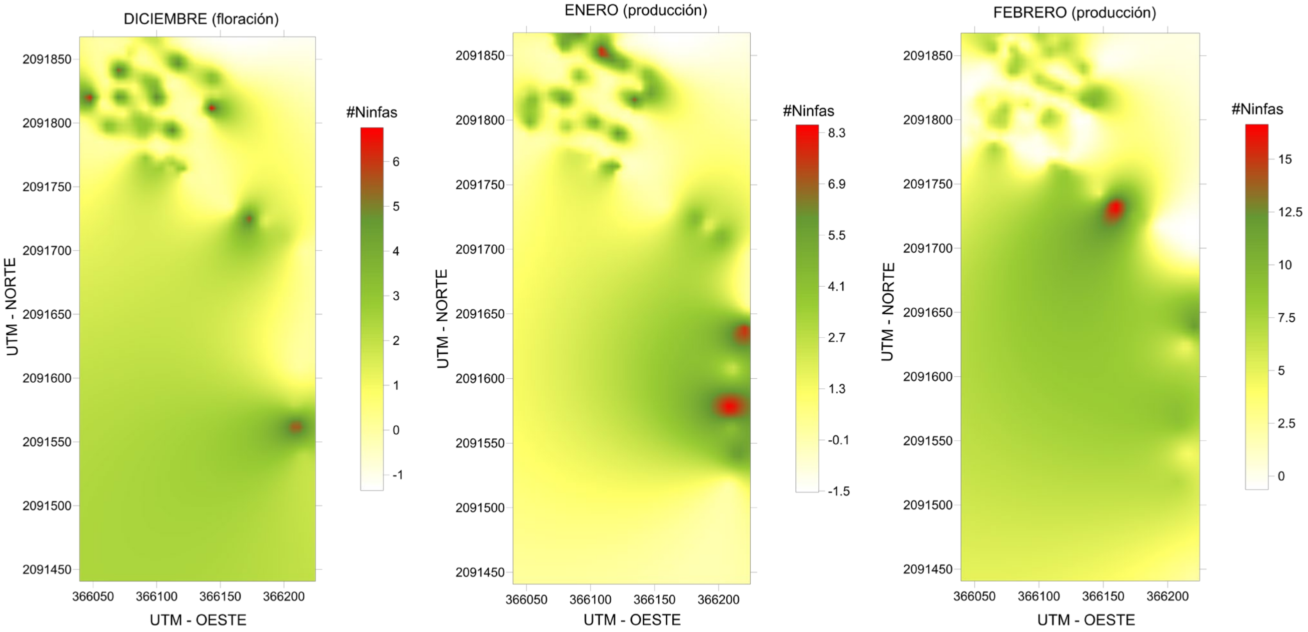
PLOT 1



PLOT 2



PLOT 3



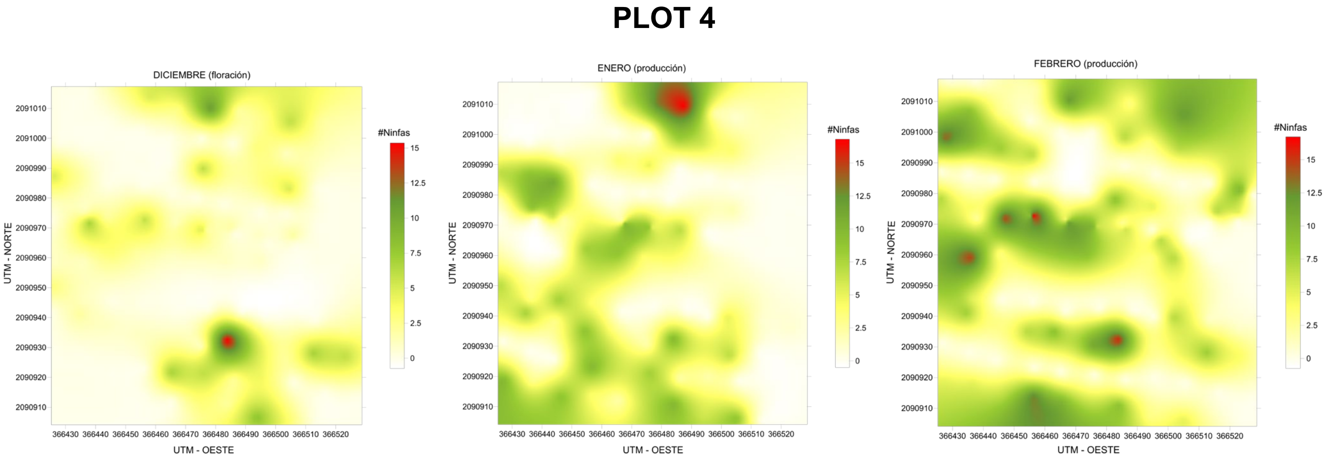


Figure 1: Maps of population density of *B. cockerelli* obtained in the four study plots

Maps in the infested surface showed that populations of nymphs of *B. cockerelli* stood at centers of aggregation, that is, their location is in specific points, for plot one, the centers of aggregation were found distributed throughout the plot, however, areas with higher density are mainly found to the margins of the plot, this happened during the three samples; in the second plot, the centers with greater density were found markedly on the left side and a bit in the central part of the map; in the case of the plot three, the centers of aggregation with higher density are on the upper part of the maps as well as small aggregations on the right side; on plot four there were centers of aggregation in the whole plot being more noticeable in the center of the map and next to the edges (Image 1).

3.2 Infested Area

In the plot 1 the percentages of infestation were between 39% and 47%. Most surface free of insect attack occurred in the first sample while the surface with more infestation was in the second sampling; in the case of parcel 2, the area without infestation in different sampling dates ranged between 52% and 59% of the total area, it is worth pointing out that it was the third sampling where the highest percentage of free surface of infestation was observed; in plot 3, free infestation rates were found between 16% and 25%. Most surface free of insect attack was found in the third sampling, on the other hand, the first sampling was the one that had the highest degree of infestation and finally in plot 4 the area without infestation for the different samples ranged from 56% and 31% of the surface, it is noteworthy that in the first sample where there was most surface free of infestation, however, the third sampling was the one which presented the most infected area (Tab. 3).

Table 3: Percentage of infested and uninfested area (%)

Plot	Sampling number	% Infested	% Uninfested
	1	39	61
1	2	47	53
	3	42	58
	1	45	55
2	2	48	52
	3	41	59
	1	84	16
3	2	80	20
	3	75	25
	1	44	56
4	2	62	38
	3	69	31

3.3 Spatial and Temporal Stability

The comparison between sampling dates of the different maps obtained in each of the plots can give us indications of the spatiotemporal dynamics of the insect. More specifically the possibility of finding a numerical stability in space and time can open doors for the use of the techniques of precision farming in this insect.

Table 4: Comparison of maps (Kriging) with the bivariate Cramér-von Mises test (Ψ)

Plot	Compared sampling	Ψ	Value of P	Difference (5%)
1	1 vs 2	0.27	0.41	Not meaningful
	2 vs 3	0.21	0.48	Not meaningful
2	1 vs 2	0.22	0.45	Not meaningful
	2 vs 3	0.25	0.43	Not meaningful
3	1 vs 2	0.32	0.46	Not meaningful
	2 vs 3	0.28	0.45	Not meaningful
4	1 vs 2	0.31	0.55	Not meaningful
	2 vs 3	0.26	0.41	Not meaningful

The results with the bivariate Cramér-von Mises statistical test, indicate no significant difference in the spatial and temporal stability of short-term between sampling dates for the 4 plots, it is, there was spatial and temporal stability in populations of *B. cockerelli* in the 4 plots in each sample analyzed.

4 Discussion

The spatial distribution adjusted to the spherical model is indicative that within the plot analyzed there are areas with more *B. cockerelli* than the rest of the sampled points, it is to say, there are zones of pest infestation which move from a point source. The use of techniques to model the spatial behavior of insects have proven to be a very efficient tool in various insect pests that attack crops of economic importance, example of this are the results reported in different studies [13-18]. These techniques have also been applied in diseases such as head smut of corn [19], all these works allowed to determine the spatial pattern of these phytosanitary problems at specific points of the plots and regions studied.

In this paper all semivariograms adjusted to the spherical model, unlike those reported by Cho et al. [20] who found a setting for several models in populations of Thrips simplex in gladiolus and Reisig et. al. [21] and in the Anaphothrips obscurus populations.

The high level of spatial dependence resulted from dividing the nugget effect between the plateau which was less than 25% for all semivariograms. The values of the nugget effect indicated a high spatial dependence which indicates that the nymph populations depend on each other and the level of aggregation is high [12]. Esquivel & Jasso [22] carried out a study of the spatial distribution of welded worms in six localities of the State of Mexico using the techniques of geostatistics, which showed the existence of an aggregate spatial structure, finding a high level of spatial dependence in the Six study locations for the year 2011.

The relationship between the average density of insects and the number of aggregation centers can be seen in the density maps produced by the technique of kriging. Among the works carried out with insects in which this relationship has been registered are those made by Jimenez et al. [23], which determined the spatial distribution and mapping of *Curculio elephans* in oak (*Quercus ilex*), Ramirez et al. [16] showed the spatial distribution of Preimaginational stages of *Bactericera cockerelli* Sulc*.,* in potatoes, Solares et al. [24] studied adult populations of *Thrips* (Insecta: Thysanoptera) in the cultivation of avocado.

4.1 Infested Area

The results that were obtained suggest that the infestation of an insect pest does not occur uniformly. Fleischer et al. [25] indicate that normally an insect pest has variable densities in the total area that infests, and that such infestation rarely reaches 100% of it, allowing, according to the authors, direct control tactics on infested areas and especially those in which the insect population exceeds the economic threshold, as long as this level is known. Ramírez et al. [16] established the spatial distribution of *Bactericera cockerelli* Sulc. In *Solanum tuberosum* L. in Donato Guerra, Mexico, where both quadrant and transect sampling were used, in both samples it was found that the spatial distribution was of an aggregate type and the maps in both quadrant and transect sampling Aggregate structure of the insect populations which did not invade 100% of the plot surface, allowing the identification of infested and infestation-free areas.

In the density maps obtained through the technique of kriging, the aggregation centers of the insect within the plot are observed, which when allows us to address control measures to protect the crop [25-29, 22] generating environmental benefits by reducing pesticide usage and economic benefits using less fuel, which will be reflected in the impact on the environment, this also helps by not generating insects' resistance to pesticides due to the creation of dynamic temporary shelters, instead of treating the entire cultivated surface [30].

Similar results have been reported by Ifoulis & Savopoulou-Soultani [31], who conducted studies which found that *Lobesia botrana* has an aggregated distribution in vineyards, in this way they determined the infested and uninfested areas, which helped them find that this insect does not infest 100% of the vineyards; Jimenez et al. [23], who determined the spatial distribution and mapping of *Curculio elephant* in oak (*Quercus ilex*), they produced four maps of density, one for each year; Ramirez & Porcayo [32] reported that the nymphs of *Jacobiasca lybica* did not invade 100% of vine plots therefore infestation was nonuniform; Jimenez et al. [17] reported that populations of *Frankliniella occidentalis* in tomatillo were not distributed in the totality of all the plots studied; Ramirez et al. [33] found that infestation maps *Bactericera cockerelli* Sulc on potato insect reflected an aggregate structure which did not invade 100% of the plot area, allowing to identify areas free of infestation.

In the case of the nymphs of *B. cockerelli* in tomatillo in the municipality of Luvianos State of Mexico methods of precision farming could be applied efficiently, since the findings that the bug does not infest the entire area it invades, so it is not necessary to perform an application of insecticides in general, but to apply them at specific points of infestation [22,28].

4.2 Spatial and Temporal Stability

The results with the bivariate Cramér-von Mises statistical test, indicate no significant difference in the spatial and temporal stability of short-term between sampling dates for the 4 plots. Similar results were obtained by Ferguson et al. [34] which show that the distributions of adults and larvae *Ceutorhynchus assimilis* were associated spatially, indicating that there was time-space stability. Ramirez & Porcayo [32] found values of the bivariate Cramér-von Mises test, both significant and non-significant of the spatial distribution of eggs of *Jacobiasca lybica*, indicating that there is and there is no time-space stability in such distribution, Solares et al. [24] determined the spatial stability of Thrips (Insecta: Thysanoptera) in the 10 comparisons made, time-space stability of the insect could be detected in the short term between the dates compared.

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