Research Article

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Assessing the spatial distribution of *Tuta absoluta* (Lepidoptera: Gelechiidae) eggs in open-field tomato cultivation through geostatistical analysis

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Abstract

BACKGROUND: The spatial distribution of insects is due to the interaction between individuals and the environment. Knowledge about the within-field pattern of spatial distribution of a pest is critical to planning control tactics, developing efficient sampling plans, and predicting pest damage. The leaf miner *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) is the main pest of tomato crops in several regions of the world. Despite the importance of this pest, the pattern of spatial distribution of *T. absoluta* on open-field tomato cultivation remains unknown. Therefore, this study aimed to characterize the spatial distribution of *T. absoluta* in 22 commercial open-field tomato cultivations with plants at the three phenological development stages by using geostatistical analysis.

RESULTS: Geostatistical analysis revealed that there was strong evidence for spatially dependent (aggregated) *T. absoluta* eggs in 19 of the 22 sample tomato cultivations. The maps that were obtained demonstrated the aggregated structure of egg densities at the edges of the crops. Further, *T. absoluta* was found to accomplish egg dispersal along the rows more frequently than it does between rows.

CONCLUSION: Our results indicate that the greatest egg densities of *T. absoluta* occur at the edges of tomato crops. These results are discussed in relation to the behavior of *T. absoluta* distribution within fields and in terms of their implications for improved sampling guidelines and precision targeting control methods that are essential for effective pest monitoring and management.

Supporting information may be found in the online version of this article.

Keywords: spatial distribution; tomato leaf miner; tomato crops; geostatistics; integrated pest management

1 INTRODUCTION

The tomato leaf miner *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) is one of the main pests of tomato crops worldwide.[1–3] *Tuta absoluta* has been reported in various European countries, the Middle East, and northern, sub-Saharan, and West Africa.[1,2,4–7] Recently, the tomato leaf miner has also been reported in East Africa and South Africa. It is now found in Algeria, Canary Island, Eritrea, Ethiopia, Egypt, Libya, Morocco, Niger, Senegal, Sudan and in South Sudan, Kenya, Tanzania and Uganda.[7–9] *Tuta absoluta* has caused notable yield losses in tomato cultivation in various European countries since its introduction, for example, into Spain in 2006.[1,2] With the exception of the roots, the larvae of this tomato leaf miner attack all other parts of tomato plants, including the leaves, flowers, stems and fruits, and may result in 100% losses in tomato crops.[10–13] Therefore, several studies have been published to estimate the climate sustainability and risk assessment for the worldwide invasion and potential spread of *T. absoluta* on a global scale.[1,14] Other research has focused on spatial distribution within the plant canopy[15–17] and between-plant distribution under greenhouse conditions.[18] However, there is a lack of research on the spatial distribution of *T. absoluta* in open-field tomato cultivation.

The spatial distribution of crop pests can provide important information to help determine the locations of their most frequent attacks on crops, their dispersion, and design-monitoring schemes; this information can optimize management programs

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Table 1. The characteristics of open-field tomato cultivation and the mean number of eggs (egg numbers / two tomato leaves) of *Tuta absoluta*

Phenological stage	Crop farm	Area (ha)	Altitude (m)	Geographic coordinates S	Geographic coordinates W	No. of cultivated plants	Age of the sampled plants (days)	Egg density[a] (means ± SE)
Vegetative growth	1	0.42	735	20°50′246″	42°50′18″	8461	30	4.90 ± 0.30
	2	1.42	771	20°50′246″	42°50′18″	28514	25	0.41 ± 0.04
	3	0.24	758	20°50′26″	42°50′32″	4674	30	0.79 ± 0.07
	4	0.36	745	20°51′25″	42°50′24″	7241	30	4.66 ± 0.23
	5	0.19	771	20°51′30″	42°51′80″	3758	31	8.15 ± 0.66
	6	1.12	771	20°51′99″	42°50′20″	22445	31	0.96 ± 0.11
	7	0.37	723	20°51′90″	42°50′20″	7369	29	0.45 ± 0.04
Initial reproduction	1	0.39	735	20°50′24″	42°50′18″	7652	38	2.45 ± 0.17
	2	0.81	738	20°51′99″	42°50′20″	16232	55	0.48 ± 0.04
	3	0.39	728	20°51′68″	42°43′38″	7866	55	0.89 ± 0.07
	4	1.07	734	20°51′99″	42°50′20″	21508	55	1.70 ± 0.13
	5	0.46	708	20°51′60″	42°51′60″	9120	53	10.13 ± 0.70
	6	0.24	725	20°51′61″	42°51′32″	4730	52	5.26 ± 0.33
Final reproduction	1	0.35	718	20°50′97″	42°50′79″	6945	75	4.48 ± 0.45
	2	0.28	771	20°50′20″	42°51′70″	5559	94	1.99 ± 0.16
	3	0.23	748	20°51′30″	42°51′80″	4652	97	0.65 ± 0.07
	4	0.49	714	20°50′16″	42°43′75″	9885	60	6.68 ± 0.47
	5	0.14	735	20°49′92″	42°48′00″	2859	70	2.16 ± 0.16
	6	0.25	745	20°51′30″	42°51′80″	5051	100	8.15 ± 0.59
	7	0.40	760	20°50′24″	42°50′18″	8046	70	2.22 ± 0.16
	8	0.39	735	20°49′38″	42°50′82″	7720	93	0.14 ± 0.02
	9	0.32	735	20°49′92″	42°48′00″	6460	96	0.16 ± 0.03

[a] Mean number of eggs per 450 plants.

and reduce insecticide applications.[19–22] Geostatistical analysis may be applied to investigate the spatial distribution of a crop pest and predict its spread during cultivation. This analysis is a technique for understanding the spatial dynamics of insects and is considered reliable because it incorporates the geographic location of the samples.[23,24]

Geostatistics enables the degree of dependence among samples in space to be measured using semivariance and permits inferences about the spatial distribution patterns of insect pests.[25,26] Thus, sampling and control efforts can be focused according to the degree of dependence.[27,28]

Spatial distribution patterns enable more efficient sample planning and pest control by directing these activities to the places where the pest is most likely to be found.[29,30] Spatial information might be an important driver for insect studies within and between crops, such as in sampling and control.[30,31] The relationship between pest density and loss of production in a crop is influenced by the degree of spatial heterogeneity in pest distribution.[31] Thus, knowledge of the spatial distribution patterns of a pest can be useful for predicting pest damage.

Knowledge about the dynamics of *T. absoluta* is fundamental for the developing management programs to control this insect pest. This provides important information to illustrate how *T. absoluta* is introduced and spreads in open-field tomato cultivation, and for avoiding economic losses by planning timely control measures. Thus, our aim in this study was to determine the distribution of *T. absoluta* in open-field tomato cultivation through geostatistical analysis.

2 MATERIALS AND METHODS

2.1 Field monitoring

The study was conducted on 22 commercial open-field tomato crops (*Solanum lycopersicum* L., hybrid Débora Plus), in Coimbra, Minas Gerais State, Brazil, in 2011. The characteristics of these open-field tomato crops are shown in Table 1. The studied cultivation areas ranged from 0.14 to 1.42 ha. Seven tomato cultivations were in the vegetative growth stage (up to 31 days after transplanting), six were in the initial reproductive stage (i.e., plant at flowering and with up to two tomato trusses; between 38 and 58 days after transplanting) and nine were in the final reproductive stage (i.e., plants had more than two tomato trusses and were between 60 and 100 days after transplanting). The plants were cultivated with a spacing of 1.0 to 0.5 m using local procedures based on standard agronomic practices, such as fertilization and the use of pesticides.[32,33] The applied fertilizers were 400 kg ha^{-1} N, 1000 kg ha^{-1} P_2O_5 and 800 kg ha^{-1} K_2O scheduled as five applications (on transplanting of the seedlings, and at 20, 45, 70 and 85 days after transplanting). Pesticides were applied using a compressed air sprayer at the recommended label rates and a pesticide rotation strategy was applied on the whole area. Insecticides were used as one to three applications per week of abamectin, acephate, alpha-cypermethrin, buprofezin, cypermethrin, chlorfenapyr, chlorpyrifos, deltamethrin, imidacloprid, indoxacarb, lambda-cyhalothrin, methamidophos, permethrin, pyriproxyfem, and thiamethoxam; and the fungicides used were: azoxystrobin, benomyl, cymoxanil + maneb, chlorothalonil, mancozeb, metalaxyl + mancozeb, dimethomorph, metconazole,

Table 2. The characteristics of the selected models for the spatial distribution of eggs of *Tuta absoluta* in tomato crops at different phenological stages

Phenological stage	Crop farm	Model	Structure	A_0 (m) 0°	A_0 (m) 90°	C_0	$C_0 + C$	β_1	β_0	RMSE	ME	R^2
Vegetative growth	1	Exponential	Anisotropic	71.12	53.15	9.1×10^{-2}	1.6×10^{-1}	0.41***	0.31	0.9747	0.0014	0.20
	2	Gaussian	Anisotropic	122.05	60.35	2.0×10^{-2}	3.1×10^{-2}	0.07***	0.02	1.0110	0.0007	0.30
	3	Exponential	Anisotropic	53.40	29.64	3.1×10^{-2}	4.8×10^{-2}	0.11***	0.12	1.0530	0.0012	0.12
	4	Exponential	Anisotropic	71.12	46.10	1.5×10^{-1}	2.4×10^{-1}	0.51***	0.26	1.0270	0.0107	0.20
	5	Gaussian	Anisotropic	64.20	43.01	8.3×10^{-2}	3.8×10^{-1}	0.71***	0.18	1.0240	0.0252	0.46
	6	Gaussian	Anisotropic	158.04	93.27	6.4×10^{-2}	1.2×10^{-1}	0.50***	0.06	0.9912	0.0036	0.29
	7	Nugget effect	–	0.00	0.00	1.2×10^{-2}	1.2×10^{-2}	0.01	0.01	1.0740	0.0023	< 0.01
Reproductive initial	1	Exponential	Anisotropic	94.83	33.30	1.0×10^{-1}	2.1×10^{-1}	0.41***	0.17	1.0470	0.0003	0.20
	2	Exponential	Anisotropic	105.70	67.27	3.0×10^{-2}	3.9×10^{-2}	0.08***	0.09	1.0310	0.0015	0.12
	3	Exponential	Anisotropic	66.18	45.82	3.8×10^{-2}	5.6×10^{-2}	0.29***	0.10	1.0050	0.0007	0.13
	4	Exponential	Anisotropic	159.04	56.48	1.0×10^{-1}	1.6×10^{-1}	0.30***	0.12	0.9979	0.0055	0.13
	5	Exponential	Isotropic	51.06	51.06	6.8×10^{-2}	2.3×10^{-1}	0.51***	0.40	1.0260	0.0082	0.36
	6	Spherical	Anisotropic	47.80	21.00	1.9×10^{-1}	2.7×10^{-1}	0.42***	0.29	0.9393	0.0060	0.22
Final reproductive	1	Exponential	Anisotropic	66.18	33.65	1.6×10^{-1}	2.4×10^{-1}	0.26***	0.31	1.0090	0.0107	0.10
	2	Gaussian	Anisotropic	59.26	44.40	1.4×10^{-1}	1.8×10^{-1}	0.08***	0.18	1.0010	0.0068	0.08
	3	Spherical	Anisotropic	69.06	56.48	2.8×10^{-2}	4.6×10^{-2}	0.27***	0.02	1.0290	0.0026	0.11
	4	Exponential	Anisotropic	52.33	42.72	1.3×10^{-1}	3.1×10^{-1}	0.50***	0.29	1.0270	0.0160	0.30
	5	Exponential	Anisotropic	59.27	34.22	1.0×10^{-1}	1.9×10^{-1}	0.27***	0.17	1.0100	0.0042	0.19
	6	Exponential	Anisotropic	52.35	21.26	0.0	3.8×10^{-1}	0.73***	0.15	1.1330	0.0079	0.61
	7	Spherical	Anisotropic	71.12	41.70	1.2×10^{-1}	1.9×10^{-1}	0.35***	0.15	1.0040	0.0094	0.18
	8	Nugget effect	–	0.00	0.00	4.2×10^{-3}	4.2×10^{-3}	−0.007	0.01	0.9888	0.001	< 0.01
	9	Nugget effect	–	0.00	0.00	9.4×10^{-3}	9.4×10^{-3}	0.01	0.01	1.1230	0.0001	< 0.01

Characteristics of the selected model: Model through R^2.

A_0 is the range at a 0° and 90° directions of the planting rows and between planting rows of tomato in the anisotropic variogram models. C_0 = nugget effect, $C_0 + C$ = sill. β_0 and β_1 are the intercept and slope of the kriging cross-validation curve, respectively. RMSE, root mean square error; ME, mean error; R^2, coefficient of determination from the cross-validation curve.
***Significant at $P < 0.001$. The models were selected based on cross-validation parameters ($< \beta_0$; $> \beta_1$ and R^2; RMSE close to 1 and ME near zero.

copper oxychloride, cuprous oxide, procymidone, propamocarb, tebuconazole and tetraconazole.

2.2 Tuta absoluta monitoring

Tuta absoluta monitoring was performed from July to December 2011. One commercial open-field tomato crop was evaluated per week. The *T. absoluta* population density was monitored by counting the number of eggs on the leaves where the largest number of eggs of *T. absoluta* might be found.[34,35] Thus, the first two leaves of the middle canopy of the plant during the vegetative growth stage and the last two leaves of the apical stratum in tomato plants at the initial and final reproductive stages were evaluated. In each crop, 450 tomato plants equidistant from each other were sampled, obtaining a regular grid of samples distributed throughout the area and eliminating directional trends.[36] Each sample point was georeferenced using a global positioning system (GPS 12XL, Garmin, Othale, KS, USA).

2.3 Geostatistical analysis

The data were first transformed adequately to approximate a normal distribution before spatial analysis. The egg counts were transformed using a logarithmic function $\log(x + 1)$, where x is the number of eggs per sample unit. A transformation was necessary to make the distribution more symmetrical and to remove the trend in variance.[37] The transformed data were subjected to an evaluation of the spatial dependence between the sampling of eggs of *T. absoluta* through a semivariogram. The semivariogram is a useful and reliable tool for evaluating the spatial dependence between sampling points.[38] The semivariogram was determined from the log-transformed sample data to obtain an empirical semivariogram.[39] The empirical semivariogram was used to adjust the best model to fit the theoretical semivariogram.[22] Anisotropic semivariograms were calculated for all datasets in two directions: along (0°) and across (90°) rows. The adjusted models can be spherical, exponential or Gaussian.[40] The models with the best fit were chosen using cross-validation. These models were those with intercepts (β_0) close to zero, slopes (β_1) close to one, larger regression coefficients and the lowest residual sum of squares. The nugget effect, range, sill and coefficient of determination were calculated for each model.[40]

The spatial dependence of a sample can be observed when the semivariance in the semivariogram increases with increasing distance. At a certain distance, the semivariance becomes constant. This constant semivariance is the sill ($C_0 + C$). The distance at which the sill is reached is the range (A_0), and the semivariance value when the distance is equal to zero is called the nugget effect (C_0).[19] The nugget effect, range and sill were calculated for each model.[38,40] These parameters were then used to verify whether the spatial dependence was the same in all directions.

The level of spatial dependence (LSD) was determined using the following formula: $LSD = C_0/(C_0 + C)$, where C_0 is the nugget

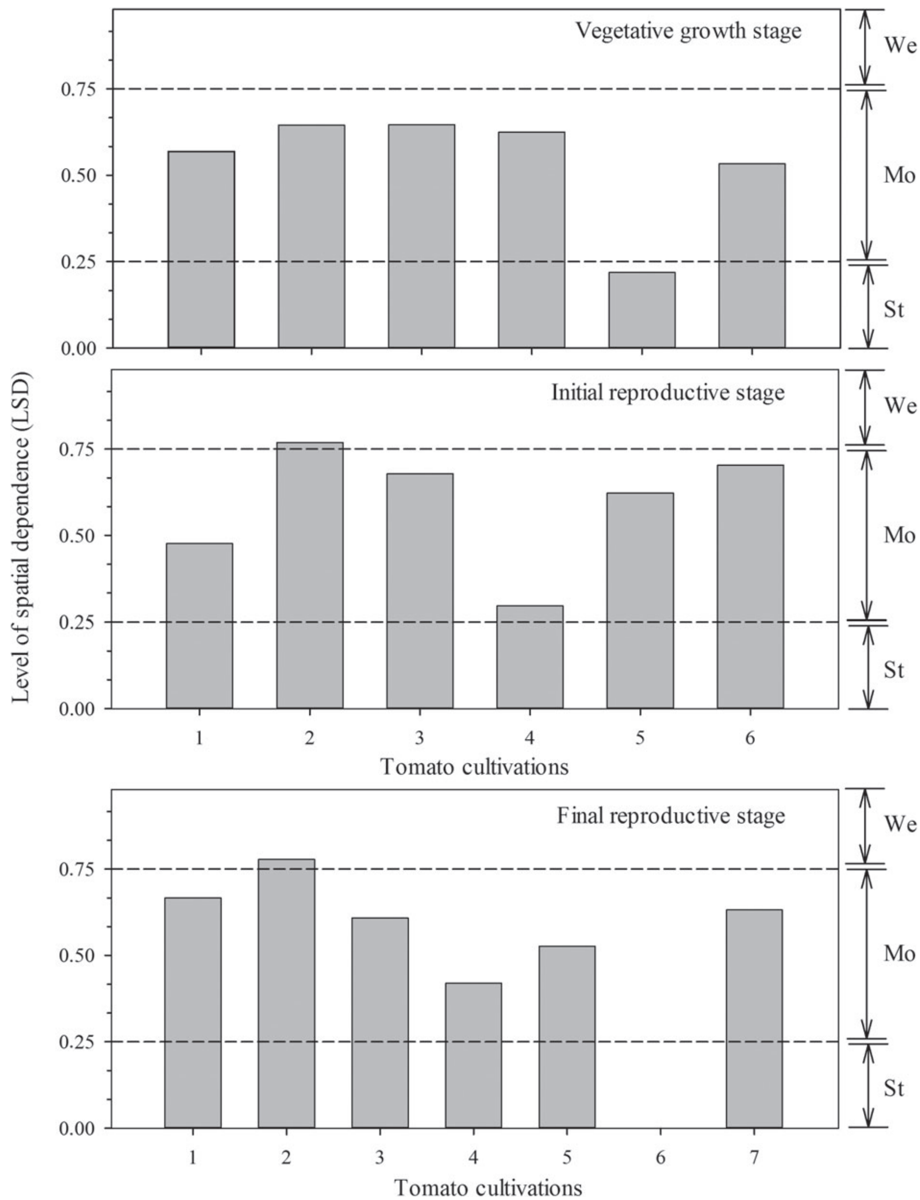

Figure 1. Level of spatial dependence of semivariogram models for egg densities of *Tuta absoluta* in 19 open-field tomato cultivations during vegetative growth, initial reproductive and final reproductive stages. (We, Mo, and St represent weak, moderate, and strong spatial dependence, respectively.)

effect and $C + C_0$ is the sill.[41] The spatial dependence of the semivariogram is considered strong when LSD ≤ 0.25, moderate when 0.25 < LSD < 0.75 and weak when LSD > 0.75.[41]

After identification of the spatial dependence, the interpolation method of ordinary kriging was used to estimate the values at unmeasured locations and create maps of the prediction surface to illustrate the spatial distribution of *T. absoluta* eggs. Kriging was applied to all tomato crops that were identified spatial dependence of the number of eggs. In total, 19 open-field tomato crops were running the kriging method of the 22 commercial open-field tomato crops evaluated. Kriging is a linear unbiased interpolation method and is considered quite appropriate for estimating the prediction of sample distribution, such as the eggs of *T. absoluta*.[42,43] All spatial analyses were performed using the ArcGiS 9.3 Software, Proc Arcmap Geostatistical Analyst (Environmental Systems Research Institute, ESRI 2008).[44]

3 RESULTS

A total of 19 semivariogram models (i.e., one for each cultivation) were selected according to the following criteria: β_0 value closer to zero, β_1 value closer to one, smaller residual sums of squares, and larger regression coefficients (Table 2). These models were selected from the 66 semivariogram models adjusted for the spatial distribution of the eggs of *T. absoluta* (Tables S1–3). All the models selected and summarized in Table 2 were used to describe the spatial dependence and run the kriging method.

Anisotropy were observed in 18 selected models, which can be noted by the inequality of the range values found for the two axis of anisotropy (0° and 90° direction of the rows of tomato, respectively) (Table 2). The anisotropic semivariogram models varied over a range between 21 (90° direction of the rows) and 159 m in the direction of the planting rows (cultivation 6 and 4 at the initial reproductive stage). The lowest ranges of distance values occurred in tomato crops at the reproductive stage (Table 2).

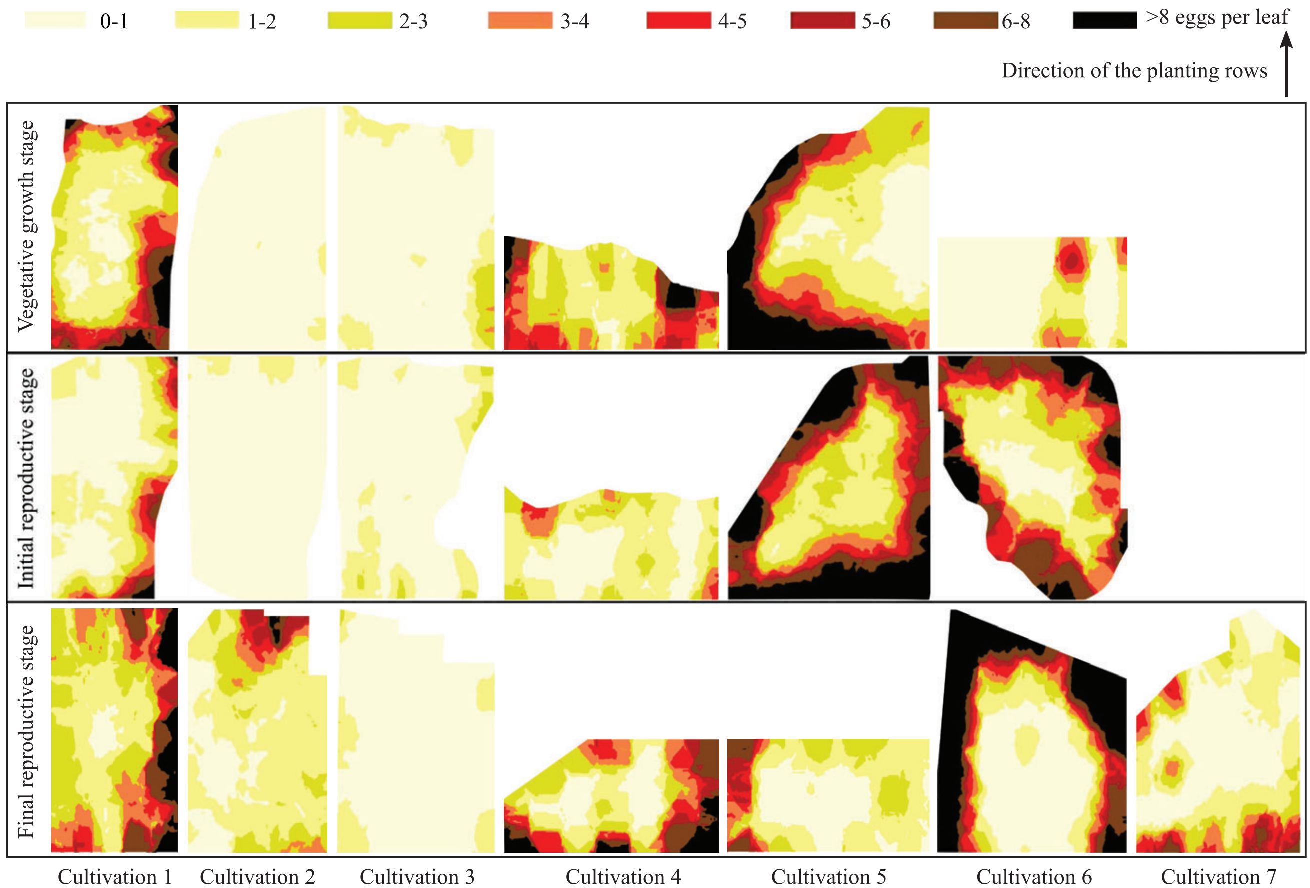

Figure 2. Maps of spatial distribution of the *Tuta absoluta* eggs in 19 open-field tomato crops at the vegetative growth, initial reproductive and final reproductive stages. The number of egg density classes was based on the economic damage level (EDL) based on *T. absoluta* egg-laying on tomato plants (EDL = three eggs per sampling unit, unpublished data).

The LSD values are shown in Fig. 1. The selected semi-variogram models exhibited moderate spatial dependence (0.25 < LSD < 0.75) to strong spatial dependence (LSD < 0.25) (Fig. 1).

The contour maps created by the kriging interpolation method and supported by cross-validation analysis exhibited an aggregated pattern in the number of *T. absoluta* eggs in tomato cultivation (Fig. 2). Although the total number of eggs varied among crops, the maps indicated that highest egg densities were located in the edge areas of tomato cultivations. The maps also indicate there is a greater dispersion of eggs along the rows than between the rows of tomato plants (Fig. 2).

4 DISCUSSION

This study provides the first evidence for characterizing and developing spatial distribution maps of *T. absoluta* in open-field tomato crops. *Tuta absoluta* may achieve 17 generations every year and fecundity of 260 eggs per female according with on environmental conditions.[45] Chemical control is the primary management tactic on commercial open-field tomato crops to control *T. absoluta*[3,46] .The characterization of the spatial distribution of *T. absoluta* on tomato crops provides crucial information for the development of an effective sampling plan, which will ultimately improve monitoring of this pest and assist in effective pest management strategies targeting this economically important pest.

Geostatistical analysis and semivariogram models exhibited spatial dependence in 19 of 22 tomato crops with *T. absoluta* egg infestations (i.e., spatial aggregation), regardless of the sampling phenological stage of the plants. Infestation density maps indicated an aggregation of *T. absoluta* eggs in the field, mainly in the edges of the tomato crop area. The occurrence of egg aggregation in open-field tomato crops can be verified by the high values of the sill ($C + C_0$), the low values of the nugget effect (C_0), the adjustment of the data to semivariogram models and a moderate and strong spatial dependence (LSD < 0.75).

The observed pattern of *T. absoluta* egg distribution decreases towards the center of tomato cultivations with both high and low infestation levels, which reflect the low flight efficiency of females among plants within the tomato crops. Market tomato crops are trained vertically to a height of 1.5–2.0 m, where the structure and plants would act as a physical barrier.[46] This makes the dispersal of *T. absoluta* within the tomato crop difficult.

The infestation of *T. absoluta* eggs presents an irregular distribution within the tomato crop. The evidence for this is the different range values for the two axes of anisotropy in 94% of the adjusted semivariograms models. The main axis of anisotropy occurred in the direction of the tomato crop rows, whereas the secondary axis occurred across the tomato crop rows. This difference in range of the egg infestation may explained by the structural orientations of tomatoes, which serve as an obstacle to the dispersal of adult *T. absoluta* between rows.[47,48] Furthermore, the wind speeds may be higher in the direction of the rows than between the rows, and may thus contribute to greater dispersion of the adults and, consequently, greater dispersion of eggs in the direction of the rows. Wind has been considered a main factor contributing to *Choristoneura fumiferana* (Lepidoptera: Tortricidae) dispersion with its host plants in the landscape.[49] Thus, we highlight that further research is needed to obtain a greater understanding of the role that wind plays in the dispersion of *T. absoluta* in open-field tomato crops. Our findings may be a starting point for future studies.

From our results, it is clear that the dispersion of *T. absoluta* within tomato cultivation starts mainly at the edges of tomato crops. *Tuta absoluta* adults should be able to migrate between tomato farms; thus, they tend to infect the tomato plants that are encountered first when they move onto a tomato farm and generate egg aggregation at the crop edges. The movement of pest insects among seasonal crop resources is often non-random and directional, and occurs as pest species disperse and colonize crops.[50,51] This movement may often result in a lack of uniformity in the infestation, with the edges of cultivation more heavily infested than the interior.[52] Knowledge about insect pest movement within crop farms may inform about the infestation risk by an insect pest prior to their subsequent population increase and may provide opportunities for pest management.[53]

The range of values tends to decrease with as the age of the tomato plant increases; plants at the end of the reproduction phase had the lowest range. One of reason could be because older plants are larger and therefore create more of an obstacle to adult dispersal.[54] The range value obtained between samples in the spatial distribution analysis of an insect is the dividing line for the application of either geostatistics or classical statistics in pest management.[37,54] Therefore, the range should be the minimum distance between the samples, which should be respected at the time of sampling. Thus, sampling should be performed at the crop edges while respecting the average distance of spatial independence. The estimated range of spatial dependence varied from 21 to 159 m, with a mean of 62 m. These values were obtained of the range at a 0° and 90° directions of the planting rows and between planting rows of tomato in the anisotropic variogram models.

Studies of spatial variation patterns and the results of the geostatistical analysis are crucial for insect pest management programs of *T. absoluta*. One of the practical implications of this study for the management of *T. absoluta* in tomato crops is to provide important information to develop an accurate sampling plan and select suitable experimental designs.[30] Furthermore, these results provide support for the planning and application of targeted control measures.[55] For example, these results provide a direction for control measures in areas of greatest risk for *T. absoluta*, in open-field tomato cultivation.

In any pest management plan, the likelihood of success will be greatest if interventions are directed when and where the probability of encountering the pest is highest. It is as important to know where a pest is located as it is to know where it is not located.[30] In this way, pesticide applications could be reduced; consequently, the optimization of pesticide use, reduced cost and minimization of collateral effects (e.g., environmental and human contamination) can be achieved by applying pesticides where the likelihood of encountering the pest is high.

5 CONCLUSION

In summary, the results of the geostatistical analysis provide important information that may be useful as a tool for tomato growers, in terms of the management of *T. absoluta*, by managing specific places where *T. absoluta* dispersion is highest. This result indicates that the greatest egg densities of *T. absoluta* occur at the edges of tomato crops, which may be a starting point for initiating timely management methods, such as sampling strategies and control with specific applications at the edges of tomato cultivation, thus reducing the use of pesticides to control *T. absoluta*.

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SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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