Revista Ciência Agronômica, v. 54, e20228420, 2023
Centro de Ciências Agrárias - Universidade Federal do Ceará, Fortaleza, CE
www.ccarevista.ufc.br

Scientific Article
ISSN 1806-6690

An analysis of spatial dispersal in *Ceratitis capitata* in an orchard of the 'Palmer' mango using McPhail traps[1]

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ABSTRACT - The aim of this study was to analyse patterns of spatial dispersal in *Ceratitis capitata* using two types of attractive traps and propose a predictive model of pest dispersal with the aim of determining management zones for decision-making. The experiment was conducted in an orchard of the 'Palmer' mango in the district of Belo Campo, Bahia. Sampling was carried out using McPhail and Jackson traps. The pattern of spatial dispersal in *C. capitata* was determined using the Perry and Mead Index of Dispersion, the Morisita Index, and the Local Moran index (LISA). The spatial variability of the abundance of *C. capitata* was obtained by geostatistical analysis, with the indicator kriging method used to prepare the location and spatial distribution maps. The Perry and Mead Index of Dispersion and the Morisita Index showed an aggregated pattern of spatial dispersal, whereas the Moran Local index showed a random pattern from 7 DFSH (days from the start of the harvest) to 35 DFSH, and an aggregated pattern at 42 DFSH. The SDI was strong at 7 and 35 DFSH and moderate at 14, 28 and 42 DFSH. The dispersal patterns of *C. capitata* allow an exponential predictive model to be produced, outlining strategies for exponential management zones of *C. capitata*, and detecting which places have the highest risk of the pest occurring.

Key words: *Mangifera indica* L. Geotechnology, Monitoring, Moscamed.

DOI: 10.5935/1806-6690.20230056
Editor-in-Chief: Prof. Alek Sandro Dutra - alekdutra@ufc.br
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Received for publication 28/03/2022; approved on 21/03/2023

[1]Parte da Dissertação de Mestrado do primeiro autor, apresentada ao Programa de Pós-Graduação em Agronomia, Universidade Estadual do Sudoeste da Bahia (UESB)

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INTRODUCTION

The mango (*Mangifera indica* L.), originally from Asia, is a typical tropical plant belonging to family Anacardiacea. In September 2021, Brazil broke the record in mango exports, with a volume of 42.1 thousand tons: an increase of 95.8% compared to August and of 19% compared to September 2020 (GERALDINI; KUBO, 2021). That year, the mango was the most-exported fruit in Brazil, the country shipping around 272.5 thousand tons, an increase of 12% compared to 2020 (MANGA, 2022). In 2021, the district of Livramento de Nossa Senhora in the state of Bahia saw an increase in production area (12,750 ha) compared to the previous year (12,122 ha) due to the better water conditions (GERALDINI; KUBO, 2021).

Brazil is considered one of the largest producers in the world with regard to fruit production and cultivated area. Due to its tropical climate, the country has an immense variety of fruits, and, according to FAO data (2021), occupies third place among the largest global producers, behind China and India.

The fruit fly (Diptera: Tephritidae) stands out among the principal pests that attack fruit trees, especially the species *Ceratitis capitata* (Wiedmann, 1824), *Anastrepha obliqua* (Macquart 1835) and *Anastrepha fraterculus* (Wiedmann, 1830), which are considered a barrier to exports.

Studying the spatial distribution of these insects affords information on the real biotic potential of pest species, which can then be used together with Integrated Pest Management (IPM) in fruit farming in Brazil. Through the use of dispersion indices it is possible to determine spatial distribution patterns. These patterns are divided into random, scattered or aggregated.

The Perry and Mead Index of Dispersion provides information on the spatial distribution of the population under study that is very close to reality. This refers to the relationship between the variance and the mean, in which the deviation from randomness can be evaluated using the chi-square test with N-1 degrees of freedom.

The Morisita Index, on the other hand, was proposed by Morisita (1959) with the aim of presenting an index that was independent of the sample mean and the total number of individuals. Values approaching one indicate a random pattern, values greater than one indicate an aggregated pattern, and values of less than one show a regular or uniform pattern.

The Local Moran index, proposed by Luc Anselin, is a statistical method that investigates local autocorrelation in order to discover spatial objects that influence the Global Moran indicator. Spatial variability is caused by the interaction between population dynamics and biotic or abiotic factors. (FLORES *et al*., 2016; SANTOS; SILVA; MIRANDA, 2020b). Kriging is a process for estimating the values of variables which are distributed in space, using other values, while indicator kriging uses the position and values of the data to produce a local instead of a global distribution (MOTOMIYA; CORÁ; PEREIRA, 2006).

Understanding how to combine existing control methods with appropriate sampling models is important, as this affords a more-effective process (PAZINI; BOTTA; SILVA, 2012). Given the above, the aim of this study was to analyse patterns of spatial dispersal in *C. capitata* using two types of attractive traps, and propose a predictive model of pest dispersal with the aim of determining management zones for decision-making.

MATERIAL AND METHODS

The study was carried out during the first year of harvest in a 12-hectare commercial orchard of the ‘Palmer’ mango (*Mangifera indica* L.), located in the district of Belo Campo, Bahia, at 15º02’15” W and 41º07’16” S, at an average altitude of 820 metres. The climate is tropical with one dry season (Koppen-Geiger climate classification: Aw), with a mean annual temperature of 20.2 °C and mean rainfall of 600 to 800 mm. The area around the orchard consisted of forest with Caatinga vegetation to the south and east, lemons grown to the north, and the ‘Tommy’ mango grown nearby. To the west is the road leading to the farm.

The experimental site was georeferenced. Following the survey, the data were processed in the QGIS 3.12.0 GIS software to generate sample meshes and subsequently determine the points. To determine spatial dependence, the sampled points were georeferenced using a geodetic GPS and then evaluated.

McPhail traps were used, which were installed around 1.5 m above ground level on the branches of the plants (Figure 2A and B), and contained 250 mL of feed attractant based on 5% hydrolysed corn protein from Biofruit®; the traps were inspected at weekly intervals. Due to evaporation of the attractant, the content was added to a collector for the captured insects to later be counted; the attractant was replaced weekly. The captured flies were placed in glass bottles containing a 70% alcohol solution.

The other type of trap used was the Jackson trap, with the parapheromone Bio Trimedilure (Trimedilure 558.8 g kg^{-1}, Bio Controle, Indaiatuba, SP) as attractant. The traps were placed in areas protected from the wind at a height of 1.5 to 2 metres, and evaluated weekly, quantifying the number of captured males and females of *C. capitata*. The traps were placed at a density of 3.08 traps/hectare, using 37 traps of each type.

The FTD index for *C. capitata* in the sampled area was calculated using the formula:

$$FTD = \frac{N}{A \times D} \quad (1)$$

where,

FTD = fly/trap/day;

N = total number of captured flies;

A = number of traps evaluated;

D = interval in days between collections.

Using the XLSTAT software, the data were correlated with temperature data for the collection period, obtained from INMET.

The spatial pattern of each species was determined using three different methods: the Dispersion Index (DI) (PERRY; MEAD, 1979), the Morisita Index, developed by Morisita (1959), and the Local Moran index (LISA), elaborated by Luc Anselin (1995).

The dispersion index for each species is calculated using the equation:

$$DI = \frac{S^2}{\overline{X}} \quad (2)$$

where,

s^2 - is the variance obtained for the data population, and

$\overline{X}$ - is the mean of this population.

The dispersion index (χ^2) was classified using the chi-square distribution with *N-1* degrees of freedom as reference. Thus, when $\chi^2(1\text{-}\alpha/2; N\text{-}1) < \chi^2 < \chi^2(\alpha/2; N\text{-}1)$, the distribution is classified as random; when $\chi^2 < \chi^2(1\text{-}\alpha/2; N\text{-}1)$, the distribution is uniform; and when $\chi^2 > \chi^2(\alpha/2; N\text{-}1)$ the distribution is aggregated; where $\chi^2(1\text{-}\alpha/2; \text{N-1})$ and $\chi^2(\alpha/2; \text{N-1})$ are the critical values for chi-square with *N-1* degrees of freedom and a significance of α.

The Morisita Index was determined using the equation:

$$MI = q\frac{\sum_{i=1}^{q} X_i(X_i - 1)}{T(T-1)} \quad (3)$$

where,

q - number of plots;

x - number of individuals in the i-th plot;

x - number of individuals in the i-th plot;

The Local Moran index (LISA) was determined from the equation:

$$I_i(d) = \frac{(X_i - \overline{X})}{S^2}\sum_j w_{ij}(d)(X_j - \overline{X}) \cdots for \cdots j \neq i \quad (4)$$

where,

wij - value in the neighbourhood matrix for region i with region j as a function of distance d, and where zi and zj are the deviations from the mean.

If the value found is greater than 1, the species has an aggregated pattern, if the value is equal to 1, the variance is equal to the mean and the pattern is random (by chance), and if the value is less than 1, the variance is greater than the mean and the pattern is regular (homogeneous). The Moran index is generally submitted to a test, where the null hypothesis is for spatial independence, its value being zero. Positive values between 0 and +1 indicate a direct correlation, while negative values between 0 and -1 indicate an inverse correlation.

The resulting data were submitted to the Kolmogorov-Smirnov test at 5% to verify normality using the SPSS Statistical software. They were then analysed using the ArcGIS 10.6 software, and submitted to descriptive statistical analysis to characterise the overall behaviour of the data, calculating the arithmetic mean, coefficient of skewness, coefficient of kurtosis and maximum and minimum values.

Spatial distribution was obtained by geostatistical analysis, where the coefficients of the theoretical model, called the nugget effect (C_0), sill ($C_0 + C_1$), and range (A) were estimated. Based on a study of the semivariogram adjusted to the best theoretical model, the spatial dependence index (SDI) was calculated: C/(C0 + C) x 100, where an index lower than 25% is considered weak spatial dependence, from 25% to 75% is considered moderate, and an index greater than 75% is considered strong.

After adjusting the semivariograms, indicator kriging was carried out using the categorised data, with the aim of defining areas on maps with a greater or lesser probability of *C. capitata* occurring. Indicator kriging transformed the original data into indicators, i.e. it changes values that are above a certain cut-off level to 1 and those that are below this level to 0. This binary transformation shows where the estimated values are higher (1), and indicates a higher probability of infestation occurring, while in places that have values below the cut-off level (0) there is less chance of pest infestation. The probability of an occurrence was graded from <0.25 (low), 0.26-0.5 (moderate to low), 0.51-0.75 (moderate to high), and >0.76 (high). Areas that are coloured red have a chance of having a higher incidence of fruit flies, and consequently of greater damage to the crop, possibly reducing its productivity. The ArcGis 10.6 computer system was used for the geostatistical analysis and to prepare the maps.

RESULTS AND DISCUSSION

According to the data obtained from capturing fruit flies using different types of traps in the Palmer cultivar of the mango, of the 37 traps distributed in the experimental area, fruit flies were only found in the McPhail traps and did not occur in the Jackson traps. During the evaluation period of the experiment, comprising May to August of 2021, giving a total of 15 evaluations, the presence of *C. capitata* was verified in the last six evaluations only. One of the factors that may have influenced the absence of the species during the earlier weeks has to do with the age of the orchard (4 years), the first year of fruit production, and the presence of other host species of *C. capitata* in the vicinity. During the study period, there was no precipitation at the site. During May, June, July and August the maximum temperature was around 32 ºC, 31 ºC, 30 ºC and 30 ºC, respectively, while the minimum temperature was 18 ºC, 18 ºC, 17 ºC and 17 ºC.

The analysis was carried out with the data obtained during the ninth week following installation of the traps in the field, i.e. starting seven days from the start of the harvest (DFSH) until the end of the harvest at 42 DFSH, during which period *C. capitata* was also found in the McPhail traps. These results were correlated with climate data on rainfall, humidity and temperature. There were, however, no variations in the rainfall data (the dry period, with no rainfall). The relative humidity varied (17% to 58%), as well as the temperature, which ranged between the minimum (16 °C) and maximum (29 °C).

From the seasonal distribution of *C. capitata* in the crop, the population fluctuation was found to be low at the time of the initial harvest, when the fruit was in the initial stage of maturation and had a dark to light green colouration (Figure 1). There is an increase of 254.94% in *C. capitata* at 14 DFSH compared to 7 DFSH. At 21 DFSH, the number of *C. capitata* increased by 125% compared to 14 DFSH.

The population peak in *C. capitata* occurred at 21, 28 and 42 DFSH. The increase in the number of *C. capitata* in the area may be related to the greater number of mangoes at a more-advanced stage of maturation, as well as to the increase in temperature. The results corroborate those of Thomas (2003), that the higher incidence of fruit flies can be related to three factors: the greater amount of fruit in the orchard, the mean humidity, and the increase in temperature.

At 28 DFSH, *C. capitata* stabilised, with an increase of 7.4% compared to 21 DFSH, i.e. the area of cultivation was uniform in terms of fruit maturation, with harvesting in the central part of the orchard, and more fruit at the maturation stage of < 30% yellow, i.e. for *C. capitata*, the colour of the fruit makes it more attractive for the species to oviposition.

At 35 DFSH, there was a reduction of 38.62% in the abundance of *C. capitata*, which can be explained both by the drop in temperature and by the hypothesis that the population dynamics may have been influenced by such management techniques as pruning. On the other hand, at 42 DFSH there was an increase of 89.88% in the abundance of *C. capitata* compared to 35 DFSH. This increase may be due to both the presence of ripe fruit and to the ripe fruit on the ground. According to Aluja (2012), population fluctuation in the fruit fly can vary depending on the availability of the host fruit, in addition to such climate factors as temperature and humidity, which can influence the biology of the insect, especially regarding the duration of each phase of the biological cycle, viability and adult fertility.

There were variations in the FTD (fly/trap/day) index (Figure 1) in the orchard. The index gradually increased during the first weeks after the start of the harvest, but at 35 DFSH, the index fell from 0.56 to 0.31 (Figure 1).

According to Camargos *et al*. (2015), special attention should be given to FTD indices that are equal to or greater than 0.5 fly/trap/day, which is the recommended rate for controlling fruit flies in commercial mango orchards, since it is essential to make a decision before the pest reaches the level of economic injury. In the present study, it was found that the FTD index exceeded the recommended value of 0.5 at 21, 28 and 42 DFSH (Figure 1).

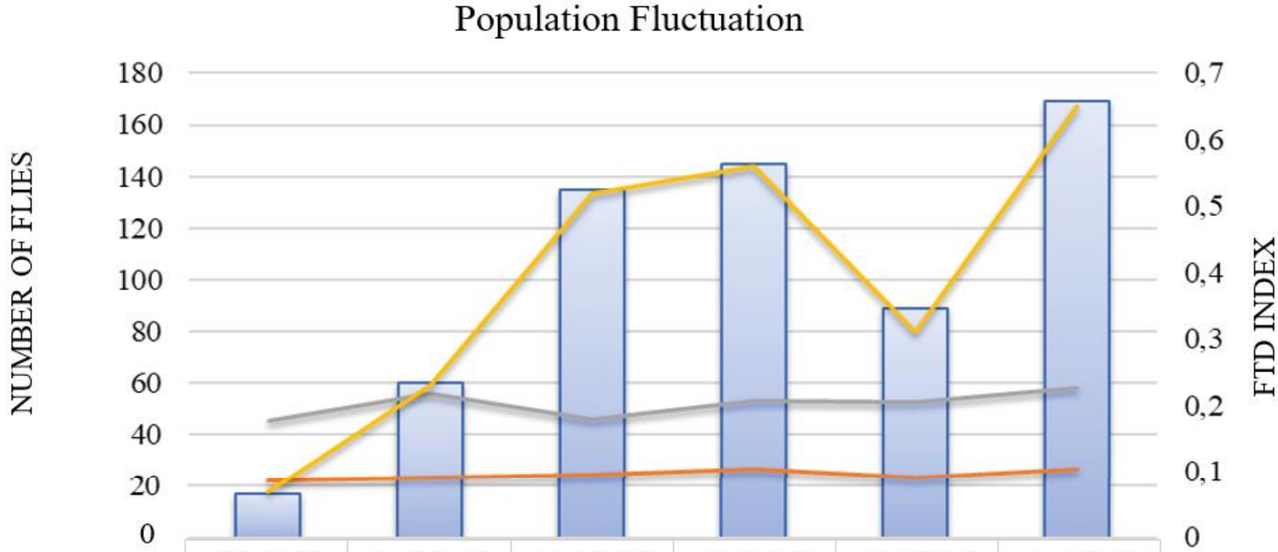
A total of 615 specimens of *C. capitata* were collected, of which 487 were females and 128 males. This species is the principal pest in fruit farming and the most frequent in orchards, causing the most damage to fruit trees in addition to attacking 115 plant species (ZUCCHI; MORAES, 2021).

A Pearson correlation analysis was carried out between the abundance of the fruit fly and the meteorological data. The results indicate a significant correlation between the abundance of the fly and the mean temperature in the region ($r = 0.93$ and $p = 0.008$) (Figure 3), showing that the values for temperature and the abundance of *C. capitata* follow the same behaviour: when the temperature increased, the abundance of the fruit flies increased, where the temperature influences 93% of the behaviour of the data on the fluctuations in abundance.

The coefficient of determination (R^2) is a statistical measure that refers to how close the data are to the fitted regression line: the closer R^2 is to one, the more the model explains all the variability of the data that are around the mean. Canesin and Uchôa-Fernandes (2007), studying the influence of abiotic factors on population fluctuation in the fruit fly using Pearson's correlation analysis, obtained results that showed a significant correlation with temperature (Figure 2).

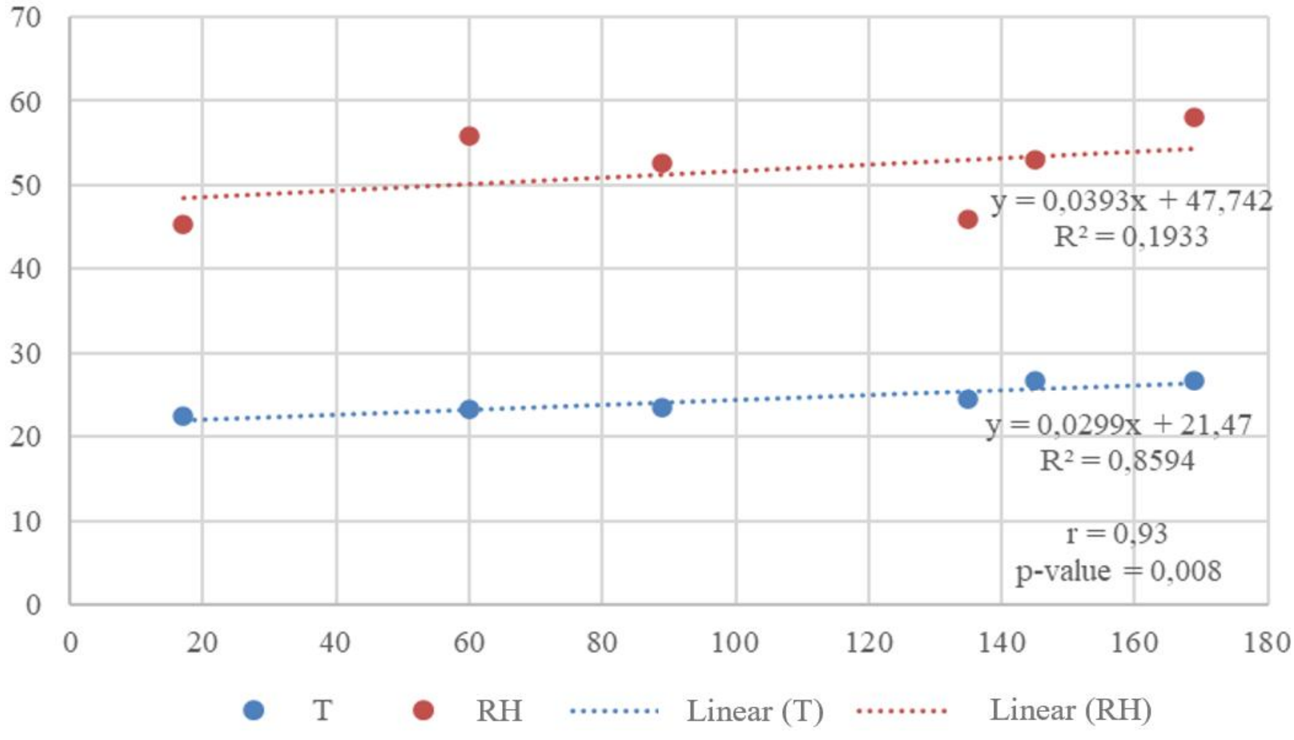
Alternative hosts may favour the continuity of the fruit fly population; as do climate factors, which can have an indirect influence on the population fluctuation of the flies by interfering with the number of fruit, or even reducing soil aeration as a result of high rainfall, causing the death of the pupae and lessening the number of flies (ALUJA *et al*., 2012).

Figure 1 - Population fluctuation in *Ceratitis capitata*, weekly mean values for temperature, humidity and abundance in an orchard of the ‘Palmer’ Mango



	7 DFSH	14 DFSH	21 DFSH	28 DFSH	35 DFSH	42 DFSH
Ab.	17	60	135	145	89	169
TºC	22.4	23.2	24.6	26.8	23.5	26.7
RH	45.3	55.8	46.0	53.0	52.5	58.0
FTD	0.07	0.23	0.52	0.56	0.31	0.65

Figure 2 - Correlation between *Ceratitis capitata* abundance, relative air humidity (%) and mean temperature (ºC) in an orchard of the ‘Palmer’ Mango



When analysing the dispersion index (PERRY; MEAD, 1979) adjusted by the chi-square test, an aggregated pattern was found (Table 1). The calculated values for χ^2 remained above the tabulated values ($\chi^2$0.975=21.33; $\chi^2$0.025=54.43) for a degree of freedom of 36. Using the dispersion index to evaluate the pattern of spatial distribution of fruit flies in guava orchards, Rêgo (2013) found an aggregated pattern on two occasions, where, with a degree of freedom of 26, the calculated values for χ^2 remained above the tabulated values ($\chi^2$0.975=13.84; $\chi^2$0.025=41.92). It was found that *C. capitata* tend to aggregate in specific areas of the orchard, which may be due to the demand for feeding areas or even as a result of mating habits and oviposition.

For the Morisita Index (1959), the pest showed an aggregated distribution, with index values ranging from 2.197 to 5.713 (Table 1). According to Malavasi and Zucchi (2000), the search for food can lead to fruit flies displaying aggregated behaviour, as can their sexual behaviour, since tephritid males have the habit of forming groups in order to attract females, which even after copulation do not disperse to oviposit. Jahnke *et al*. (2014) obtained results of high aggregation in *A. fratelercus* using the Morisita index. In a study carried out by Nicácio *et al.* (2022), the Morisita index did not provide a reliable model for determining the status of *C. capitata* in guava orchards.

The Moran Local index showed a random distribution from 7 DFSH to 35 DFSH, and an aggregated pattern at 42 DFSH. The use of this index is of great importance, as it measures the difference between the values of the attribute associated with location, i.e. it detects the existence of spatial autocorrelation. In results obtained by Souza *et al*. (2013), studying the spatial distribution of *Euschistus heros* in the soybean, the variance/mean ratio in adults of *E. heros* for most sampling times in both areas was greater than one, indicating an aggregated pattern. The Morisita indices obtained here corroborate the results of the variance/mean ratio, and differ from the results obtained using the Moran Local index.

Pellenz, Almeida and Freitas (2019), evaluating the changes caused by the Commodity Boom in the spatial distribution of soybean production in the state of Rio Grande do Sul using the Moran index, found spatial autocorrelation between the districts being studied, with positive spatial autocorrelation between neighbours, i.e. the districts with high production are located close to each other. Araújo, Uribe-Opazo and Johann (2014) promoted studies using the Moran index as a tool for verifying spatial autocorrelation and estimating soybean productivity in the west of Paraná; in the same way that Seffrin, Araújo and Bazzi (2018) concluded that there was spatial autocorrelation in soybean productivity for the 2007/2008 seasons during an exploratory spatial analysis by area, using statistical techniques such as the Moran index. It can be seen that the Moran index is widely used in a series of studies that seek to discover a spatial pattern that may be related to the geographic location of events that occurred in a given area of interest.

The Local Moran index is a statistical technique for testing local autocorrelation by analysing the covariance between a stipulated polygon and a certain neighbourhood defined as a function of a distance d.

The zones marked in red are classified as ‘High-High clusters’ with significantly high positive values that demonstrate the presence of a group of equally high values, i.e. the indicated location has a high value, with neighbours that also have high values, indicating aggregation. The locations with a light pink colour, classified as ‘High-Low outliers’ are areas that have a high value while their neighbours have low values (Figure 3).

The dark green colour, called a ‘Low-Low cluster’, shows significantly low values, indicating a spatial pattern of equally low values in that region; while the areas coloured light green, called ‘Low-High outliers’, mean the location has a low value whereas its neighbours have high values (Figure 3). The region with high values surrounded by regions that also have high values, shows a greater aggregation of *C. capitata*: the environment is favourable to them, whether for feeding, mating or oviposition. The places that have low values indicate that there is no aggregation in that environment, showing that some factor is interfering, making the environment unsuitable for the pest.

Table 1 - Indices of spatial distribution in *Ceratitis capitata* collected in McPhail traps in an orchard of the ‘Palmer’ mango

DFSH	DISP. χ^2 upr= 54,437 χ^2 lwr= 21,336	MORISITA INDEX					MORAN INDEX	
		IMOR	MCLU	MUNI	IMST	PCHISQ	ZSCORE	PVALUE
7	111.91Ag	5.713 Ag	2.152	0.083	0.551	1.23 e^{-09}	-0.310 $_{Al}$	0.757
14	254.66 Ag	4.703 Ag	1.312	0.751	0.547	1.06 e^{-34}	-0.157 $_{Al}$	0.875
21	322.32 Ag	3.137 Ag	1.137	0.890	0.527	1.01 e^{-47}	0.165 $_{Al}$	0.868
28	208.37 Ag	2.197 Ag	1.128	0.898	0.514	3.74 e^{-26}	0.889 $_{Al}$	0.373
35	249.31 Ag	3.429 Ag	1.209	0.833	0.531	8.05 e^{-34}	1.16 $_{Al}$	0.244
42	349.92 Ag	2.869 Ag	1.109	0.912	0.524	4.02 e^{-53}	1.891 $_{Ag}$	0.059

Aggregations can be defined according to the position of the initial immigrants, which can influence the behaviour of other individuals by emitting pheromones, or even result in the formation of new plant volatiles. Similarly, colonisation techniques are strongly influenced by birth/death rates that diverge locally, so that the total population density over the whole area increases, while in limited areas, the population becomes extinct, leading to a clustered spatial pattern (FLEISCHER *et al*., 1997).

At 7 DFSH, the traps near the edges of the orchard captured what was considered a high number of flies; however, there was no aggregated pattern with the neighbouring traps (Figure 3). It should be noted that two traps installed on the upper and lower edges signalled the capture of fruit flies, this indicates that there may be an alternative host for the flies in the neighbouring vegetation, and that when mangoes enter the maturation process, they release odorous substances that attract the flies to the orchard.

During the evaluations at 7, 14, 21, 28 and 35 DFSH, *C. capitata* was more dispersed along the upper and lower edges of the orchard, which acted as entry points, with the vegetation in the lower part comprising Caatinga-like vegetation, and surrounded by plants that act as secondary hosts, such as okra (*Pereskia bahiensis* Gürke), which are used as living fences surrounding the property, as well as crops of the forage palm in areas close to the mango plantation (LEITE *et al*., 2017). According to Zucchi and Moraes (2021), *C. capitata* has a wide range of hosts, and can be associated with 115 plant species in Brazil.

In addition to its high fecundity, another factor that may contribute to the abundance of the fruit fly is the availability of fruit hosts around the orchard. In the upper part of the orchard, there is another possible entry point for the pest, in addition to an older mango plantation around 300 metres from the experiment bearing fruit during the same period as the orchard under study, which suggests the hypothesis that that this orchard could have fruit flies that migrated to the site of the experiment.

At 14 DFSH, one point was considered 'HH', i.e. the traps near the edges have a high value, with nearby traps also having high values, indicating an aggregated pattern. In a study analysing the spatial and temporal distribution of pests on palm trees, Anhe *et al*. (2022) applied the Moran Index to their data and found on the maps a trend towards a greater spatial concentration in a location close to the edge of the study area under direct influence of the native vegetation, meaning that traps close to the forested regions show a strong spatial autocorrelation with the location and with neighbouring traps.

At 21 DFSH, one aggregation point with high values and two aggregation points with low values can be seen. There was an increase in the number of *C. capitata* at the centre of the orchard, probably due to more fruit being available. The most obvious reason for this aggregation is the heterogeneity of the habitat: certain factors, such as luminosity, temperature, wind, humidity and other ecological factors, including sexual stimuli and competition for food, can interfere with the aggregated patterns of the fruit fly. Various elements, such as availability, fruit maturity and the attributes of areas near the orchards may have influenced the spatial distribution of *C. capitata*.

At 28 DFSH, it can be seen that the area with an aggregation of low values increased, and that the aggregation of high values moved towards the centre of the orchard. At 42 DFSH, *C. capitata* migrated to the traps positioned in the centre, tending towards the left lateral edge of the area. One fact that may have contributed to this migration were the crop treatments that began on the right side of the orchard. Insects rarely disperse at random when they are in their natural environment, as few environments are homogeneous, and the behavioural responses that govern their dispersal are generally unique and not random. Crop treatments may have driven the flies towards areas of the plantation where the fruit had not been harvested or that had not been pruned, the flies remaining in places with more oviposition sites, thereby maintaining an aggregated pattern in the environment.

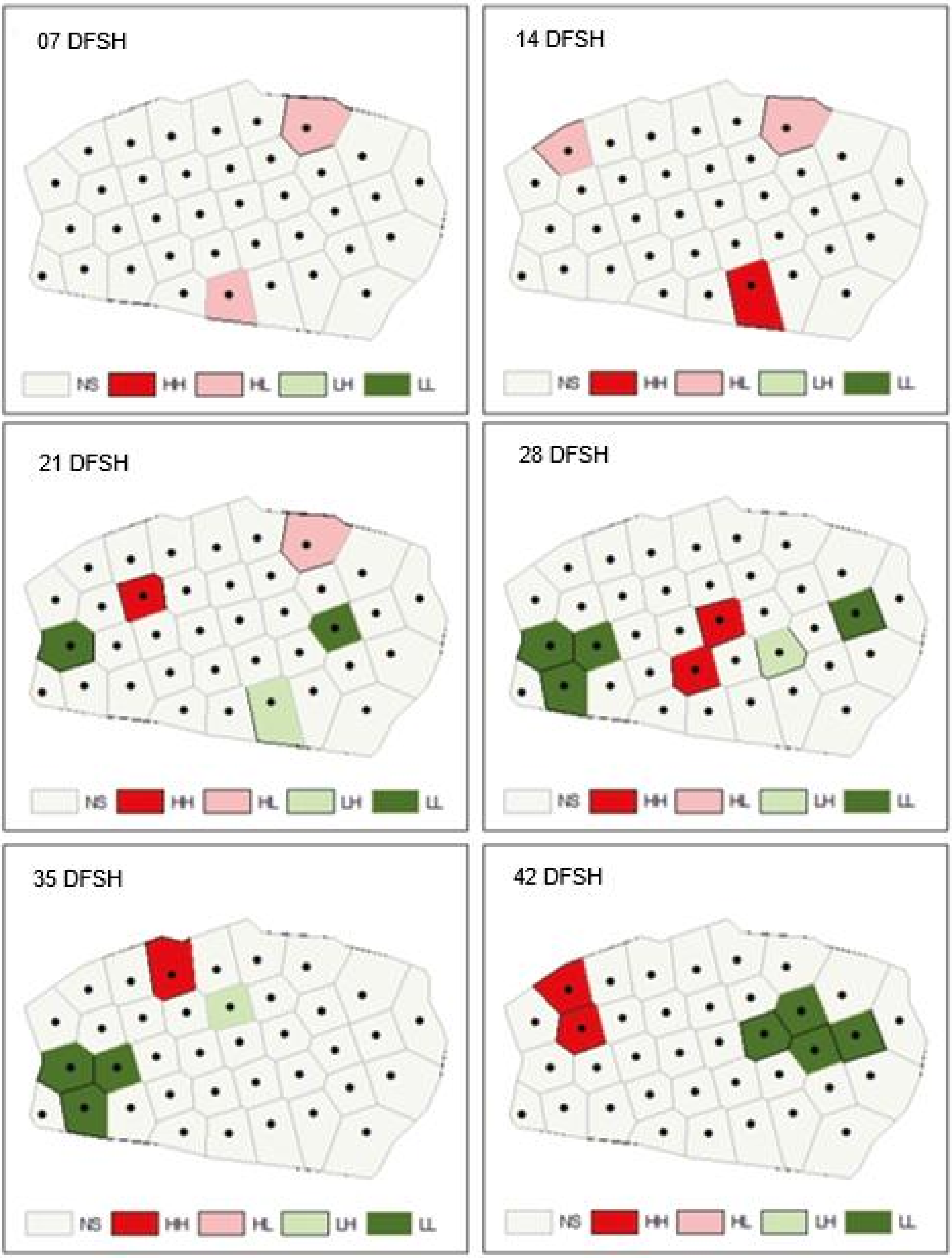
Uramoto, Walder and Zucchi (2004) recommend carrying out crop treatments in orchards to remove fallen fruit from the ground, as this practice eliminates oviposition sites of the fruit fly, reducing the population.

The Local Moran index shows that this tool can be important in applying the spatial distribution of *C. capitata*, since it shows aggregations of both low values and high values, making the application of management techniques more precise, and consequently, generating greater economy for the producer.

The number of flies found per trap in each evaluation varied greatly, with a minimum of 0 and maximum of 31, and a coefficient of variation that ranged from 121.53 to 259.69. The evaluations at 7 and 14 DFSH show greater variability than the other evaluations, indicating a possible tendency towards aggregation in specific traps (Table 2). These values demonstrate how much the data are dispersed around the mean, leading to a non-parametric distribution, as confirmed by the Shapiro-Wilk test.

In geostatistical analysis, by means of the semivariogram, it is possible to obtain various important parameters to characterise spatial dependence. The models fitted to the semivariograms varied between exponential (7, 14, 28 and 35 DFSH) and spherical (21 and 42 DFSH) based on the model that best suited the evaluation that was carried out (Table 3). The range (m) defines the distance

Figure 3 - Aggregation pattern of *Ceratitis capitata* using the Local Moran index in an orchard of the 'Palmer' Mango



at which there is spatial dependence between the samples, and varied between 99.5 m at 7 DFSH and 515.2 m at 42 DFSH, showing that samples separated from each other by distances smaller than 99.5 m or 515.2 m, respectively, are spatially correlated, with any points collected at distances greater than these values considered independent. The SDI ranged from 61.90% to 98.80%, showing a wide variation over the course of the evaluations.

Since the first evaluation, the exponential predictive model and the SDI pointed to the possibility of management zones, with the SDI of the first evaluation classified as strong, which none of the other indices indicated. From 14 to 35 DFSH, the SDI was moderate, showing that the pest was well-distributed in the area, as there was a balance between the random and spatially dependent variations. In the fifth evaluation, the SDI was classified as strong, as there was a change in the spatial distribution of the flies due to the management that was beginning to be applied in the area.

The evaluations that gave a strong spatial dependence (at 7 DFSH and 35 DFSH) also presented the shortest distances (99.57 and 104.43 metres, respectively). From these results, it is recommended that future evaluations use a spacing of 100 metres between traps.

One of the results of geostatistics is the elaboration of maps of spatial distribution and risk assessment for pest management, a tool that has been increasingly used. Maps are acquired by combining data obtained in the field, and are important aids for understanding the behaviour of pests (PAZINI *et al*., 2015).

Evaluating the modelled area by indicator kriging, it can be seen that at 7 DFSH the model estimated 74.31% of the area under study as having a low probability of infestation, with only 0.41% of the area considered to have a high probability (> 75%), making it possible to define a management strategy for the effective control of an area of only 0.05 ha that is at the start of an infestation and is therefore more easily controlled.

At 14 DFSH, it was found that the region with a low probability of infestation decreased to 46.99%, increasing the area of moderate to low (36.56%), moderate to high (15.69%) and high (0.76%). Thus, it is possible to see an increase in the probability of infestation, and map the potential displacement of the pest within the plantation, moving from the lower edge to the centre of the area.

Table 2 - Maximum, mean and minimum values, coefficients of variation, skewness, kurtosis and test of normality (Shapiro-Wilk) for the abundance of *Ceratitis capitata* at 7, 14, 21, 28, 35 and 42 DFSH

DFSH	Minimum	Maximum	Mean	Coefficient			Shapiro-Wilk
				Variation	Skewness	Kurtosis	
7	0.00	5.00	0.46	259.69	2.64	8.99	< 0.0001
14	0.00	12.00	1.62	208.75	2.12	6.16	< 0.0001
21	0.00	20.00	3.68	155.08	1.85	5.08	< 0.0001
28	0.00	24.00	3.92	121.53	2.22	9.57	< 0.0001
35	0.00	16.00	2.40	169.89	2.33	7.34	< 0.0001
42	0.00	31.00	4.57	145.90	2.29	8.65	< 0.0001

Table 3 - Theoretical semivariogram models adjusted for 7, 14, 21, 28, 35 and 42 days from the start of the harvest (DFSH) in an orchard of the 'Palmer' Mango

DFSH	Model	Nugget Effect (Co)	Sil (C)	Reach (m)	SDI* (C/C + Co)	Mean Error
07	Exponential	0.047	0.152	99.570	76.44	-0.012
14	Exponential	0.120	0.231	125.341	65.74	-0.007
21	Spherical	0.138	0.293	216.425	67.98	-0.001
28	Exponential	0.176	0.285	277.319	61.90	0.011
35	Exponential	0.003	0.264	104.430	98.80	0.011
42	Spherical	0.142	0.371	515.237	72.28	0.001

It can be seen that at 21 and 28 DFSH the pest already occupies the central part of the area (Figure 4). However, at 21 DFSH the percentage area classified as having a high probability of infestation, which at the beginning was 0.41%, has now increased to 16.51%. During this period, there is a greater probability of *C. capitata* infesting the interior of the orchard, while the lateral edges have a low probability of infestation.

At 28 DFSH, the percentage area with a low probability of infestation fell by 72.41% compared to the percentage at 7 DFSH. This may be associated with the dispersal process of the pest in the orchard. At 35 DFSH there is an increase in the area of low infestation, from 1.90% (28 DFSH) to 39.42%. This increase may be associated with the start of the control strategies seen in the field evaluation.

Even so, the highest probability for the occurrence of C. capitata (> 75%) can still be seen across a central band of the orchard (Figure 4), perhaps due to fruit at a maturation stage > 30% in the area resulting in greater infestation.

At 42 DFSH, there was a reduction in the number of flies. This can be explained by the number of fruits decreasing due to the harvest and the application of crop treatments that included pruning, resulting in a low probability for the occurrence of *C. capitata* (< 25%). Pest infestation is related to the availability of oviposition sites (fruit); as the harvest progresses, the flies disperse to areas with more fruit.

From this information it can be inferred which places need greater attention when making decisions. Moura and Moura (2006), studying flies associated with the guava, found that the low number of fruit flies captured in the study area may be associated with the removal of fallen fruit by the crop treatments, which may have prevented the population of these tephritids from developing and increasing at the site. Vieira *et al* (2014), evaluating the population fluctuation and spatial dependence of the black fly in an orchard of Tahiti lime with the help of kriging, were able to determine that the aggregation area of *A. woglumi* during the rainy season is greater than during the dry season. With the aim of characterising the spatial distribution of *A. gemmatalise Chrysodeixis includens* in the soybean, Magano *et al*. (2023) used kriging, which allowed them to determine the spatial and temporal distribution of the caterpillar complex as an aid to decision-making.

The aggregation area of *A. woglumi* during the rainy season is greater than during the dry season. As such, the use of probability maps can avoid an area becoming conducive to aggregations of the pest, and prevent it from spreading to other regions, affording less probability of attack.

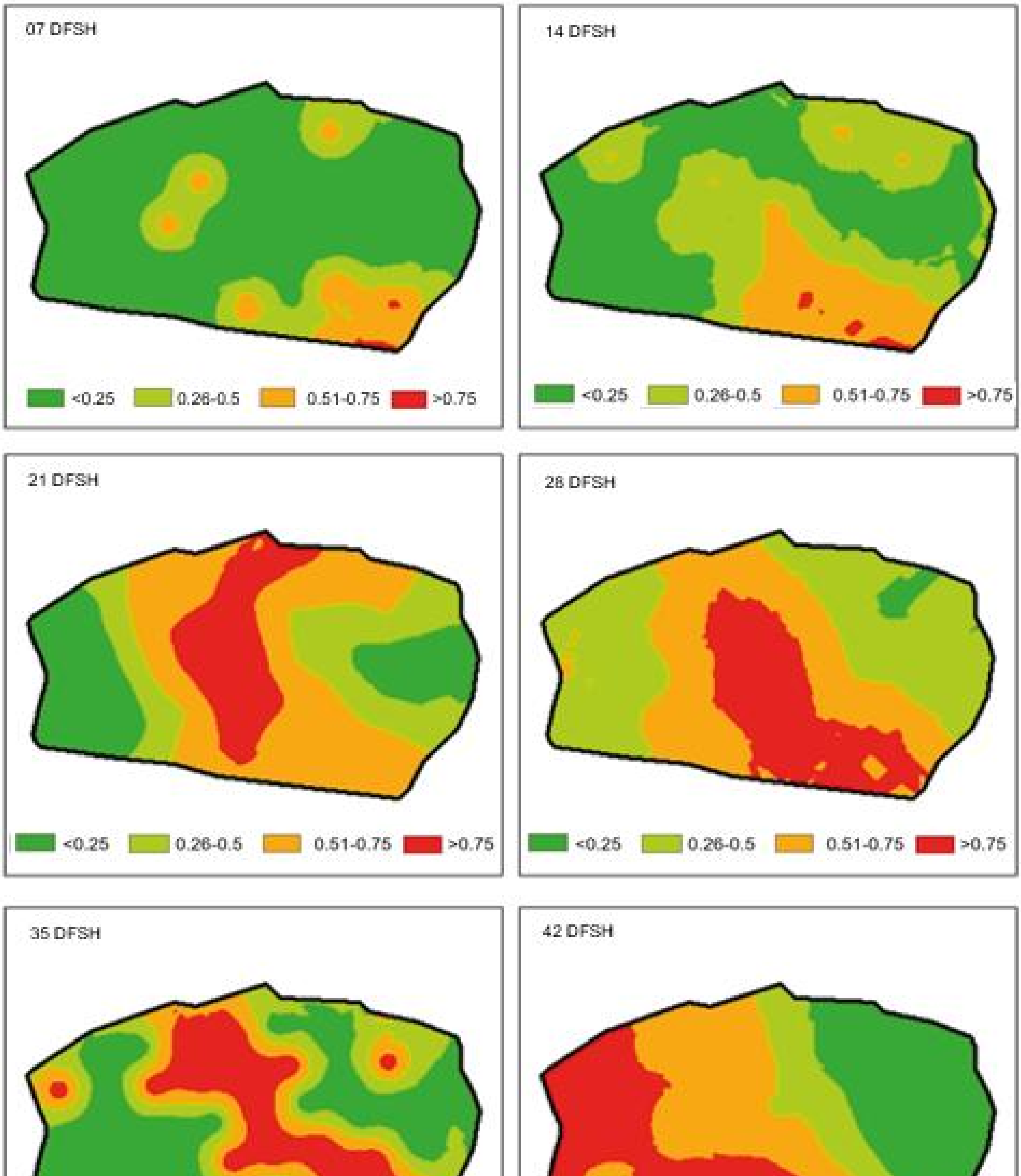
In this case, the map supports the selection of sectors of the orchard for the correct positioning of each trap, including a reliable indication of the range limit, making it possible to draw up management strategies right from the start of the attack, since the probability maps are able to detect which places have the highest and lowest risk of the pest occurring.

The producer should pay greater attention to areas that have a higher probability of occurrence, and use more-severe controls, such as spraying with insecticide; while in areas that have a low probability, the producer can start preventative control with the use of toxic baits, so that this low probability does not evolve into a high probability of infestation. It is possible to bring forward the introduction of preventative measures against the pest in the area under study, resulting in a reduction in the use of insecticides, with more-localised applications instead of the total area, reducing not only the costs to the producer, but also avoiding greater damage to the environment.

Table 4 - Area and percentage area based on the levels of probability of an occurrence of Ceratitis capitata in an orchard of the ‘Palmer’ Mango

DFSH	< 25% Low		25 – 50 Moderate to Low		51 – 75 Moderate to High		> 75% High	
	Area	%	Area	%	Area	%	Area	%
7	9.40	74.31	2.18	17.22	1.02	8.06	0.05	0.41
14	5.95	46.99	4.63	36.56	1.99	15.69	0.10	0.76
21	2.92	23.07	2.85	22.53	4.80	37.89	2.09	16.51
28	0.24	1.90	5.42	42.83	4.18	33.01	2.82	22.26
35	4.99	39.42	2.80	22.13	2.19	17.28	2.68	21.17
42	3.49	27.62	1.84	14.54	3.80	30.06	3.52	27.79

Figure 4 - Thematic maps of the probability of an occurrence of fruit flies of species *Ceratitis capitata* in an orchard of the 'Palmer' Mango, ranging from < 0.25 to > 0.75



CONCLUSIONS

1. The population dynamics of *C. capitata* becomes greater when the amount of ripe fruit in the orchard begins to increase. Population fluctuation in the area is reduced following interventions in the form of crop treatments (pruning);
2. The abundance of *C. capitata* has a significant and positive correlation with temperature;
3. The dispersal patterns analysed by the Perry and Mead and Morisita dispersion indices point to aggregations of *C. capitata* during each period under analysis, however the aggregated pattern cannot be spatialised;
4. It is possible to model the variation in space by producing maps for each management zone using the exponential predictive model, demonstrating the viability of using this tool in other areas containing host plants of *C. capitata*;
5. The maps obtained using indicator kriging make it possible to assign the probabilities of an occurrence, and thus draw up integrated pest-management plans based on the level of infestation and the needs of the crop.

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