Geostatistical analysis of the spatial variation of the berry borer and leaf miner in a coffee agroecosystem

Marcelo C. de Alves · Fábio M. da Silva · Jair Campos Moraes · Edson A. Pozza · Marcelo S. de Oliveira · Júlio C. S. Souza · Luciana S. Alves

Abstract The advent of geostatistics and geographical information systems has made it possible to analyze complex spatial patterns of ecological phenomena over large areas in applied insect ecology and pest management. The objective of this study was to use geostatistics to characterize the spatial structure and map the spatial variation of damage

M. C. de Alves (✉)
Faculty of Agronomy and Veterinary Medicine, Soil and Rural Engineering Department, Federal University of Mato Grosso, Av. Fernando Correa da Costa S/N, Coxipo District, Cuiabá, MT 78060-900, Brazil
e-mail: marcelocarvalhoalves@gmail.com

F. M. da Silva
Engineering Department, Federal University of Lavras, P.O. Box 3037, Lavras, MG 37200-000, Brazil
e-mail: famsilva@ufla.br

J. C. Moraes
Department of Entomology, Federal University of Lavras, Campus of Federal University of Lavras, cx 3037, Lavras, MG CEP 37200-000, Brazil
e-mail: jcmoraes@ufla.br

E. A. Pozza
Department of Phytopathology, Federal University of Lavras, P.O. Box 3037, Lavras, MG 37200-000, Brazil
e-mail: eapozza@ufla.br

M. S. de Oliveira
Department of Exact Sciences, Federal University of Lavras, P.O. Box 3037, Lavras, MG 37200-000, Brazil
e-mail: marcelo.oliveira@ufla.br

J. C. S. Souza
Engineering Department, Federal University of Lavras, Campus of Federal University of Lavras, cx 3037, Lavras, MG CEP 37200-000, Brazil
e-mail: julioeagricola@yahoo.com.br

L. S. Alves
Department of Sanitary and Environmental Engineering, Federal University of Mato Grosso, Av. Fernando Correa da Costa S/N, Coxipo District, Cuiabá, MT 78060-900, Brazil

caused by the berry borer (*Hypothenemus hampei*) and leaf miner (*Leucoptera coffeella*) in a coffee agroecosystem planted with the cultivar Catuai Vermelho IAC-99. Infestations of berry borer and leaf miner were evaluated in fruits and leaves, respectively. The pests were monitored at 67 georeferenced points in an area of 6.6 ha in 2005, 2006 and 2007. Variograms estimated by the method of moments (MoM) and residual maximum likelihood REML were compared. The latter were generally better in terms of the kriging error coefficients. Spherical variograms estimated by REML for berry borer infestation in fruits had ranges of spatial dependence of 34.62–118.4 m and for the leaf miner they were 53.93–133.7 m. For models fitted by weighted ordinary least squares (OLS) to the MoM experimental variogram, the ranges varied between 37.22 and 68.67 m for the berry borer and 100 and 155.4 m for leaf miner infestation. The variogram model parameters were used with the data for ordinary kriging to map the spatial variation of coffee pests for different monitoring periods. If there was no suitable variogram, inverse distance weighting was used to map the variation. The maps enabled visualization of the intensity of infestation of the insect pests for the different periods evaluated.

Introduction

Assessing the levels of infestation of pests is essential in a program of integrated pest management and decision support to determine where unacceptable economic damage begins to occur (Gutierrez and Wang 1977; Koul et al. 2004; Horowitz and Ishaaya 2004). The adoption of integrated pest management concepts in a coffee agroecosystem (*Coffea arabica* L.) is important because of injury caused by the leaf miner (*Leucoptera coffeella*) (Guérin-Mèneville and Perrottet 1842) (Lepidoptera: Lyonetiidae) and the berry borer (*Hypothenemus hampei* Ferrari 1867) (Coleoptera: Scolytidae) to coffee leaves and fruits, respectively. The leaf miner attacks coffee leaves and reduces their areas and causes leaf fall, and the berry borer attacks coffee fruits reducing productivity and quality (Le Pelley 1968; Gallo et al. 2002).

The adoption of strategies to control leaf miners and berry borers requires knowledge about their bioecology, dynamics and spatial patterns in the field, to determine whether site-specific management is feasible in relation to their potential spread. Monitoring levels of infestation of insect pests in crops is done traditionally by sampling based on rates of dispersal and indices such as the variance:mean ratio, Taylor coefficients, Lloyd index (Horn 1988), Wald probabilities ratio and Iawo confidence interval (Bearzoti and Aquino 1994). These simple and low cost methods base control of the pests on the total field area; they disregard sample location and do not quantify the spatial structure and pattern.

Statistical methods that take into account the spatial dependence of samples, such as geostatistics, are currently being used in modern entomology to study spatial patterns of pests and insect ecology (Liebhold et al. 1993; Rossi et al. 1992). Applications of geostatistics and spatial analysis are related to establishing integrated pest management control strategies (Liebhold et al. 1991; Hughes and McKinlay 1988), campaigns to guide the eradication of pests and studies of the impact of climate change on their distribution (Estrada-Peña 1999). Brase (2006) also showed that geospatial analysis could help in the rationalization of inputs, energy consumption and optimization of production, resulting in less environmental impact and improved sustainability of agricultural production (Brase 2006).
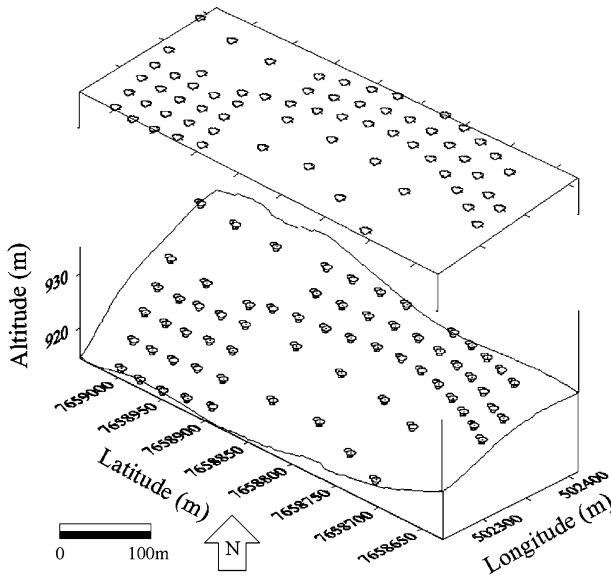
Geostatistics enables the structure and magnitude of spatial variation of environmental phenomena to be quantified which traditional methods do not (Isaaks and Srivastava 1989). Wright et al. (2002) used geostatistics to characterize small scale spatial variation in the European corn borer (Lepidoptera: Crambidae), caused by *Ostrinia nubilalis* (Hübner) (Lepidóptera: Crambidae) larvae and to quantify damage at the whorl stage of maize, *Zea mays* L. According to these authors, damage was spatially correlated among plants at distances of up to 2.84 m apart. Larvae were spatially correlated among plants at distances of up to 3.05 m apart, which suggested that at the time when eggs hatched there was an aggregation of neonates associated with an egg mass on a plant. These larvae spread out over the plant and may migrate to adjacent plants, decreasing the degree of aggregation at the scale of individual plants. Liebhold et al. (1991) also verified the possibility of using variograms to characterize the pattern of dispersion of masses of gypsy moth eggs from four different databases. The spatial dependence in egg mass densities had patterns of aggregation at different spatial scales ranging from 25 m to 100 km.

In coffee farming, infestation by the berry borer and leaf miner can be affected by the weather, season, predators and presence of parasitoids, density of planting, crop management, physiological status, plant growth and its mineral nutrition (Souza et al. 1998; Nestel et al. 1994; Caixeta et al. 2004; Gutierrez et al. 1998; Meireles et al. 2001; Nestel et al. 1994; Tuelher et al. 2003; Gallo et al. 2002). Therefore, the intensity of infestation of insect pests can vary according to the physical, chemical and biological variation of various factors in the coffee agroecosystem. Remond et al. (1993) used variograms to study the spatial distribution of berry borer in El Salvador, however, they could not model the experimental variogram to characterize the spatial pattern of the insect in the field. Baker (1984) observed that berry borer infestations were aggregated in the field, and that the damage caused by insects in the fruits increased the release of volatile compounds by the host, which attracted other berry borers.

Based on the hypothesis that there is spatial variation in the infestations of pests in coffee agroecosystems, the objective of this study was to use geostatistics to characterize and map the spatial variation in the infestation of berry borer in fruits and of leaf miner in leaves of the Catuai Vermelho IAC-99 cultivar.

Materials and methods

The experiment was carried out in 2005, 2006 and 2007 at Cafua farm (latitude 21°10′11″ South and longitude 44°58′37″ West), in the Ijaci municipal district south of Minas Gerais, Brazil. The study site was about 6.6 ha and planted 16 years ago with the coffee cultivar (*Coffea arabica* L.) Catuaí Vermelho IAC-99. This cultivar is susceptible to berry borer and leaf miner attack. There is a spacing of 4 m between rows and 1 m between plants, with a total of 2500 plants per hectare. The mean altitude of the site is 934 m and it has a slope of 0.84% north–south and of 12% east–west. The site was sampled at 67 locations on a grid with distances between the nodes of 25 × 25 m and 50 × 50 m (Fig. 1). The monthly averages of maximum, mean and minimum air temperature (°C), total rainfall (mm), mean relative humidity (%) and mean insolation (hours) from August 2004 to August 2007 were obtained from INMET for the metereological station of Lavras, Minas Gerais, 5.09 km from the experimental site. The georeferencing of sampling sites was done with a GPS TRIMBLE 4600 LS® associated with an Electronic Station Leica TC600®. The GPS data were post-processed based on known coordinates of geodetic marks of the Brazilian Institute of Geography (IBGE) located on the campus of the Federal University of Lavras (UFLA). The

Fig. 1 Sample design to monitor intensity of attack by the berry borer (*Hypothenemus hampei*) and leaf miner (*Leucoptera coffeella*) in a coffee (*Coffea arabica* L.) agroecosystem, where each point on the map represents five sampled coffee trees

crop was fertilized in November 2004, 2005 and 2006 with applications to the soil of 42, 10 and 42 kg ha^{-1} of N, P and K, respectively, followed by spraying an aqueous solution on the leaves with 0.24, 0.14 and 0.24 kg ha^{-1} of Zn, B and KCl, respectively. Micronutrients were applied to leaves because they are absorbed efficiently by them and can be mixed with other chemical products. In January 2005, 2006 and 2007, 148, 37 and 148 kg ha^{-1} of N, P and K, respectively, were applied to the soil. In February 2005, 2006 and 2007, an aqueous solution was applied to the leaves with 0.086, 0.052 and 0.086 kg ha^{-1} of Zn, B and KCl, respectively. In September 2006 1700 kg ha^{-1} of lime was applied to the soil. The chemical control of pests in the crop was done in November 2004 with the application of 0.6 l ha^{-1} of Opus$^{®}$ (epoxiconazol). In April 2005 0.01 kg ha^{-1} of Amistar$^{®}$ (azoxystrobin), 0.4 l ha^{-1} of Opus$^{®}$ (epoxiconazol), 2.0 l ha^{-1} of endosulfan AG$^{®}$ (endosulfan) and 2.0 l ha^{-1} of Nimbus$^{®}$ (paraffinic mineral oil) were applied for pest control. In November 2005 0.12 kg ha^{-1} of Verdadero 600WG$^{®}$ (Tiametoxam and Ciproconazol) was applied. In February 2005 and 2006 0.9 l ha^{-1} of Nimbus$^{®}$, 1.4 l ha^{-1} of endosulfan AG$^{®}$ and 0.4 kg ha^{-1} of Roundap WG$^{®}$ (glifosato) were applied for pest and weed control. In December 2006 0.69 kg ha^{-1} of Actara 250WG$^{®}$ (tiametoxam), 0.045 kg ha^{-1} of Amistar$^{®}$ and 0.9 L ha^{-1} of Nimbus$^{®}$ were applied. In February 2007 0.5 L ha^{-1} of Priori$^{®}$ (azoxistrobin) and 1.4 l ha^{-1} of endosulfan AG$^{®}$ were applied for pest and disease control.

Infestations of berry borer (*Hypothenemus hampei*) (Ferrari 1867) (Coleoptera: Scolytidae) in fruits were evaluated on 05/20/2005, 05/28/2006 and 05/30/2007. The evaluations were done on fruit samples at the cherry stage because of berry borer's preference to attack fruits at this stage of development (Cure et al. 1998). At each sampling point ($n = 100$) the sample support comprised five plants. Fruit samples were collected randomly from each side of the planting row (West and East) from the middle third of the plant. Ten fruits were detached from each plant resulting in 6700 fruits for each period of evaluation. The fruits

were analyzed in the laboratory of the Department of Epidemiology and Management of Phytopathology of the Federal University of Lavras. The percentage of infestation of berry borer at each sampling point was calculated by counting fruits with a hole in the crown and a larvae gallery inside the fruit, following the methodology of Gallo et al. (2002).

Infestations of leaf miner (*Leucoptera coffeella*) (Guérin-Mèneville 1842) (Lepidoptera: Lyonetiidae) were evaluated on 06/15/2005, 05/29/2006 and 06/30/2007 by observing insect mines in leaves. Evaluations were done on a sample support of five plants at each georeferenced point in the field ($n = 100$). A total of 6700 leaves for each period of evaluation were taken randomly from each side of the planting row (West and East) from the middle third of plants, and were analyzed in the same laboratory as above. Ten leaves were sampled per plant on each side of the planting row from the third and fourth pair of leaves counted from the end of plagiotropic branch (Gallo et al. 2002) because they are considered the most representative (Huerta 1963). There is also more frequent insect oviposition in the third and fourth leaves internodes. A leaf was considered to be infested when there was at least one mine, the surface of the leaf lamina was irregular and the color was greenish-brown; this was 1% of infestation. Although this method gives an indirect measurement of population size, it has been recommended as a useful way of assessing the approximate population abundance of any type of leaf miner (Nestel et al. 1994).

The pattern of spatial dependence of infestation by the berry borer and leaf miner was analyzed by the variogram, and ordinary kriging was used for prediction. Field observations were considered to be a random function $Z(\mathbf{x})$, where $\mathbf{x}$ denotes the spatial location.

In geostatistics, estimating and modeling the variogram are an important step because the parameters of the chosen model describe the spatial correlation structure and are used in kriging (Liebhold et al. 1993, Burrough and McDonnell 1998). Webster and Oliver (2007b) recommended a minimum of 100 data from which to compute a reliable experimental variogram by the usual method, i.e. Matheron's (1965) method of moments estimator

$$\hat{\gamma}(\mathbf{h}) = \frac{1}{2N(\mathbf{h})} \sum_{i=1}^{N(\mathbf{h})} \{z(\mathbf{x}_i) - z(\mathbf{x}_i + \mathbf{h})\}^2, \tag{1}$$

where, $\hat{\gamma}(\mathbf{h})$ is the estimated semivariance, $N(\mathbf{h})$ is the number of pairs of observations $z(\mathbf{x}_i)$, $z(\mathbf{x}_i + \mathbf{h})$, separated by the lag distance, $\mathbf{h}$. The series of semivariances, $\hat{\gamma}(\mathbf{h}_1)$, $\hat{\gamma}(\mathbf{h}_2)$,...., at particular lags, $\mathbf{h}_1, \mathbf{h}_2,...$, comprise the experimental variogram. A theoretical function is then fitted to the experimental values to summarize the spatial relations in the data. The parameters of the fitted model can be used to estimate or predict at unsampled places at points or over blocks by kriging (Webster and Oliver 2007a, b).

Several isotropic authorized functions were fitted by weighted ordinary least squares (OLS), but spherical functions (Olea 2003) provided the best fit.

$$\text{Spherical} = \gamma(h) = \begin{cases} c_0 + c\left(\frac{3h}{2a} - \frac{1}{2}\left(\frac{h}{a}\right)^3\right) & 0 \leq h < a, \\ c & h \geq a, \end{cases} \tag{2}$$

where c_0 is the nugget variance, c is the sill of the spatially correlated component, a is the range of spatial dependence and h is the separating distance.

As our survey resulted in fewer than 100 data for each time period, we also estimated the variogram by residual maximum likelihood (REML) because Pardo-Igúzquiza (1998) said that "a few dozen data may suffice" to estimate a variogram by maximum likelihood.

The best fitting models were chosen by cross-validation (Cressie 1993; Chilès and Delfiner 1999).

In ordinary kriging, $\hat{Z}(\mathbf{x}_0)$ can be estimated at a point or over a block. For this study we used punctual kriging. A kriged estimate is a simple weighted mean of the data, $z(\mathbf{x}_1)$, $z(\mathbf{x}_2),\ldots, z(\mathbf{x}_i)$ within a neighbourhood (Burrough and McDonnell 1998)

$$\hat{Z}(\mathbf{x}_0) = \sum_{i=1}^{n} \lambda_i z(\mathbf{x}_i), \tag{3}$$

where λ_i are the kriging weights. The weights that minimize the estimation variance are found subject to the constraint that they sum to 1 and the expected error is $E\left[\{\hat{Z}(\mathbf{x}_0) - z(\mathbf{x}_0)\}\right] = 0$. The estimation variance is

$$\begin{aligned} \text{var}\left[\hat{Z}(\mathbf{x}_0)\right] &= E\left[\{\hat{Z}(\mathbf{x}_0) - z(\mathbf{x}_0)\}^2\right] \\ &= 2\sum_{i=1}^{N} \lambda_i \gamma(\mathbf{x}_i, \mathbf{x}_0) - \sum_{i=1}^{N}\sum_{j=1}^{N} \lambda_i \lambda_j \gamma(\mathbf{x}_i, \mathbf{x}_j), \end{aligned} \tag{4}$$

where $\gamma(\mathbf{x}_i, \mathbf{x}_j)$ is the semivariance of Z between the data points $\mathbf{x}_i$ and $\mathbf{x}_j$ and $\gamma(\mathbf{x}_i, \mathbf{x}_0)$ is semivariance between the ith data point and the target point $\mathbf{x}_0$.

Kriging was performed using a global neighbourhood.

Ordinary kriged predictions were compared to the observed values by cross-validation to assess how well the model performs (Cressie 1993; Goovaerts 1997). The mean deviation or mean error (ME) to assess the bias is given by

$$ME = \frac{1}{N}\sum_{i=1}^{N} \left(\hat{Z}(\mathbf{x}_i) - z(\mathbf{x}_i)\right), \tag{5}$$

where $\hat{Z}(\mathbf{x}_i)$ is the kriged estimate, $z(\mathbf{x}_i)$ is the observed value for location $\mathbf{x}_i$. The value of the ME should be zero. The mean squared deviation ratio, MSDR is computed from the squared errors and kriging variances, $\hat{\sigma}^2(\mathbf{x})$, by:

$$MSDR = \frac{1}{N}\sum_{i=1}^{N} \frac{\left(\hat{Z}(\mathbf{x}_i) - z(\mathbf{x}_i)\right)^2}{\hat{\sigma}^2(\mathbf{x}_i)}. \tag{6}$$

If the model for the variogram is accurate the MSDR should be 1 (Webster and Oliver 2007a, b).

When a satisfactory variogram could not be obtained, inverse distance weighting was used for interpolation to map the spatial variation of the leaf miner for 05/29/2006.

Summary statistics including the minimum, maximum, mean, variance and skewness coefficient, were determined for the berry borer and leaf miner data. If the skewness values were >1 or <−1, a logarithmic transformation was applied to the data. In these situations, kriged predictions were back-transformed and returned to the same scale as the original data (Diggle and Ribeiro 2007).

Kriging and cross-validation were done using the R software, geoR package (Diggle and Ribeiro 2007).

Results and discussion

Table 1 gives the summary statistics for the berry borer and leaf miner for the dates studied. The skewness coefficients for the berry borer data of 05/20/2005 and 05/28/2006,

Table 1 Summary statistics to characterize the infestation of berry borer (*Hypothenemus hampei*) and leaf miner (*Leucoptera coffeella*) in coffee leaves (*Coffea arabica* L.) before and after logarithmic transformation

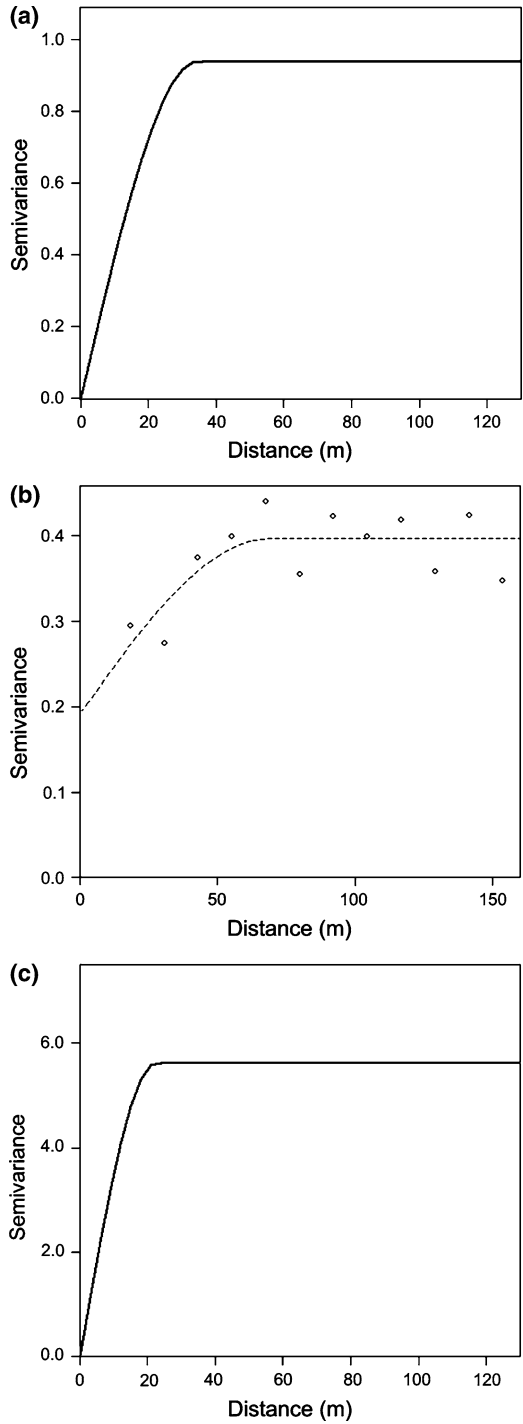| Transformation	Statistics	Pest and evaluation period					
		Berry borer 2005	Berry borer 2006	Berry borer 2007	Leaf miner 2005	Leaf miner 2006	Leaf miner 2007
No	Min	1.000	2.000	1.000	6.000	1.000	1.000
No	Max	45.00	43.00	10.00	32.00	25.00	29.00
No	Mean	5.149	11.75	3.522	19.90	8.806	6.537
No	Variance	46.49	59.37	5.344	38.10	31.80	15.16
No	Skewness	3.692	1.871	0.8655	−0.1012	0.9432	3.099
Yes	Min	0	0.6931	–	–	–	0.0000
Yes	Max	3.807	3.761	–	–	–	3.367
Yes	Mean	1.133	2.271	–	–	–	1.741
Yes	Variance	0.9283	0.4147	–	–	–	0.2886
Yes	Skewness	0.4867	−0.3191	–	–	–	−0.5282

Table 2 Parameters of spherical variogram functions estimated by residual maximum likelihood (REML) and the method of moments (MoM) modelled by weighted least squares approximation for the berry borer (*Hypothenemus hampei*) and leaf miner (*Leucoptera coffeella*) in coffee leaves (*Coffea arabica* L.), and cross-validation results for ordinary kriging using the relevant model parameters and data

Pest	Method of prediction	Evaluation period	Method of variogram estimation	Nugget effect (c_0)	Spatially dependent component (c)	Range (a)	Mean error	Mean squared deviation ratio
Berry borer	Kriging	05/20/2005	REML*	0	0.9397	34.62	0.2158	1.2205
	Kriging	05/28/2006	REML*	0.2637	0.1671	118.4	−0.2626	0.7718
	Kriging	05/30/2007	REML	0	5.612	22.49	0.0009	1.0135
Leaf miner	Kriging	06/15/2005	REML	16.74	20.01	133.7	−0.0518	1.0124
	IDW	05/29/2006	–	–	–	–	0.2069	–
	Kriging	06/30/2007	REML*	0.2536	0.0311	53.93	−0.0469	1.0397
Berry borer	Kriging	05/20/2005	MoM*	0	0.9432	47.65	0.3100	1.5279
	Kriging	05/28/2006	MoM*	0.1917	0.2047	68.67	−0.1583	0.9576
	Kriging	05/30/2007	MoM	0	5.927	37.23	0.0068	1.1633
Leaf miner	Kriging	06/15/2005	MoM	13.22	31.69	155.4	−0.0566	1.1028
	Kriging	06/30/2007	MoM*	0.2100	0.0896	100.0	−0.0304	1.0586

* Logarithmic transformation

and leaf miner data of 06/30/2007 suggested a need for transformation. A logarithmic transformation reduced the skewness to acceptable levels for these sets of data. Variograms were estimated for the raw or transformed data as indicated in Table 2 by the method of moments and REML. A variogram could not be estimated for the leaf miner for 05/29/2006 by either method. Table 2 gives the model parameters of the fitted spherical functions for both methods for the berry borer and leaf miner data. It was these parameters that were used for cross-validation to determine the appropriate models for kriging.

Fig. 2 Spherical variograms
estimated by residual maximum
likelihood (*continuos line*) and
method of moments (*broken
line*), to characterize the spatial
variation of the berry borer in a
coffee agroecosystem for:
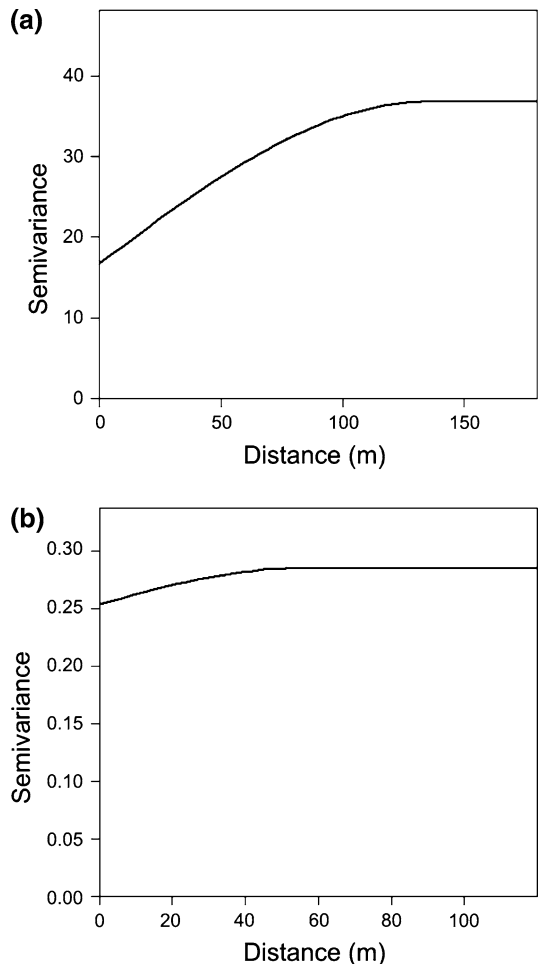**a** 05/20/2005, **b** 05/28/2006
and **c** 05/30/2007

Overall, the variograms estimated by REML have resulted in MSDRs closer to 1 (Table 2) than have those estimated by the method of moments apart from for berry borer 05/28/2006. Therefore, for the latter the experimental variogram estimated by the method of moments and modelled by weighted least squares approximation was selected for kriging. For all other dates for which a variogram could be computed, parameters of the variograms estimated by REML were used for kriging.

According to Webster and Oliver (2007a, b), a variogram estimated by REML is valuable where it is impractical to obtain as many as 100 data. Kerry and Oliver (2007) compared variograms estimated by the method of moments and residual maximum likelihood for kriging soil properties for precision agriculture and observed that predictions based on the latter were generally more accurate than those from MoM variograms with fewer than 100 sampling sites.

Figure 2 shows the variograms for infestations of berry borer in coffee fruits. The variogram for berry borer 05/28/2006 has a large nugget variance compared to the spatially correlated component, whereas the variograms for 05/20/2005 and 05/30/2007 estimated by REML have small nugget effects. The range of spatial dependence varies from 22 m to
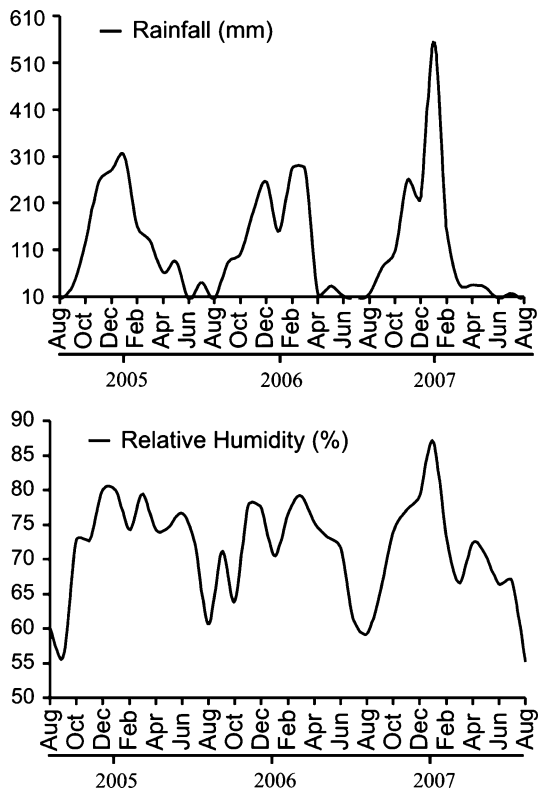

Fig. 3 Spherical variograms estimated by residual maximum likelihood (*continuos line*) to characterize the spatial variation of the leaf miner in a coffee agroecosystem for: **a** 06/15/2005 and **b** 06/30/2007

almost 69 m. For the evaluation of berry borer in 2007, the sill variance and range of the spherical model are smaller than for 2006 and 2005. The result for 2007 probably reflects the application of chemical products in December 2006 and February 2007 and high pluvial precipitation and relative humidity values which may have contributed to the reduction of pest infestation (Fig. 4). Ferreira et al. (2000) studied population dynamics of berry borer in Lavras, Minas Gerais, Brazil, and observed an increase in attack and a reduction in abandoned galleries by the insect that corresponded with a reduction in rainfall from January to June 1998. Cure et al. (1998) studied the phenology and population dynamics of berry borer in Paula Cândido, Minas Gerais, and also observed an increase in attack by the berry borer in coffee fruits from March to May 1993 of approximately 10–80%.

The spherical variograms fitted to the leaf miner data for 06/15/2005 and 06/30/2007 have larger nugget variances relative to the spatially correlated component than for berry borer. The range of spatial dependence for 06/15/2005 is also substantially longer than the ranges for berry borer and also for leaf miner for 06/30/2007 (Fig. 3). This was possibly due to the availability of fruit for the berry borer and the insect's preference to attack specific regions in the field. The effect of wind on disseminating the leaf miner (Baker 1984; Souza and Reis 1997) is probably greater than for the berry borer and so its infestations are less localized. Souza et al. (1998) suggested that coffee tree architecture, when subjected to winds, can cause the spread of leaf-miner. Such a crop provides favorable conditions for larval development because of the greater evaporation of water from leaves (Souza et al. 1998, Meireles et al. 2001). In 2007, the smallest sill variance and
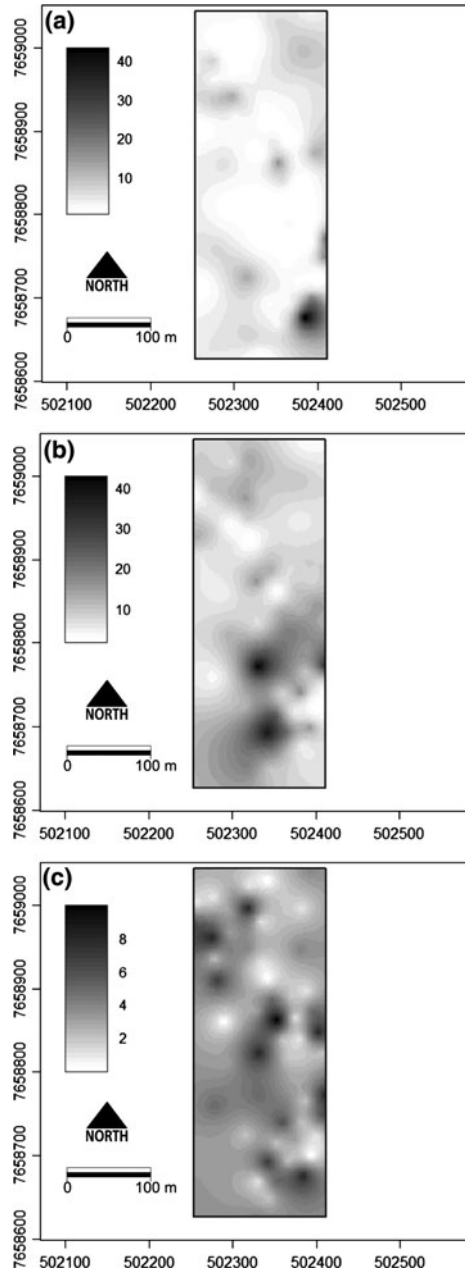

Fig. 4 Monthly total rainfall (mm) and average relative humidity (%) from August 2004 to August 2007 recorded at the principal INMET climatological station of Lavras, Minas Gerais

range for the model may be associated with the chemical control in December 2006 and in February 2007 when there was high pluvial precipitation and relative humidity values in this period (Fig. 4).
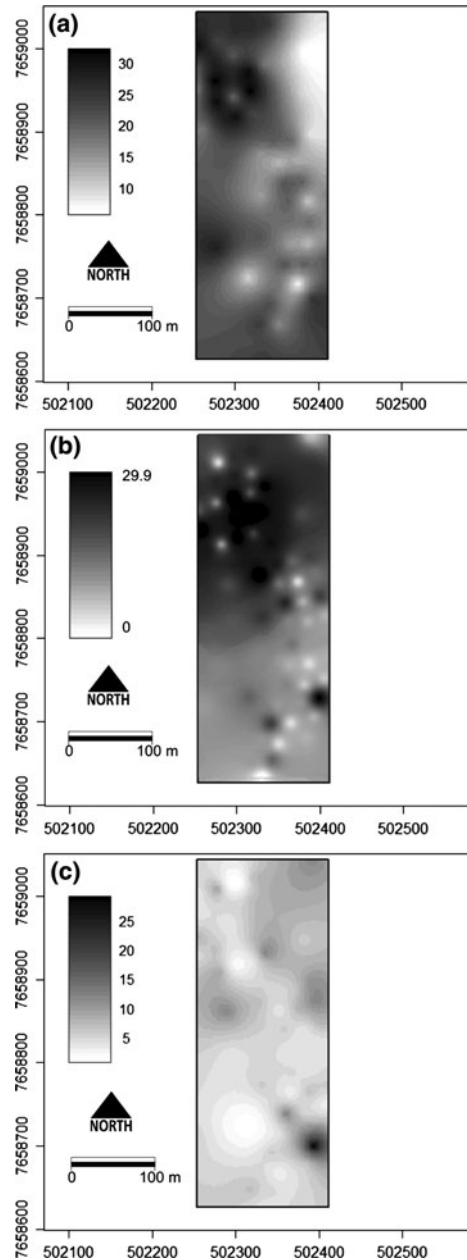
The parameters of the models selected by cross-validation were used with the relevant data for punctual kriging. The kriged predictions were mapped to show the dispersion and intensity of attack of insect pests studied (Figs. 5 and 6). The maps show that the intensity

Fig. 5 Maps of kriged predictions using variograms estimated by: **a**, **c** residual maximum likelihood and **b** method of moments to characterize the spatial variation of the berry borer in a coffee agroecosystem for 05/20/2005, 05/28/2006 and 05/30/2007, respectively

of infestation of berry borer is in the form of scattered patches of large and small values across the field. The intensity of infestations is greater for 2005 and 2006 than for 2007 (Fig. 5). For leaf miner 05/29/2006, the interpolation was done by inverse distance weighting. The leaf miner maps show that the infestation is mainly in the northern and central portions of the field, for all the dates evaluated (Fig. 6). The variation in nutrients in the soil and plants might have influenced the preference of the insect for the host in specific

Fig. 6 Maps of kriged predictions using variograms estimated by **a** and **c** residual maximum likelihood, and **b** map of predictions by inverse distance weighting to characterize the spatial variation of the leaf miner in a coffee agroecosystem for 05/20/2005, 05/29/2006 and 05/30/2007, respectively

areas of the field. The mineral nutrition can change the chemical composition, morphology, anatomy and phenology of coffee plants (Marschner 1987), which in turn can affect the leaf-miner's oviposition preference according to the coffee plants' nutritional status (Caixeta et al. 2004).

Conclusions

The spatial analysis approach adopted in this study enabled us to detect spatial variation in the infestation of coffee pests in the field, indicating the possibility of developing strategies to provide more effective control, less environmental impact and sustainability of coffee crop production, according to the philosophy of integrated pest management and precision agriculture.

The residual maximum likelihood variogram estimator characterized the spatial variation of berry borer and leaf miner better overall in terms of the MSDR than the method of moments because of the size of the data sets. Spherical functions described the structure and magnitude of spatial variation of the berry borer and leaf miner in the coffee crop. Kriged maps enabled visualization of the intensity of infestation of berry borer and leaf miner for different periods and characterization of their spatial patterns in the field. Where a variogram could not be modelled satisfactorily, inverse weighted distance can be used for mapping.

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