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Using Geostatistical Analysis to Evaluate the Presence of *Rotylenchulus reniformis* in Cotton Crops in Brazil: Economic Implications[1]

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Abstract: In recent years, the productivity of cotton in Brazil has been progressively decreasing, often the result of the reniform nematode *Rotylenchulus reniformis*. This species can reduce crop productivity by up to 40%. Nematodes can be controlled by nematicides but, because of expense and toxicity, application of nematicides to large crop areas may be undesirable. In this work, a methodology using geostatistics for quantifying the risk of nematicide application to small crop areas is proposed. This risk, in economic terms, can be compared to nematicide cost to develop an optimal strategy for Precision Farming. Soil (300 cm^3) was sampled in a regular network from a *R. reniformis*-infested area that was a cotton monoculture for 20 years. The number of nematodes in each sample was counted. The nematode number per volume of soil was characterized using geostatistics, and 100 conditional simulations were conducted. Based on the simulations, risk maps were plotted showing the areas where nematicide should be applied in a Precision Farming context. The methodology developed can be applied to farming in countries that are highly dependent on agriculture, with useful economic implications.
Key words: conditional simulations, cotton, geostatistics, kriging, Precision Farming, *Rotylenchulus reniformis,* semivariogram.

Brazil is currently the sixth-largest cotton producer in the world, reporting approximately 3% of global cotton production. However, production of cotton in Brazil decreased by 50% from 1991 to 1998. As a result, Brazil no longer exports cotton but instead imports it, with a strong influence on the Brazilian import/export balance. Among the causes for decreased cotton production is the reniform nematode, *Rotylenchulus reniformis,* which ranks either first or second to the root-knot nematode (*Meloidogyne incognita*) in damaging Brazilian cotton (Lordello, 1992), as occurs in other important cotton-producing countries such as the United States (Wrona et al., 1996).

The spatial distribution of nematodes in the field is often described as aggregated, with the frequency distribution following a negative binomial distribution (Ferris and Wilson, 1987; Seinhorst, 1982). Some investigators (Boag and Topham, 1984; Boag et al., 1987; Ferris et al., 1990; McSorley et al., 1985; McSorley and Dickson, 1991) have used Taylor's Power Law (Taylor, 1984) to describe the spatial distribution of nematodes and to design sampling methods. In these studies, the b' coefficient of Taylor's Law resulted in values higher than 1, indicating aggregation and spatial dependence in the nematode data. Geostatistical procedures analyze and model the spatial relationships of entities. Unlike other methods that infer spatial relationships from dispersion or mean-variance associations, geostatistical methodology allows analysis of the spatial dependence and independence of the mean-variance.

Caswell and Chellemi (1986) studied the spatial distribution of *R. reniformis* in a pineapple field in Hawaii and concluded that the spatial distribution was strongly aggregated. The authors computed the variogram and fit to the estimated values a spherical model with a range of 10 m. Chen and Bird (1992) also used geostatistics for studying the distribution of *Pratylenchus penetrans* in a potato field using a grid of 100 × 100 m, and a spherical model was fit with the northwest direction representing low population density and revealing anisotropy (i.e., the semivariogram was not the same to all directions). Webster and Boag (1992) studied the spatial distribution of *Globodera rostochiensis* and *Heterodera avenae* in east Scotland potato fields, based on viable cysts extracted from the topsoil. The authors concluded that there was no evidence of anisotropy; the semivariogram showed the same spherical form in all samplings, resulting in an effective range of 60 m. Wallace and Hawkins (1994) studied the application of geostatistics to evaluate soil and nematode data from 200 soil samples collected from the A_p horizon of a canary-grass field in north Minnesota. They observed that the soil and nematode data followed a spherical semivariogram model, with low random variability associated with soil data and great variability associated with nematode data.

Most geostatistical studies conducted in crops simply apply kriging to obtain maps of agronomic or biological variables, such as crop production and parasite distribution. All types of kriging lead to smooth maps. A drawback of kriging is that it does not capture extreme values, and that makes the method inappropriate whenever extreme values are critical. For example, if the number of nematodes exceeds a certain threshold, the crop is considered highly infested and the field must be abandoned (Gómez-Hernández and Journel, 1993). It may be more appropriate to assess the data using a conditional simulation framework to reproduce the spatial variability of the entity of interest. It is necessary to simulate large numbers of replications so that the variable of interest can be subject to statistical analysis (Monte Carlo method). This was the framework for our study.

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Nematicides are expensive and highly toxic to humans. Therefore, applying nematicides to entire fields is economically and environmentally unacceptable. The techniques of Precision Farming allow nematicide application only to certain areas, selected after detailed sampling and analysis.

Here, we propose a methodology developed for selecting crop areas where nematicides need to be applied and for quantifying the economic risk of using nematicides only in those areas. The economic risk can then be compared with the cost of nematicides to develop an optimal strategy using Precision Farming. The approach consists of two parts: (i) a survey in a cotton-producing field where *R. reniformis* has been detected, and (ii) a geostatistical analysis of nematode spread in that field.

Materials and Methods

Field location, nematode sampling, and extraction: The experimental field, a long-term monocultivated cotton area infested with *R. reniformis,* was near the city of Jaboticabal, Sao Paulo State, Brazil (21°15′ S; 48°18′ W). The soil is a dusky (Oxisolo) Latossol. The field, 48 × 32 m, was divided in a regular sampling pattern of 6 × 4-m grids resulting in a total of 64 sampling points. Soil samples (300 cm^3) were collected 25 to 30 cm deep with a 7.6-cm bucket-type auger, one at each sampling point. Samples were collected twice, to establish both the nematode initial population (Pi) just after crop germination and the final population (Pf) at harvest. Nematodes were extracted by centrifugal flotation (Jenkins, 1964).

Damage threshold level: Starr and Page (1990) considered that a population level of 100 *R. reniformis* per 100 g of soil causes serious damage to cotton. One count of reniform nematodes above this threshold is enough to consider control with nematicides or by crop rotation. We have adopted a conservative threshold equal to 250 nematodes per 300 cm^3 soil (safety threshold).

Semivariogram: The spatial dependence between neighboring samples/counts was measured with the semivariance (Vieira et al., 1983), estimated by:

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

where *N(h)* is the total number of pairs of nematode counts separated by a distance *h*. The graph of $\gamma^*(h)$ vs. the corresponding values of *h,* called a semivariogram, is a function of the distance *h* and, therefore, depends on distance magnitude and direction. A mathematical equation is fit to the semivariogram to express the spatial dependence among samples to allow estimation of values for unsampled locations. For properties that are spatially dependent, the increment $[Z(x_i)\text{-}Z(x_i\text{+}h)]$ is expected to increase with distance, up to some distance beyond which it stabilizes at a *still* value, symbolized as *C,* and is numerically almost equal to the variance of the data. This distance is called the *range* (*a*) and represents the radius of a circle within which the observations are correlated. The semivariance value at the intercept to the γ^* (*h*) axis is called *nugget effect* (C_0) and represents the variability at distances smaller than the minimum sampling distance.

Kriging: Often, one may be interested in going beyond modeling the spatial structure, such as when values for unsampled locations must be estimated to build a detailed, precise map of the variable under study. In this case, it is necessary to interpolate between the sampled points. An estimation, z*, is made for any location, as linear combination of the neighboring measured values (x_0), as:

$$z^*(x_0) = \sum_{i=1}^{N}\lambda_i\, z(x_i)$$

where N is the number of measured values $z(x_i)$ involved in the estimation and λ_i are the weights associated with each measured value. If the spatial correlation expressed through the semivariogram is used to define the weights, λ_i, then the estimation process is called kriging. This estimation is unbiased and has minimum variance (Deutsch and Journel, 1992).

Conditional simulation: Some of the simulation processes correspond to the so-called conditional simulation processes (Gómez-Hernández and Journel, 1993). A conditional simulation process can be produced using kriging, because of its exact estimation property and the fact that kriging estimation inaccuracy is orthogonal to the estimated values (Journel and Huijbregts, 1978). The conditionally estimated values $Z_{sc}(x)$ can be obtained by:

$$Z_{sc}(x) = Z^*(x) + [Z_s(x) - Z_s^*(x)]$$

where $Z^*(x)$ is the estimated value in x obtained by kriging, $Z_s(x)$ is the simulated value (without conditional processing), and $Z_s^*(x)$ is the kriging estimated value taking into account the simulated values in the sampling points. The expression above can be written as:

$$Z_{SC}(x) = Z^*(x) + e_{SC}(x)$$

where $e_{SC}(x)$ represents the kriging inaccuracy of the simulated values Z_S without conditional processing. Taking into account the original data $Z^*(x)$, the kriging values are obtained by:

$$Z(x) = Z^*(x) + e_K(x)$$

Because the kriging value is estimated, it can be assumed that $E[e_{SC}(x)] = E[e_K(x)] = 0$. The $Z_{sc}(x)$ covariance has the same value of $Z(x)$ covariance because the kriging inaccuracies $e(x) = [Z(x) - Z^*(x)]$ and $e_{SC}(x) = [Z_S(x) - Z_{s*}^*(x)]$ have the same covariance and $e(x)$ and $Z^*(x)$ are orthogonal.

In kriging it is assumed that:

$$Z_S(x_i) = Z_{S*}(x_i) \text{ and } Z(x_i) = Z^*(x_i)$$

with $Z_{SC}(x_i) = Z(x_i)$ for all i. Therefore, a simulation process that keeps the covariance structure of Z and coincides with the observations is chosen and, consequently, Z_{SC} is accepted as the conditionally simulated process of Z.

Results and Discussion

Geostatistical analysis: The best-fit variogram corresponding to the initial population of the nematode (Pi) was obtained with an isotropic spherical model, with a Sill of 9,100 and an effective range of 8.5 m (Fig. 1). Caswell and Chellemi (1986), Chen and Bird (1992), Wallace and Hawkins (1994), and Webster and Boag (1992) also fitted spherical models to their semivariogram. Caswell and Chellemi (1986) reported an effective range of 10 m in a *R. reniformis*-infested pineapple field in Hawaii.

Kriging and conditional simulations: The cotton field distribution of *R. reniformis* was plotted by Ordinary Kriging in a 0.5 × 0.5-m mesh (Fig. 2A). The areas where the damage threshold was exceeded correspond to zones surrounding the only three sampling points where counts exceeded the threshold.

In a simulation approach, we performed 100 conditional simulations of the number of nematodes in a 0.5 × 0.5-m mesh. At each point in the mesh we drew the *ccdf* (conditional cumulative distribution function). If we selected a probability value P*, for any given point we read the nematode value corresponding to P* directly from the *ccdf*. As an example, we fixed P*=50%; then, at any point the median value from 100 repetitions was selected (Fig. 2B).

Figures 2A and 2B are similar, showing that the kriging map is representative of the nematode numbers at any point, although there is a 50% chance of the estimate being exceeded at a particular point. This may be a risky situation relative to the damage threshold. The same methodology was applied with other P* values (Fig. 3). Increasing P* lead to larger areas where the threshold was exceeded (Fig. 3A-F). By applying nematicides to this increasing area, the probability of not applying nematicide to an infested area is reduced, while at the same time application of nematicide to an uninfested area is increased. Thus, the more we reduce the risk of not treating an area that exceeds the threshold, the higher the cost of nematicide. Notice that with increasing P* we can find nematodes above the threshold in many different areas (initially, in the kriged map we could observe only three areas).

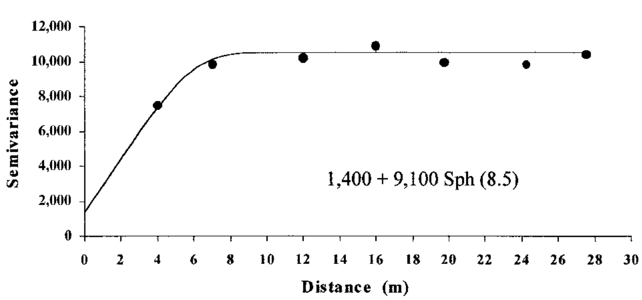

Fig. 1. Raw semivariogram and best fit for the initial population (Pi) of *Rotylenchulus reniformis.*

Maps from Figure 3 were used to develop the first part of the risk-benefit study. For this purpose, the percent area where the variable exceeded the safety threshold versus P* was plotted (Fig. 4), and a continuously increasing relationship was observed.

To complete the risk-benefit analysis, additional information about the price of nematicides and some empirical relationship between presence of nematodes and reduction in crop yield is required. At this stage, these terms cannot be quantified. Nevertheless, Figure 4 can be employed to develop this concept. At the 80% risk level (P*=0.80), the infested area was only 6.3%, which can be integrated perfectly in a nematode control strategy designed under the Precision Farming context. Note that the infested area above the threshold quickly increased to 16.8% for P*=0.95, which is probably a highly conservative value. These results show the economic importance of using geostatistical methods in risk analyses.

The final population: To complete the picture, results for the final population of nematodes in the field under study are presented. Initially, the area was infested in at least three points. In spite of this, cotton was cultivated and the nematode spread considerably. Both the mean and variance of the final population clearly reflected the increase. The variogram corresponding to the final population of *R. reniformis* presented a nugget C_0=130,000 and a total Sill S=490,000 (Fig. 5).

The final spatial distribution of the nematode (Fig. 6) corresponds to the map obtained by ordinary point kriging. In this map, an increase in aggregation (also found in the increase in the variogram range) and strong anisotropy were observed. An increase in the nematode population near the y axis following the direction of the contour levels is demonstrated (Fig. 6). This was probably due to soil tillage that spread the nematode in the field.

Geostatistics are useful in the study of the spatial distribution of *R. reniformis* on cotton. Because the reniform nematode significantly reduces cotton production whenever it exceeds a certain threshold level, management decisions may benefit from use of the conditional simulation framework. The *ccdf* probability of the nematode number exceeding a certain safety threshold can be used to define and demark risk for areas in a field. Where the threshold is exceeded, nematode infestations can expand to larger areas in the crop, as was observed here for the final population.

The proposed methodology requires further devel-

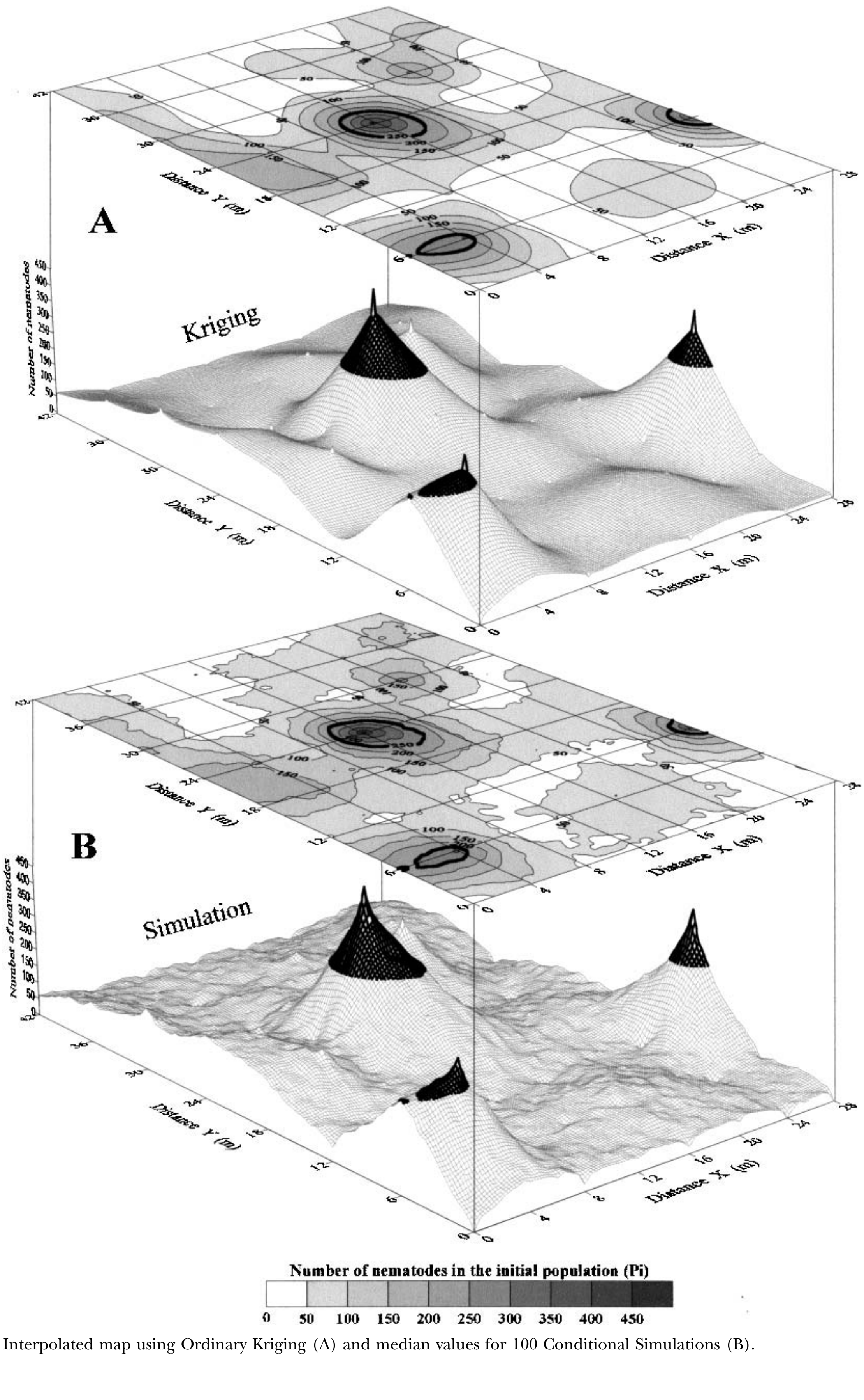

FIG. 2. Interpolated map using Ordinary Kriging (A) and median values for 100 Conditional Simulations (B).

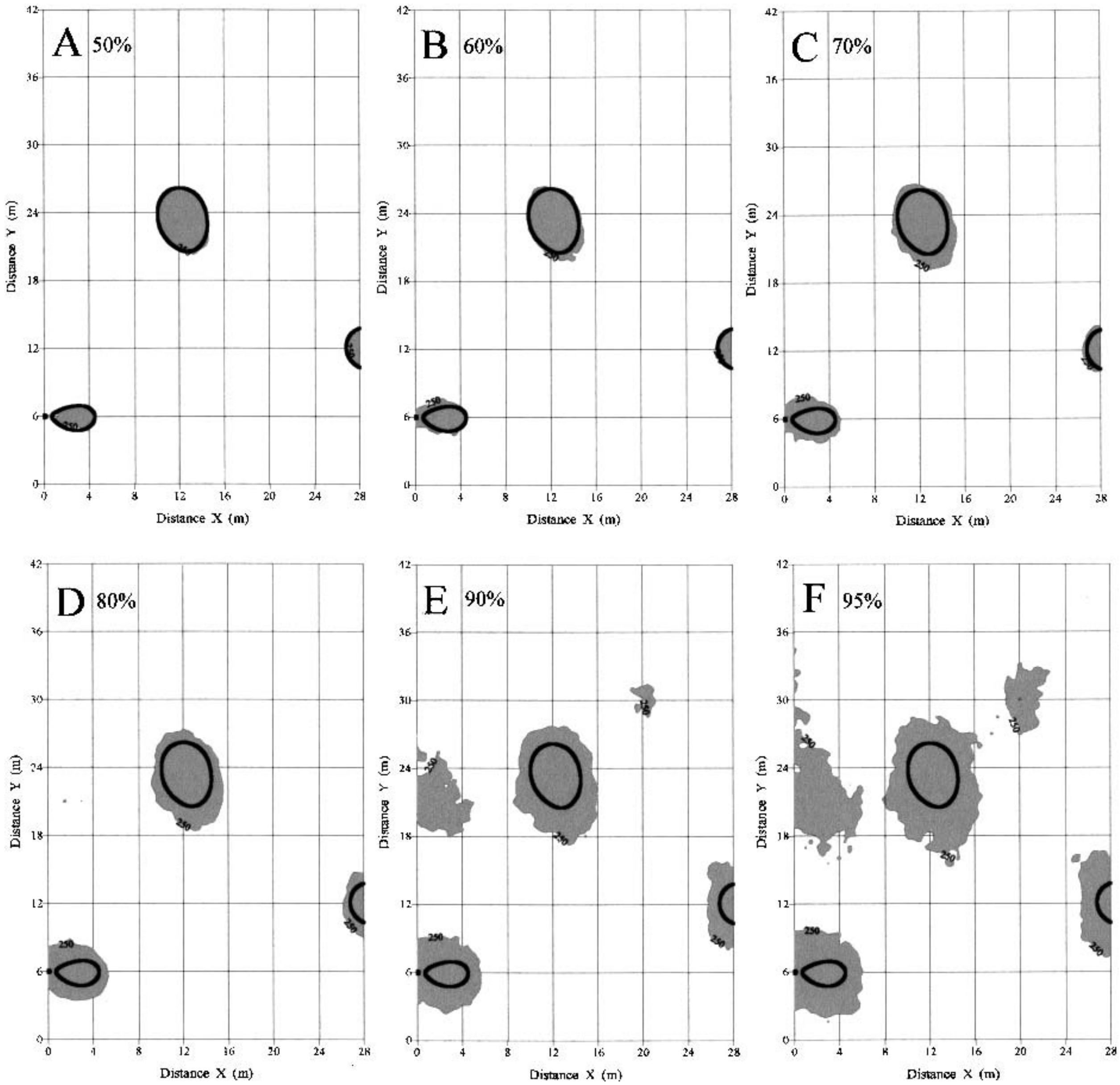

FIG. 3. Plots of zones where, for a probability value P*, the corresponding value from the *ccdf* exceeds the predefined safety threshold (250 nematodes/300 cm^3 of soil). The zones where the threshold is exceeded in the kriging map are marked for comparison purposes.

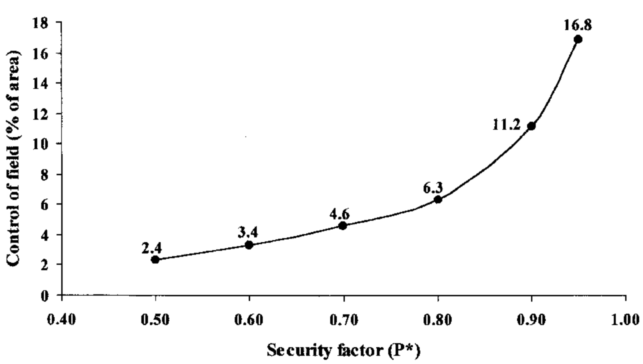

FIG. 4. The percent area where the number of nematodes per volume of soil exceeds the safety threshold vs. probability value P*.

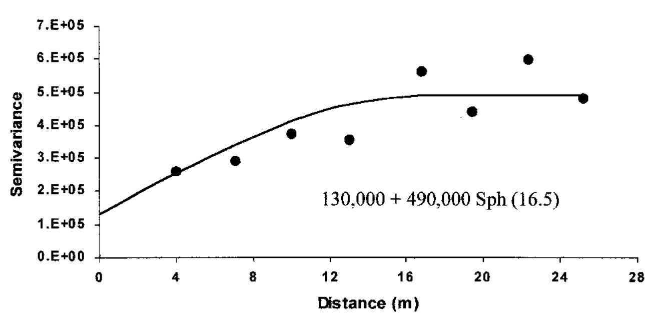

FIG. 5. Semivariogram of the final population (Pf) of *Rotylenchulus reniformis.*

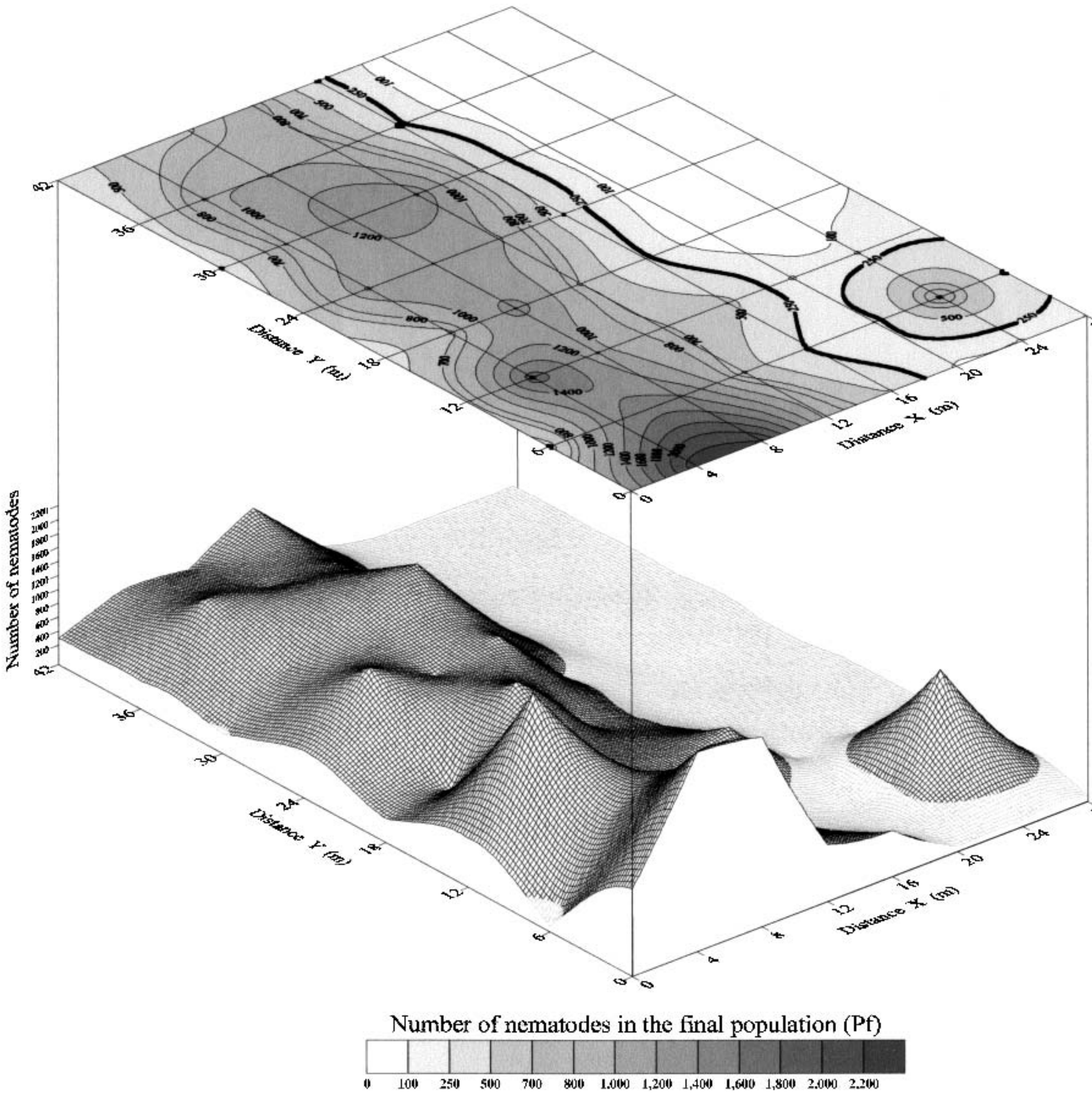

FIG. 6. Kriging map for the final population (Pf) of *Rotylenchulus reniformis.*

opment and testing on a larger field scale. A detailed analysis using a non-regular sampling pattern should be performed to obtain a better estimation of the nugget effect because large nugget values would reflect a high degree of uncertainty, possibly compromising the methodology.

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