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CROP PROTECTION

Semivariogram models for rice stem bug population densities estimated by ordinary kriging

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ABSTRACT. *Tibraca limbativentris* is considered one of the main species of insect pests in irrigated rice. This species can be found in plants in the vegetative and reproductive stages. This study aimed to select semivariogram models to estimate rice stem bug population densities by ordinary kriging. Two fields were used to survey the *T. limbativentris* population in *Oryza sativa*. A grid of 30 x 30 m was drawn, which generated 143 and 385 sample units for the first and second fields, respectively. Seven evaluations of two hundred plants per sampling unit were performed during cultivation. From the insect counts, the results were input into circular, spherical, pentaspherical, exponential, Gaussian, rational quadratic, cardinal sine, K-Bessel, J-Bessel, and stable semivariogram models via ordinary kriging interpolation and the best model was selected via cross-validation. Each assessment had a particular spatial structure and semivariogram model that best fit the experimental data.

Key words: *Oryza sativa*; *Tibraca limbativentris*; interpolators; geostatistics; spatial variability.

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Introduction

Tibraca limbativentris (Hemiptera: Pentatomidae) is considered one of the main species of insect pests in irrigated rice (Pazini, Botta, & Silva, 2012; Rampelotti et al., 2008; Silva, Lima, & Oliveira, 2010; Sociedade Sul-Brasileira de Arroz Irrigado [SOSBAI], 2014). This species can be found in vegetative and reproductive stages directly affecting yield components and causing symptoms of dead heart when they attack the stems, causing the formation of white panicles or partial spikelet sterility, which is the most influential component in income reduction in rice grains yield (Costa & Link, 1992; Souza et al., 2009).

According to Lasmar, Zanetti, Santos, and Fernandes (2012), the spatial distribution insects can vary with time, which interferes with pest management measures. The insect populations in growing areas can be estimated by interpolation procedures, which can generate continuous surfaces through spot-sampling units (Webster & Oliver, 2007). Ordinary kriging is one such interpolation method, as reported by Bottega, Queiroz, Pinto, and Souza (2013) and Silva et al. (2010).

Kriging uses the spatial dependence between neighboring samples, expressed in a semivariogram, to estimate values at any position within the experimental area with no tendency and minimum variance (Webster & Oliver, 2007; Coelho, Souza, Uribe-Opazo, & Pinheiro Neto, 2009; Silva et al., 2010; Souza, Lima, Xavier, & Rocha, 2010; Dinardo-Miranda, Fracasso, & Perecin, 2011). The semivariogram is the central part of geostatistics, capable of qualitatively and quantitatively describing the spatial dependence structure and is the key point in the determination of the interpolator. According to Webster and Oliver (2007), selecting a model that adequately represents the semivariances is highly desirable in the kriging process and influences the prediction of unknown values.

According to Gundogdu and Guney (2007) and Pasini, Lúcio, and Cargnelutti Filho (2014), every dataset has a different spatial structure; therefore, it is necessary to identify the semivariogram model that best fits the data, providing reliable results and with reduced error estimates.

For this purpose, Gundogdu and Guney (2007) studied groundwater levels and tested circular, spherical, pentaspherical, exponential, Gaussian, rational quadratic, cardinal sine, K-Bessel, J-Bessel and stable models and achieved the best with the rational quadratic model. Farias et al. (2008) studied the spatial distribution of *Spodoptera frugiperda,* and the best fit was obtained with the spherical model. Lasmar, Zanetti, Santos, and Fernandes (2012) determined the spatial distribution of leafcutter ants in eucalyptus plantations following the format of spherical, exponential and Gaussian semivariograms, achieving the best fit with the exponential model. Using geostatistics to describe the distribution of *T. limbativentris*, Pazini et al. (2015) achieved the best results with Gaussian and exponential models.

Thus, the study aimed to select semivariogram models to estimate the population density of the rice stem bug by ordinary kriging.

Material and methods

The study was carried out in Santa Maria, Rio Grande do Sul State, Brazil (UTM, E 785672 m, N 6720053 m, 21 J), subdivided into two fields of 4.91 and 14.1 ha. According to Köppen climate classification, the local climate is a Cfa climate: humid subtropical without dry seasons and hot summers (Heldwein, Buriol, & Streck, 2009). There was application of pesticides during the research period.

For each crop, a grid of 30 x 30 m was defined, which led to 143 sampling units for Field 1 (F1) and 385 sampling units for Field 2 (F2). The fields were evaluated for each 1 m^2, which had 200 rice plants. There was a direct count of *T. limbativentris* individuals in each plant, using the number of insects per m^2 (200 plants) for data analysis.

After cultivation, there were seven assessments in both fields. The first assessment (E1) was implemented in the V3 growth stage, the second assessment (E2) was in the V6 growth stage, the third evaluation (E3) was in the V9 growth stage, the fourth assessment (E4) was in the R0 stage, the fifth assessment (E5) was in the R4 stage, the sixth assessment (E6) was in the R6 stage and the seventh evaluation (E7) was in the R9 stage (Counce, Keisling, & Mitchel, 2000).

Then, the data were geostatistically analyzed and were plotted as a box plot to verify the existence of spatial dependence and, if so, quantify the degree of attributes under study, departing from the adjustment of the models to the isotropic experimental semivariograms estimated by the expression: $\gamma(h) = \frac{1}{2N(h)}\sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2$, which is the semivariance; *N(h)* is the number of measured pairs, and the $Z(x_i)$ and $Z(x_i+h)$ values are separated by a vector h (Webster & Oliver, 2007).

Eleven semivariogram theoretical models were adjusted: circular, spherical, tetrasherical, pentaspherical, exponential, Gaussian, rational quadratic, hole effect, K-Bessel, Bessel, stable; the models were estimated according to the methodology proposed by Johnson, Ver Hoef, Krivoruchko, and Lucas (2001) and utilized by Pasini et al. (2014). Once the presence of spatial dependence was confirmed, inferences were performed by ordinary kriging (OK), following the method of Johnston et al. (2001), and values at locations that were not measured were estimate.

To verify the existence of spatial dependence, the spatial dependence index (SDI) was applied, which is a ratio representing the percentage of data variability explained by spatial dependence. The SDI is estimated with the expression $SDI = [C1/(C0 + C1)]100$. The spatial dependence can be classified as strong (SDI > 75%), medium (25 < SDI ⩽ 75%), and low (SDI ⩽ 25%).

For the selection of the semivariogram model, the Pasini, Lúcio, and Cargnelutti Filho (2014) cross-validation technique was used. According to Webster and Oliver (2007), cross-validation allows the comparison of the impact of interpolators among the estimated values, where the model with more accurate predictions is chosen.

The indicators utilized by cross-validation were based on the methodology of Pasini et al. (2014). As a first indicator of cross-validation, linear regression was used, where the estimated values (dependent variable) were regressed with the sampled values (independent variable). From the expression, the intersect "a" was obtained, the angular coefficient "b" and the coefficient of determination "R^2". The best adjustment for the relation sampled and estimated values are obtained when the estimation of "a" approaches zero and "b" and "R^2" approach 1.

The following metrics were used as indicators: the mean prediction errors ($\bar{E}$), the standard deviation of the prediction errors (*SD*), the variation coefficient (*VC*), and the mean absolute error ($\bar{E}\bar{A}$). The closer these values are to zero, the better the model. In addition, the root-mean-square prediction error (*RMS*) and the root-mean-square standardized prediction errors (*RMSS*) were calculated. The best adjusted model is indicated when $\bar{E}$, *SD*, *VC*, $\bar{E}\bar{A}$, and *RMS* are close to zero and *RMSS* is close to 1.

From the estimated indicators, cross-validation grades, which range from 1 to 10, were assigned according to the selected criterion of each indicator: for b, R^2 and *RMSS,* a value closer to 1 was assigned a grade of 10, and the value farthest from 1 was assigned a grade of 1. For $\bar{E}$, *SD*, *VC*, $\bar{E}\bar{A}$, and *RMS,* a value close to zero or equal to zero was assigned a grade of 10, and the value the farthest from zero was assigned a grade of 1. After grading, the sum of the grades within each model was adjusted, and the situation was evaluated adopting the criterion of choice of the model with the highest sum of the grades.

Results and discussion

While monitoring 13,806 adults, *T. limbativentris* was found to correspond to an average adult of 3.61 m^{-2} $field^{-1}$ $evaluation^{-1}$. In F2, the highest number of adults was recorded, 10,454; however, the average number of adults per sample was 3.87 m^{-2} $evaluation^{-2}$ $adult^{-1}$, which was greater than the average value found in the crop, which was in F1 (3.35 m^{-2} $evaluation^{-2}$ $adult^{-1}$). The observed data distribution is presented in a box plot (Figure 1).

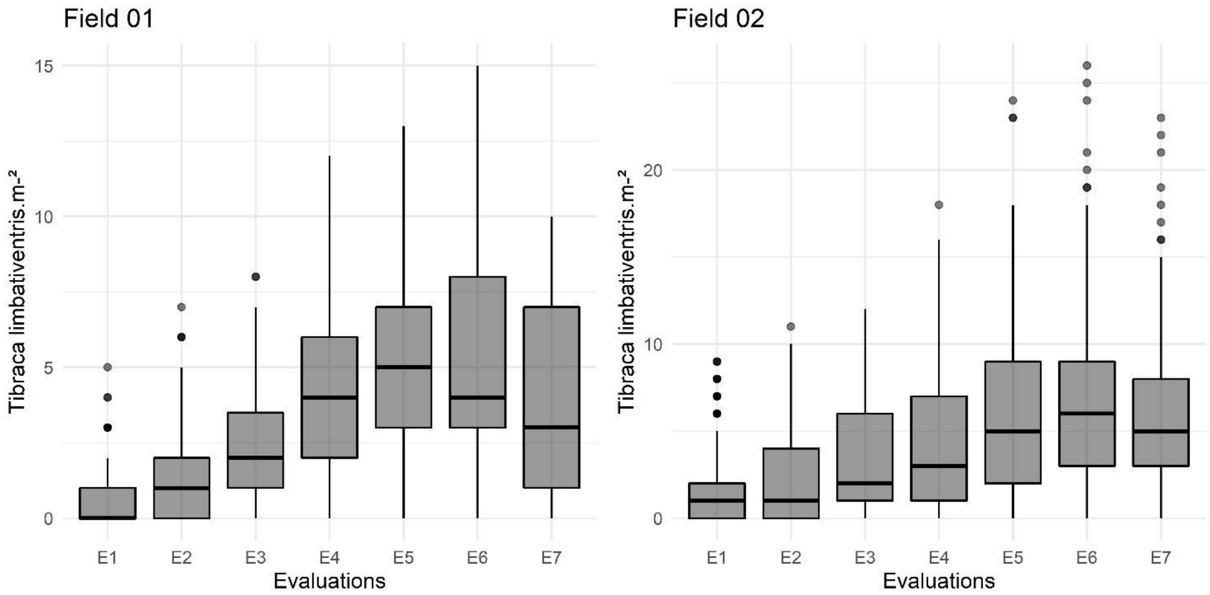

Figure 1. Box plot of the *Tibraca limbativentris* (Hemiptera: Pentatomidae) sampled per square meter in different evaluations. Santa Maria, Rio Grande do Sul State, Brazil.

This behavior of the data distribution is linked to the spread of *T. limbativentris* in tilled fields and its concentration in areas near the borders of crops, mainly in larger fields. According to Yamamoto and Landim (2013), when the distribution is positively skewed, it is necessity to transform the data during processing to avoid the influence of few high outlier on the estimates in areas characterized by low values. However, for normally distributed or symmetrical data, there is no need for data transformation. Given the above consideration, data transformation was needed.

Tables 1 and 2 present the estimates of cross-validation from the OK and their significance. From the criterion of choice, 42 semivariogram models were selected in which most of these models with a greater sum did not achieve the highest score for all indicators, revealing a discrepancy between the estimated values, which underscores the importance of using a larger number indicators for decision making (Pasini et al., 2014). Thus, there is the possibility of a better fit of the theoretical models to the experimental semivariogram, a better representation of spatial variability and estimates with minor errors (Webster & Oliver, 2007).

In Field 1, the pentaspherical model showed a higher sum of notes between the models for evaluation A1; the circular model for evaluations A2 and A4, the tetrasherical model for evaluation A3, the Gaussian model for evaluations A5 and A7 and the K-Bessel model for evaluation A7 were the optimal models (Table 3). In Field 2, the circular model for evaluations A1 and A4, the tetrasherical model for evaluation A2, the pentaspherical model for evaluation A3, the K-Bessel model for evaluation A4, the stable model for evaluations A6 and A7 were identified as the optimal models (Table 3). In crops and ratings, there was a selection of different semivariogram models, agreeing with the hypothesis of Gundogdu and Guney (2007) and Pasini, Lúcio, and Cargnelutti Filho (2014); each dataset has a different spatial structure requiring the definition of different semivariogram models to find the best fit for the data.

Table 1. Cross-validation indicators and grades attributed (in brackets), in the Field 1 evaluation, obtained from ordinary kriging, for the following semivariogram models: circular (C), spherical (S), tetraspherical(T), pentaspherical(P),exponential (E), Gaussian (G), rational quadratic (R), hole effect (H), K-Bessel (K), J-Bessel (J); and stable (St).

Indicator	C	S	T	P	E	G	R	H	K	J	St
						Evaluation 1					
a	0.768(7)	0.758(4)	0.758(4)	0.758(4)	0.746(3)	0.804(10)	0.816(11)	0.684(1)	0.726(2)	0.796(9)	0.795(8)
b	0.163(7)	0.184(3)	0.184(3)	0.184(3)	0.191(2)	0.122(9)	0.129(8)	0.166(6)	0.202(1)	0.120(11)	0.122(9)
R^2	0.732(7)	0.739(11)	0.739(11)	0.739(11)	0.735(8)	0.595(4)	0.624(5)	0.359(1)	0.727(6)	0.550(3)	0.534(2)
$\bar{E}$	-0.022(5)	-0.009(10)	-0.009(10)	-0.003(11)	-0.011(8)	-0.034(3)	-0.017(6)	-0.086(1)	-0.017(7)	-0.042(2)	-0.041(3)
$\bar{A}\bar{E}$	0.363(6)	0.347(7)	0.347(7)	0.347(7)	0.346(11)	0.432(2)	0.428(5)	0.582(1)	0.346(11)	0.450(4)	0.458(3)
SD	0.563(7)	0.555(11)	0.555(11)	0.555(11)	0.558(8)	0.750(4)	0.715(5)	1.049(1)	0.566(6)	0.812(3)	0.836(2)
RMS	0.562(7)	0.553(11)	0.553(11)	0.553(11)	0.557(8)	0.748(4)	0.713(5)	1.049(1)	0.565(6)	0.811(3)	0.834(2)
$RMSS$	1.266(9)	1.284(7)	1.289(6)	1.277(8)	1.059(10)	11.943(4)	9.620(5)	13.256(3)	0.984(11)	60.219(1)	33.369(2)
Σ	55	64	63	65	58	36	50	15	50	36	31
						Evaluation 2					
a	0.721(7)	0.721(7)	0.721(7)	0.720(6)	0.668(1)	0.745(10)	0.750(11)	0.705(2)	0.718(5)	0.713(3)	0.714(4)
b	0.373(2)	0.373(2)	0.372(4)	0.372(4)	0.413(1)	0.284(10)	0.294(9)	0.281(11)	0.368(6)	0.299(8)	0.358(7)
R^2	0.662(9)	0.662(9)	0.661(7)	0.661(7)	0.667(11)	0.511(3)	0.542(4)	0.431(1)	0.659(6)	0.470(2)	0.653(5)
$\bar{E}$	-0.001(11)	-0.002(10)	-0.003(8)	-0.003(8)	-0.033(5)	-0.059(3)	-0.042(4)	-0.115(1)	-0.011(7)	-0.086(2)	-0.026(6)
$\bar{A}\bar{E}$	0.521(10)	0.522(7)	0.522(7)	0.522(7)	0.512(11)	0.697(2)	0.664(4)	0.733(1)	0.525(6)	0.676(3)	0.533(5)
SD	0.877(9)	0.877(9)	0.878(7)	0.878(7)	0.864(11)	1.155(3)	1.097(4)	1.292(1)	0.881(6)	1.212(2)	0.889(5)
RMS	0.874(9)	0.874(9)	0.875(7)	0.875(7)	0.862(11)	1.153(3)	1.094(4)	1.292(1)	0.878(6)	1.211(2)	0.887(5)
$RMSS$	1.508(6)	1.511(5)	1.472(7)	1.469(8)	0.931(11)	7.458(3)	4.392(4)	8.956(2)	1.264(9)	11.256(1)	1.090(10)
Σ	63	59	54	54	62	37	44	22	51	23	47
						Evaluation 3					
a	0.828(8)	0.817(6)	0.813(5)	0.809(2)	0.812(3)	0.839(9)	0.812(3)	0.874(10)	0.791(1)	0.823(7)	0.895(11)
b	0.415(8)	0.427(6)	0.435(3)	0.432(4)	0.443(2)	0.401(9)	0.432(4)	0.183(11)	0.484(1)	0.420(7)	0.238(10)
R^2	0.827(8)	0.829(11)	0.829(11)	0.827(8)	0.823(6)	0.815(3)	0.821(5)	0.675(1)	0.823(6)	0.820(4)	0.789(2)
$\bar{E}$	-0.004(11)	-0.021(6)	-0.023(5)	-0.035(2)	-0.017(8)	0.008(10)	-0.027(3)	-0.123(1)	-0.025(4)	-0.011(9)	-0.018(7)
$\bar{A}\bar{E}$	0.585(8)	0.579(11)	0.579(11)	0.582(9)	0.587(7)	0.614(3)	0.594(6)	0.852(1)	0.597(5)	0.607(4)	0.682(2)
SD	0.801(8)	0.797(11)	0.797(11)	0.801(8)	0.812(7)	0.829(4)	0.815(4)	1.194(1)	0.813(5)	0.817(3)	0.916(2)
RMS	0.798(9)	0.794(11)	0.794(11)	0.799(8)	0.809(7)	0.827(3)	0.813(5)	1.197(1)	0.810(6)	0.814(4)	0.913(2)
$RMSS$	1.010(11)	0.869(8)	0.832(6)	0.814(5)	0.727(3)	1.079(10)	0.744(4)	2.569(1)	0.873(9)	0.857(7)	1.751(2)
Σ	62	70	63	46	43	51	34	27	37	45	38
						Evaluation 4					
a	0.806(2)	0.806(2)	0.806(2)	0.806(2)	0.797(1)	0.845(8)	0.841(7)	0.876(11)	0.838(6)	0.849(9)	0.850(10)
b	0.813(2)	0.813(2)	0.812(4)	0.812(4)	0.843(1)	0.593(8)	0.597(7)	0.517(11)	0.606(6)	0.585(9)	0.582(10)
R^2	0.788(11)	0.788(11)	0.788(11)	0.788(11)	0.785(7)	0.618(2)	0.661(6)	0.580(1)	0.627(5)	0.618(2)	0.621(4)
$\bar{E}$	-0.015(10)	-0.016(8)	-0.016(8)	-0.017(7)	-0.023(6)	-0.068(3)	-0.084(1)	-0.011(11)	-0.084(1)	-0.059(4)	-0.056(5)
$\bar{A}\bar{E}$	0.919(11)	0.919(11)	0.919(11)	0.920(8)	0.923(7)	1.287(4)	1.206(6)	1.479(1)	1.260(5)	1.298(2)	1.288(3)
SD	1.312(11)	1.312(11)	1.313(9)	1.313(9)	1.320(7)	1.943(3)	1.773(6)	2.153(1)	1.897(5)	1.950(2)	1.941(4)
RMS	1.307(11)	1.308(9)	1.308(9)	1.309(8)	1.315(7)	1.937(3)	1.769(6)	2.146(1)	1.892(5)	1.945(2)	1.935(4)
$RMSS$	1.253(7)	1.230(8)	1.212(9)	1.181(10)	0.960(11)	13.568(5)	8.401(6)	15.236(4)	37.935(1)	18.756(3)	24.369(2)
Σ	65	62	63	59	47	36	45	41	34	33	42
						Evaluation 5					
a	0.840(2)	0.821(1)	0.851(6)	0.850(5)	0.840(2)	0.920(9)	0.929(10)	1.012(11)	0.885(8)	0.841(4)	0.882(7)
b	0.817(2)	0.897(1)	0.768(6)	0.768(5)	0.815(3)	0.374(9)	0.312(10)	0.035(11)	0.539(8)	0.796(4)	0.557(7)
R^2	0.888(8)	0.877(5)	0.865(3)	0.865(3)	0.864(2)	0.890(10)	0.895(11)	0.777(1)	0.887(7)	0.880(6)	0.888(8)
$\bar{E}$	-0.011(9)	-0.027(6)	-0.004(11)	-0.005(10)	-0.014(8)	-0.039(5)	-0.052(4)	0.099(1)	-0.057(3)	-0.027(7)	-0.053(2)
$\bar{A}\bar{E}$	0.833(7)	0.885(5)	0.920(3)	0.920(3)	0.927(2)	0.803(11)	0.814(9)	1.238(1)	0.817(8)	0.856(6)	0.811(10)
SD	1.098(7)	1.154(5)	1.193(4)	1.194(3)	1.203(2)	1.081(10)	1.057(11)	1.761(1)	1.092(8)	1.133(6)	1.087(9)
RMS	1.095(7)	1.150(5)	1.189(4)	1.190(3)	1.199(2)	1.078(10)	1.055(11)	1.758(1)	1.090(8)	1.129(6)	1.084(9)
$RMSS$	0.704(5)	0.681(4)	0.944(10)	0.933(9)	0.760(6)	1.114(7)	1.592(2)	5.124(1)	0.963(11)	0.669(3)	0.907(8)
Σ	47	32	47	41	27	71	68	28	61	42	60
						Evaluation 6					
a	0.869(7)	0.840(1)	0.866(6)	0.865(5)	0.860(4)	0.894(9)	0.854(3)	0.909(11)	0.877(8)	0.822(2)	0.904(10)
b	0.683(8)	0.855(2)	0.728(6)	0.731(5)	0.769(3)	0.586(9)	0.769(3)	0.493(10)	0.683(7)	0.927(1)	0.491(11)
R^2	0.868(4)	0.882(10)	0.874(7)	0.874(7)	0.874(6)	0.866(3)	0.874(9)	0.762(1)	0.884(11)	0.872(5)	0.849(2)
$\bar{E}$	-0.034(2)	-0.022(5)	-0.008(7)	-0.008(7)	0.000(11)	0.007(9)	-0.030(4)	-0.006(10)	0.010(6)	-0.048(1)	-0.034(2)
$\bar{A}\bar{E}$	1.038(4)	0.982(11)	1.019(8)	1.018(7)	1.020(6)	1.066(3)	1.007(9)	1.396(1)	0.991(10)	1.022(5)	1.113(2)
SD	1.356(4)	1.297(10)	1.329(8)	1.329(7)	1.330(6)	1.371(3)	1.327(9)	1.931(1)	1.271(11)	1.352(5)	1.468(2)
RMS	1.352(4)	1.292(10)	1.324(7)	1.324(7)	1.326(6)	1.366(3)	1.322(9)	1.924(1)	1.266(11)	1.348(5)	1.463(2)
$RMSS$	0.897(11)	0.705(5)	0.769(8)	0.747(7)	0.742(6)	1.139(10)	0.658(2)	5.333(1)	0.808(9)	0.663(3)	1.331(4)
Σ	44	54	57	52	48	49	48	36	73	26	35

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a	0.847(1)	0.852(4)	0.859(5)	0.859(5)	0.851(2)	0.917(7)	0.928(11)	0.925(9)	0.926(10)	0.851(2)	0.919(8)
b	0.589(1)	0.545(6)	0.554(4)	0.554(4)	0.578(2)	0.291(8)	0.252(10)	0.343(7)	0.242(11)	0.559(3)	0.264(9)
R^2	0.868(9)	0.865(7)	0.864(4)	0.864(4)	0.863(3)	0.872(11)	0.872(11)	0.756(1)	0.864(4)	0.866(8)	0.858(2)
$\bar{E}$	-0.014(8)	-0.041(4)	-0.003(11)	-0.004(10)	-0.011(9)	-0.038(5)	-0.033(6)	0.045(3)	-0.049(2)	-0.030(7)	-0.055(1)
$\bar{A}\bar{E}$	0.826(8)	0.837(7)	0.869(4)	0.869(4)	0.872(3)	0.813(10)	0.822(9)	1.104(1)	0.848(6)	0.802(11)	0.873(2)
SD	1.054(9)	1.062(7)	1.066(6)	1.067(5)	1.071(4)	1.045(11)	1.048(10)	1.533(1)	1.083(3)	1.059(8)	1.107(2)
RMS	1.050(9)	1.059(7)	1.063(5)	1.063(5)	1.068(4)	1.042(11)	1.045(10)	1.529(1)	1.080(3)	1.056(8)	1.105(2)
RMSS	0.821(8)	0.764(6)	0.974(11)	0.952(10)	0.772(7)	1.132(9)	1.864(2)	3.857(1)	1.812(4)	0.728(5)	1.850(3)
Σ	53	48	50	47	34	72	69	24	47	52	29

b, angular coefficient; a, intersection; R^2, coefficient of determination; $\bar{E}$, mean prediction errors; SD, standard deviation of prediction errors; $\bar{A}\bar{E}$, mean prediction absolute errors; RMS, root-mean-square prediction errors; RMSS, root-mean-square standardized prediction errors; Σ, summation.

Table 2. Cross-validation indicators and grades attributed (in brackets), in the Field 2 evaluation, obtained from ordinary kriging, for the following semivariogram models circular (C), spherical (S), tetraspherical (T), pentaspherical (P),exponential (E), Gaussian (G), rational quadratic (R), hole effect (H), K-Bessel (K), J-Bessel (J); and stable (St).

Indicator	C	S	T	P	E	G	R	H	K	J	St
	----------------------------------- Evaluation 1 -----------------------------------										
a	0.933(7)	0.938(10)	0.933(7)	0.933(7)	0.929(5)	0.877(3)	0.944(11)	0.921(4)	0.864(1)	0.932(6)	0.866(2)
b	0.041(6)	0.033(11)	0.041(6)	0.041(6)	0.043(4)	0.053(2)	0.033(11)	0.052(3)	0.063(1)	0.043(4)	0.060(5)
R^2	0.939(11)	0.938(7)	0.939(11)	0.939(11)	0.938(7)	0.875(1)	0.930(6)	0.916(4)	0.897(3)	0.919(5)	0.880(2)
$\bar{E}$	-0.001(8)	-0.006(4)	-0.001(8)	-0.001(8)	-0.002(5)	-0.023(2)	-0.002(5)	0.002(5)	-0.022(3)	0.000(11)	-0.024(1)
$\bar{A}\bar{E}$	0.144(11)	0.152(7)	0.144(11)	0.144(11)	0.145(8)	0.209(1)	0.157(6)	0.181(4)	0.190(3)	0.176(5)	0.204(2)
SD	0.280(11)	0.281(7)	0.280(11)	0.280(11)	0.281(7)	0.401(1)	0.300(6)	0.328(4)	0.366(3)	0.324(5)	0.392(2)
RMS	0.279(11)	0.281(7)	0.279(11)	0.279(11)	0.281(7)	0.401(1)	0.300(6)	0.328(4)	0.366(3)	0.323(5)	0.392(2)
RMSS	0.878(11)	0.802(7)	0.868(10)	0.860(9)	0.715(6)	1.506(4)	3.015(1)	2.637(2)	1.197(8)	2.416(3)	1.385(5)
Σ	76	60	75	74	49	15	52	30	25	44	21
	----------------------------------- Evaluation 2 -----------------------------------										
a	0.899(6)	0.898(5)	0.899(6)	0.899(6)	0.895(3)	0.923(11)	0.896(4)	0.882(1)	0.893(2)	0.913(9)	0.923(11)
b	0.223(6)	0.224(5)	0.223(6)	0.223(6)	0.230(2)	0.163(11)	0.229(3)	0.269(1)	0.225(4)	0.198(9)	0.163(11)
R^2	0.900(11)	0.900(11)	0.900(11)	0.900(11)	0.899(7)	0.873(1)	0.892(5)	0.876(3)	0.893(6)	0.882(4)	0.873(1)
$\bar{E}$	-0.009(5)	-0.009(5)	-0.009(5)	-0.009(5)	-0.010(4)	-0.015(2)	-0.009(5)	-0.001(11)	-0.020(1)	-0.001(11)	-0.015(2)
$\bar{A}\bar{E}$	0.528(11)	0.528(11)	0.528(11)	0.528(11)	0.531(7)	0.603(3)	0.557(5)	0.613(1)	0.544(6)	0.573(4)	0.603(2)
SD	0.778(11)	0.778(11)	0.778(11)	0.778(11)	0.782(7)	0.885(1)	0.810(5)	0.865(3)	0.802(6)	0.847(4)	0.885(1)
RMS	0.777(11)	0.777(11)	0.777(11)	0.777(11)	0.781(7)	0.884(1)	0.809(5)	0.863(3)	0.802(6)	0.846(4)	0.884(1)
RMSS	1.109(8)	1.126(7)	1.100(9)	1.089(11)	0.906(10)	6.444(2)	1.652(5)	5.505(4)	1.133(6)	16.628(1)	6.444(2)
Σ	69	66	70	72	47	32	37	27	37	46	31
	----------------------------------- Evaluation 3 -----------------------------------										
a	0.927(4)	0.935(5)	0.922(2)	0.922(2)	0.920(1)	0.930(6)	0.947(9)	0.953(10)	0.939(8)	0.954(11)	0.930(6)
b	0.239(4)	0.209(7)	0.288(2)	0.288(2)	0.291(1)	0.222(6)	0.192(9)	0.183(10)	0.193(8)	0.125(11)	0.222(5)
R^2	0.929(7)	0.927(5)	0.930(11)	0.930(11)	0.930(11)	0.920(2)	0.929(7)	0.927(5)	0.923(4)	0.900(1)	0.920(2)
$\bar{E}$	-0.031(5)	-0.031(5)	-0.001(11)	-0.002(10)	-0.006(8)	-0.039(2)	-0.004(9)	0.009(7)	-0.034(4)	-0.046(1)	-0.039(2)
$\bar{A}\bar{E}$	0.667(6)	0.680(5)	0.662(9)	0.662(9)	0.663(8)	0.695(2)	0.659(11)	0.665(7)	0.685(4)	0.766(1)	0.695(2)
SD	0.926(7)	0.939(6)	0.920(9)	0.919(11)	0.920(9)	0.981(2)	0.925(8)	0.944(5)	0.969(4)	1.117(1)	0.981(2)
RMS	0.926(7)	0.938(6)	0.918(9)	0.918(11)	0.919(9)	0.980(2)	0.924(8)	0.943(5)	0.968(4)	1.117(1)	0.980(2)
RMSS	0.879(8)	0.904(9)	0.918(11)	0.909(10)	0.754(4)	1.152(6)	5.221(3)	5.467(2)	1.241(5)	6.690(1)	1.152(6)
Σ	48	48	64	66	51	28	64	51	41	28	27
	----------------------------------- Evaluation 4 -----------------------------------										
a	0.893(4)	0.901(6)	0.891(1)	0.892(3)	0.890(2)	0.927(8)	0.943(10)	0.932(9)	0.923(7)	0.954(11)	0.898(5)
b	0.487(4)	0.440(6)	0.494(3)	0.498(2)	0.519(1)	0.315(9)	0.261(10)	0.353(7)	0.337(8)	0.192(11)	0.456(5)
R^2	0.909(3)	0.914(9)	0.909(3)	0.909(3)	0.907(1)	0.913(8)	0.912(6)	0.917(11)	0.914(9)	0.902(2)	0.912(6)
$\bar{E}$	-0.015(8)	-0.024(3)	-0.018(7)	-0.009(9)	0.006(10)	-0.025(2)	-0.003(11)	0.036(1)	-0.021(5)	-0.024(3)	-0.020(6)
$\bar{A}\bar{E}$	0.883(5)	0.856(8)	0.885(4)	0.887(3)	0.897(2)	0.842(9)	0.858(7)	0.836(11)	0.839(10)	0.917(1)	0.863(6)
SD	1.219(5)	1.190(9)	1.222(4)	1.224(3)	1.235(2)	1.191(8)	1.210(6)	1.169(11)	1.184(10)	1.282(1)	1.199(7)
RMS	1.218(5)	1.188(9)	1.220(4)	1.222(3)	1.234(2)	1.190(8)	1.208(6)	1.168(11)	1.183(10)	1.280(1)	1.198(7)
RMSS	0.895(8)	0.873(5)	0.876(7)	0.896(9)	0.801(4)	1.036(10)	1.382(3)	2.275(1)	1.005(11)	1.574(2)	0.874(6)
Σ	42	58	33	35	24	62	59	62	70	33	48
	----------------------------------- Evaluation 5 -----------------------------------										
a	0.894(3)	0.901(6)	0.895(4)	0.895(5)	0.893(2)	0.911(8)	0.922(9)	0.888(1)	0.908(7)	0.936(11)	0.929(10)
b	0.605(5)	0.558(6)	0.629(3)	0.629(3)	0.636(2)	0.500(8)	0.457(9)	0.718(1)	0.520(7)	0.353(11)	0.399(10)
R^2	0.905(11)	0.905(11)	0.905(11)	0.905(11)	0.905(11)	0.901(5)	0.899(4)	0.893(3)	0.903(6)	0.884(1)	0.891(2)
$\bar{E}$	-0.018(7)	-0.025(2)	0.012(8)	0.012(8)	0.006(10)	-0.024(4)	-0.005(11)	0.056(1)	-0.022(5)	-0.025(2)	-0.020(6)
$\bar{A}\bar{E}$	1.072(10)	1.067(11)	1.077(7)	1.077(7)	1.078(6)	1.084(5)	1.095(4)	1.179(2)	1.076(9)	1.191(1)	1.143(3)
SD	1.455(10)	1.453(11)	1.456(8)	1.456(8)	1.458(7)	1.486(5)	1.504(4)	1.548(3)	1.474(6)	1.633(1)	1.569(2)
RMS	1.453(10)	1.451(11)	1.455(8)	1.455(8)	1.456(7)	1.484(5)	1.502(4)	1.547(3)	1.473(6)	1.631(1)	1.567(2)
RMSS	0.941(6)	0.941(6)	1.033(8)	1.024(10)	0.854(4)	1.000(11)	1.084(5)	2.078(1)	0.976(9)	1.425(2)	1.271(3)
Σ	71	64	57	60	49	51	48	15	55	30	38

---------- Evaluation 6 ----------											
a	0.868(5)	0.877(7)	0.865(4)	0.864(3)	0.863(2)	0.917(11)	0.900(9)	0.848(1)	0.889(8)	0.908(10)	0.869(6)
b	0.859(6)	0.796(7)	0.878(4)	0.887(3)	0.923(2)	0.539(11)	0.668(9)	1.073(1)	0.720(8)	0.589(10)	0.862(5)
R^2	0.876(8)	0.878(11)	0.875(6)	0.875(6)	0.874(4)	0.863(2)	0.874(4)	0.853(1)	0.877(10)	0.869(3)	0.876(9)
$\bar{E}$	-0.029(2)	-0.031(1)	-0.028(4)	-0.026(5)	0.005(11)	-0.022(8)	-0.008(10)	0.053(1)	-0.024(7)	-0.029(3)	-0.018(9)
$\bar{A}\bar{E}$	1.364(7)	1.337(9)	1.369(5)	1.372(4)	1.378(3)	1.403(2)	1.330(10)	1.539(1)	1.319(11)	1.364(6)	1.356(8)
SD	1.861(8)	1.846(11)	1.865(7)	1.867(6)	1.871(5)	1.974(2)	1.876(4)	2.024(1)	1.854(10)	1.924(3)	1.855(9)
RMS	1.858(8)	1.844(11)	1.863(7)	1.865(6)	1.869(5)	1.971(2)	1.874(4)	2.022(1)	1.852(10)	1.922(3)	1.853(9)
RMSS	0.961(7)	0.974(10)	0.949(6)	0.948(5)	0.979(11)	1.435(2)	1.185(4)	2.291(1)	1.025(9)	1.198(3)	0.968(8)
Σ	51	66	43	38	43	40	54	8	73	41	64
---------- Evaluation 7 ----------											
a	0.875(6)	0.880(7)	0.870(4)	0.869(3)	0.861(1)	0.925(8)	0.928(11)	0.851(2)	0.874(5)	0.925(8)	0.925(8)
b	0.744(7)	0.673(6)	0.780(4)	0.815(3)	0.846(2)	0.469(11)	0.471(9)	0.926(1)	0.771(5)	0.506(8)	0.469(11)
R^2	0.859(3)	0.897(11)	0.864(4)	0.864(4)	0.864(4)	0.894(9)	0.878(8)	0.832(1)	0.874(7)	0.855(2)	0.894(9)
$\bar{E}$	-0.031(3)	-0.075(1)	-0.027(4)	0.001(11)	-0.017(6)	0.002(8)	0.025(5)	-0.001(11)	-0.016(7)	0.042(2)	0.002(8)
$\bar{A}\bar{E}$	1.326(3)	1.127(11)	1.297(4)	1.293(5)	1.286(6)	1.185(9)	1.263(7)	1.436(2)	1.245(8)	1.452(1)	1.185(9)
SD	1.781(3)	1.526(11)	1.747(4)	1.746(5)	1.745(6)	1.554(9)	1.673(8)	1.942(1)	1.681(7)	1.841(2)	1.554(9)
RMS	1.778(3)	1.526(11)	1.745(4)	1.744(5)	1.742(6)	1.552(9)	1.671(8)	1.939(1)	1.679(7)	1.839(2)	1.552(9)
RMSS	1.039(8)	0.860(4)	0.989(10)	0.993(11)	0.890(7)	1.129(5)	2.158(2)	3.169(1)	0.972(9)	2.084(3)	1.129(5)
Σ	36	62	38	47	38	58	52	20	55	28	68

b, angular coefficient; a, intersection; R^2, coefficient of determination; $\bar{E}$, mean prediction errors; SD, standard deviation of prediction errors; $\bar{A}\bar{E}$, mean prediction absolute errors; RMS, root-mean-square prediction errors; RMSS, root-mean-square standardized prediction errors; Σ, summation.

Table 3. Nugget effect (C0), sill (C1), range (a), gamma function (Γ), and spatial dependence index (SDI) estimated in the second year of evaluation, for the following semivariogram models: circular (C),; spherical (S), tetraspherical(T), pentaspherical(P),exponential (E), Gaussian (G), rational quadratic (R), hole effect (H), K-Bessel (K), J-Bessel (J); and stable (St).

Model	Estimative														
	C_0	C_1	a	Γ	SDI	C_0	C_1	a	Γ	SDI	C_0	C_1	a	Γ	SDI
	------ F1 E1 ------					------ F1 E2 ------					------ F1 E3 ------				
C	0.000	0.904	92.8		100	0.000	3.830	256.5		100	0.000	0.991	35.8		100
E	0.000	1.395	181.2		100	0.000	3.297	245.0		100	0.000	1.094	35.9		100
T	0.000	1.422	210.9		100	0.000	2.916	232.8		100	0.000	1.132	38.3		100
P	0.000	1.574	252.9		100	0.000	2.951	259.2		100	0.000	1.326	46.1		100
Ex	0.000	1.601	274.9		100	0.000	1.417	69.2		100	0.000	2.303	80.3		100
G	0.000	1.009	69.1		100	0.000	1.888	64.8		100	0.000	1.094	33.5		100
RQ	0.000	1.479	274.9		100	0.000	2.698	208.1		100	0.000	2.056	71.8		100
SC	0.000	1.087	125.5		100	0.000	2.386	145.8		100	0.000	1.805	109.8		100
KB	0.000	0.914	121.8	0.5	100	0.000	2.916	234.4	0.6	100	0.000	1.129	47.4	0.6	100
JB	0.000	1.089	118.1	10.0	100	0.000	2.995	175.7	10.0	100	0.000	1.243	42.8	4.7	100
Es	0.000	1.086	106.9	2.0	100	0.000	1.913	75.8	1.3	100	0.000	1.414	43.9	2.0	100
	------ F1 E4 ------					------ F1 E5 ------					------ F1 E6 ------				
C	0.000	1.912	261.8		100	0.000	3.619	34.9		100	0.000	4.295	40.5		100
E	0.000	12.327	263.8		100	0.000	4.055	39.4		100	0.000	4.424	36.9		100
T	0.000	11.143	261.8		100	0.000	14.987	360.0		100	0.000	9.114	85.6		100
P	0.000	11.167	274.8		100	0.000	14.689	274.9		100	0.000	9.745	85.6		100
Ex	0.000	10.873	274.9		100	0.000	14.262	274.9		100	0.000	18.563	247.9		100
G	0.000	9.666	117.8		100	0.000	4.378	43.4		100	0.000	4.657	39.9		100
RQ	0.000	10.268	265.9		100	0.000	12.443	188.1		100	0.000	9.506	89.7		100
SC	0.000	8.888	184.4		100	0.000	11.429	176.1		100	0.000	8.862	133.6		100
KB	0.000	8.912	115.1	10.0	100	0.000	4.946	56.2	2.9	100	0.000	4.649	36.9	10.0	100
JB	0.000	9.264	179.4	10.0	100	0.000	4.103	44.4	4.0	100	0.000	4.691	39.7	4.0	100
Es	0.000	9.667	129.9	2.0	100	0.000	4.378	46.2	1.8	100	0.000	4.857	41.5	2.0	100
	------ F1 E7 ------					------ F2 E1 ------					------ F2 E2 ------				
C	0.000	2.969	39.7		100	0.000	0.962	153.9		100	0.000	7.269	311.3		100
E	0.000	3.032	42.0		100	0.000	2.030	466.7		100	0.000	9.451	463.8		100
T	0.000	12.157	274.9		100	0.000	1.882	478.4		100	0.000	8.762	478.4		100
P	0.000	11.515	274.9		100	0.000	1.780	490.3		100	0.000	8.294	490.3		100
Ex	0.000	22.226	274.9		100	0.000	1.735	521.6		100	0.000	8.120	524.8		100
G	0.000	3.063	41.4		100	0.000	0.259	39.2		100	0.007	2.899	83.1		100
RQ	0.000	7.868	187.7		100	0.006	1.568	434.4		100	0.182	7.228	483.8		98
SC	0.000	6.494	146.2		100	0.012	0.454	127.7		97	0.021	2.916	183.0		99
KB	0.000	3.996	56.6	10.0	100	0.000	0.258	40.4	10.0	100	0.008	2.817	124.1	0.9	100
JB	0.000	3.035	44.4	4.1	100	0.014	0.794	164.7	4.3	98	0.002	4.734	222.1	10.0	100
Es	0.000	3.634	48.9	2.0	100	0.000	0.249	38.0	2.0	100	0.007	2.899	83.1	2.0	100

	F2 E3					F2 E4					F2 E5				
C	0.000	2.826	50.6		100	0.000	3.328	39.4		100	0.000	4.259	39.5		100
E	0.000	2.439	54.4		100	0.000	3.687	51.6		100	0.000	4.687	51.3		100
T	0.000	17.449	475.4		100	0.000	3.631	55.5		100	0.000	32.737	461.0		100
P	0.000	16.514	487.3		100	0.000	4.300	74.4		100	0.000	30.931	472.5		100
Ex	0.000	16.190	521.6		100	0.000	18.741	381.9		100	0.000	30.242	508.3		100
G	0.002	2.241	39.1		100	0.003	3.600	38.8		100	0.004	4.180	34.8		100
RQ	0.015	14.989	466.9		100	0.009	8.790	163.5		100	0.009	8.923	124.1		100
SC	0.016	4.218	120.6		100	0.123	8.314	145.8		99	0.438	22.095	343.2		98
KB	0.000	2.574	46.2	10.0	100	0.000	3.762	42.2	9.1	100	0.000	4.291	37.1	10.0	100
JB	0.000	2.493	64.5	1.6	100	0.000	3.833	62.6	4.2	100	0.000	4.764	60.6	6.2	100
Es	0.002	2.241	39.1	2.0	100	0.004	3.600	44.1	1.6	100	0.004	4.880	40.8	2.0	100

	F2 E6					F2 E7				
C	0.000	6.712	40.0		100	0.000	5.144	37.3		100
E	0.000	6.736	47.1		100	0.000	5.564	48.4		100
T	0.000	6.799	52.6		100	0.000	5.473	52.1		100
P	0.000	7.031	59.8		100	0.000	5.711	60.3		100
Ex	0.000	37.974	505.7		100	0.000	12.552	152.8		100
G	0.023	7.951	43.4		100	0.018	5.999	40.0		100
RQ	0.012	11.942	124.1		100	0.014	14.008	186.8		100
SC	0.615	23.344	333.9		97	0.293	19.334	280.1		99
KB	0.045	6.972	124.1	7.8	99	0.490	6.494	59.1	1.2	93
JB	0.000	6.961	39.7	10.0	100	0.000	5.878	59.0	4.2	100
Es	0.229	7.951	61.3	1.4	97	0.018	5.999	40.3	2.0	100

SDI: small, SDI > 75%; M, medium, 25 < SDI ≤ 75%; L, large, SDI ≤ 25%.

From the parameters generated by the method of least squares weighted theoretical models selected semivariograms, only in plowing 01 was there no presence of a nugget effect. In crop 02 in the A6 and A7 evaluations, there was a nugget effect, but this effect was not significant and did not affect the IDE of these assessments (Table 3). The nugget of a semivariogram the value of the function at the origin [γ (0)] and represents a discontinuity caused by random variance and may be a result of spatial variability of the phenomenon under study in the sampling range (Yamomoto & Landin, 2013).

The range is an important parameter for semivariogram interpretation, indicating the distance for which the sample points are correlated. The values obtained were 36.5 m and 487.3 m, indicating that the sampling grid used was adequate and sufficient to express the spatial variability of *T. limbativentris*.

As Webster and Oliver (2007), the range is the maximum distance of spatial autocorrelation, representing the points located in an area whose radius is the scope, are more similar to each other than those separated by greater distances, representing the maximum distance of spatial dependence. According to Yamomoto and Landin (2013), the range of values can influence the quality of the estimates, since it determines the number of values used in the interpolation, so estimates with interpolation by ordinary kriging using larger ranges of values tend to be more reliable.

Conclusion

Each dataset has a different spatial structure and is necessary to define a model of semivariogram with the best fit to the experimental.

The utilization of many semivariograms is recommended, and the model that adequately represents the semivariances is highly desirable in the kriging process and influences in predicting unknown values and significant reduction in estimative errors.

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