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Spatial distribution of agronomic attributes of corn plants in integrated production systems in Brazilian Amazonia

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***Abstract*— *Crop-livestock-forest systems are a sustainable production alternative based on the integration of several components and configurations that increase the complexity of management and soil-plant relationships. The aim of this study was to investigate the spatial distribution of many agronomic characteristics of maize intercropped with grass (Urochloa brizantha 'Xaraés') in an integrated crop-livestock and crop-livestock-forest system. To assess the yield components of maize intercropped with grass, 120 plant samples were collected in a normal 30 x 30 m grid at 120 positions. The GeoR software was used to perform for geostatistical and Kriging analyses. There were found spatial dependencies in ear insertion height, number of kernels per row, number of kernel rows per ear, ear length, and ear diameter. In the crop-livestock-forest systems, we detected geographical variation in corn plant characteristics, although with a weak spatial relationship. The observed wavy pattern illustrates the sensitivity of corn characteristics to the presence of eucalyptus trees. To increase maize yield components in crop-livestock-forest systems in the southwestern region of the Amazon, 42-meter-wide tree strips are suggested*

I. INTRODUCTION

The recovery of degraded areas is a strategy to minimize the pressure for new agricultural frontier areas, particularly in the Amazon region, by minimizing the amount of native vegetation that is burned. The need to reduce deforestation and greenhouse gas emissions requires the use of more sustainable food production technology (Soares et al., 2020).

In this perspective, crop-livestock-forest systems are an alternative farming system based on the combination of annual crops, livestock, and forest plantations that aims to increase income in as well as provide social and ecological advantages (Coser et al., 2018, Cortner et al., 2019). These systems permit the recovery and the reinsertion of degraded land into agricultural production and are part of the Brazilian National Low-Carbon Agriculture Plan (ABC Plan), which aims to reduce the agricultural sector's greenhouse gas emissions (MAPA, 2012, Silva et al., 2022).

The improvement of the physical (Feitosa et al., 2019), chemical (Assis et al., 2015), and biological properties of soil from the increase of organic matter (Jakelaitis et al., 2008), when combined with the conservative practices of soil management, is one of the expected benefits of the use of these integrated systems (Loss et al., 2012). In terms of economic sustainability, these systems are more efficient in their use of inputs, with lower production costs, better profitability, and fewer risks and soil quality loss (Martha Júnior et al., 2009; Zolin et al., 2020).

In face of the dystrophic character of tropical and Amazonian soils and the spatial and temporal complexity of integrated farming systems, enhancing the agricultural management of these systems necessitates an understanding of soil variables and spatial heterogeneity (Vian et al., 2016). To achieve this objective, it is usual to analyze soil and crop characteristics by using the large plots or field average as a reference for these variables, neglecting their spatial dependencies. Nonetheless, several authors have demonstrated the existence of spatial dependency on the chemical (Dalchiavon et al., 2012) and physical (Vieira et al., 2011, Feitosa et al., 2019) attributes of the soil, as well as crop yield (Silva et al., 2008, Vian et al., 2016).

The heterogeneity of soils is imputable to the complex interactions of several factors and processes under different types of management, which promote vertical and horizontal variation in the soil (Zanão Júnior et al., 2010) with direct influence on plant physiology and performance. The study of spatial variation by geostatistics in agriculture aids in the adequacy of production systems and the planning of agricultural operations (Grego et al., 2012), with a lower cost-benefit ratio from the use of thematic maps obtained by interpolation of the data by using the Kriging method (Zano Jnior et al., 2010a). Despite the significance of such techniques, there are few studies that evaluate sustainable or alternative farming systems in the Amazon.

In this regard, the aim of this study was to examine the spatial distribution of corn plant yield components and their interactive effects in an integrated crop-livestock and crop-livestock-forest systems in a typical Amazon biome in Brazil.

II. MATERIAL AND METHODS

The study was carried out in an experimental area of EMBRAPA (Brazilian Agricultural Research Corporation), located between 406272 S, 9027783 W and 406897 S, 9027312 W, in the city of Porto Velho, in Brazil's northwest region. According to the Köppen climate classification, the climate is the Am - tropical monsoon climate -, with a well-defined dry period, yearly average rainfall between 1,400 and 2,600 mm, and annual average air temperature ranging from 24 to 26°C (Sedam, 2012). The predominant soil of the area is classified as dystrophic Red-Yellow Latosol (Oxisol) (Valente et al., 1997), with a clay-silt texture and the following granulometric characteristics: 183 g kg^{-1} of sand, 422 g kg^{-1} of silt, and 398 g kg^{-1} of clay for a depth of 0 to 0.20 meters.

The experimental area of approximately 10 hectares was established in a 15-year-old degraded pasture managed since 2008 with no-tillage and the cultivation of single soybean (Glycine max), corn (Zea Mays), rice (Oryza sativa), and sorghum (Sorghum bicolor) for grazing by dairy cattle (Townsend et al., 2013). In 2012, the area was remodeled and subdivided into a crop-livestock system and 3 integrated crop-livestock-forestry systems, managed in alleys of four rows of eucalyptus (Eucalyptus spp.), planted in March 2013, spaced by 18, 30, and 42-m (Ribeiro et al., 2020), (Figure 1).

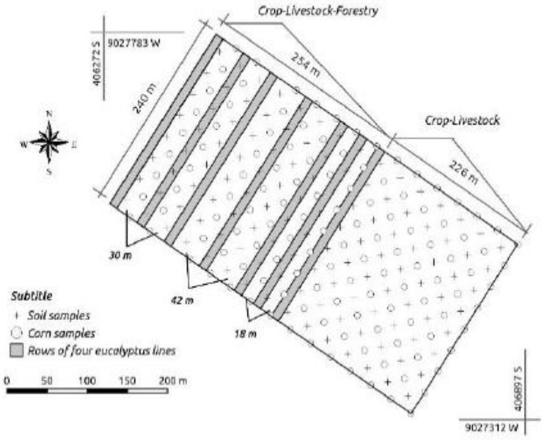

Fig.1 - Sampling grid in the integrated crop-livestock and crop-livestock-forest system, in the city of Porto Velho (Rondônia state, Brazil).

To gather plant samples, we utilized a regular rectangular area 240 m wide and 480 m long, with 120 points equitably distributed every 30 × 30 m across the experimental area (Figure 1). Before sowing corn in October 2015, we collected samples of disturbed soil at depths of 0 to 0.10, 0.10 to 0.20, and 0.20 to 0.40 m at each sample site. This paper does not incorporate this data.

The LG6038 PRO hybrid was used to sow corn on January 13, 2016, with 0.90 m between rows and an initial population of 65,000 plants per hectare. The seeds were treated with 600 g L-1 of Imidacloprid at a concentration of 4 mL kg-1. The maize was intercropped with Urochloa brizantha 'Xaraés' grass intra and inter rows simultaneously. After removing the animals from the area, the maize was harvested for feeding and straw production.

At the physiological maturity of the maize, eight linear meters were used at each sampling point to evaluate the grain yield components (Cargnelutti Filho et al., 2011). We measured the plants at the sample location to determine the ear insertion height (EH), ear length (EL), number of kernel rows per ear (NR), number of kernels per row (NKR), and ear diameter (ED). Initially, we conducted an exploratory analysis using descriptive statistics to determine the central trend (mean, median) and dispersion of the data (standard deviation, coefficient of variation, skewness, and kurtosis) using the program R (R Core Team, 2015). Employing box plots, we were able to identify outliers in the data set (Braga, 2014).

Before constructing the experimental semivariogram, when a significant trend was found in the data, we modeled the trend to the second order using the geoR tool (Ribeiro Junior & Diggle, 2001). We evaluated anisotropy from the semivariographic analysis in the directions of 0º, 45º, 90º, and 135º, and we later verified the necessity to adjust the maximum distance for the generation of the semivariogram, taking into account a minimum number of 30 pairs (Vieira, 2000).

We used the estimation of Cressie & Hawkins (1980) due to its robustness in the presence of outliers that could not be eliminated from the dataset (eqn. 1):

$$2\hat{\gamma}_{CH}(h) = \left[\frac{1}{N(h)}\sum_{i=1}^{N(h)} |(Z(x_i+h)-Z(x_i))|^{\frac{1}{2}})\right]^4 \Big/ \left(0.457+\frac{0,494}{N(h)}\right)$$

where γ(h) is the value of the estimate of the semivariance at position h, N(h) refers to the number of sample pairs separated by a distance h, being Z(xi+h) and Z(xi) the observed numerical values of an attribute sampled at point xi +h and point xi, respectively.

To determine the parameters of the semivariogram, we fitted the most common models used in soil studies: Exponential (eqn. 2), Gaussian (eqn. 3), Spherical (eqn. 4), and Wave (eqn. 5), where: C0 is the nugget effect, C1 is the partial sill, a is the range, and h are the distances values. The range of the spatial dependence is a parameter that allows us to observe the spatial continuity and horizontal variability of the attributes (Silva et al., 2008; Silva et al., 2010a; Bottega et al., 2013), besides the sample planning (Zanão et al, 2010a). The following requirements were used to select the best fit: 1) data validation, 2) the lowest mean error (ME), 3) the standard error of the mean (SEM), and 4) the root mean square error (RSME).

$$\gamma(h) = \begin{cases} 0, & if \quad h = 0 \\ \gamma(h) = C_0 + C_1\left[1 - e^{[-3(h/a)]}\right], & if \quad h \neq 0 \end{cases} \tag{2}$$

$$\gamma(h) = \begin{cases} 0, & if \quad h = 0 \\ C_0 + C_1\left[\frac{3}{2}\left(\frac{h}{a}\right) - \frac{1}{2}\left(\frac{h}{a}\right)^3\right], & if \quad 0 < h \leq a \\ C_0 + C_1, & if \quad h > a \end{cases} \tag{3}$$

$$\gamma(h) = \begin{cases} 0, & if \quad h = 0 \\ \gamma(h) = C_0 + C_1\left[1 - e^{[-3(h/a)^2]}\right], & if \quad h \neq 0 \end{cases} \tag{4}$$

$$\gamma(h,\beta) = C_0 + \frac{a}{h} sen\left(\frac{h}{a}\right) \tag{5}$$

In the semivariograms that were fitted with the Wave model, we subsequently conducted an individual spatial analysis for the crop-livestock, and crop-livestock-forest areas, respectively, to determine the behavior of the variable as a function of the presence or absence of eucalypt rows in these systems at various distances.

The analysis of the spatial dependence was determined by the evaluation of the experimental semivariogram and its parameters (C = sill, C0 = nugget effect, C1 = partial sill, a = range). To determine the degree of spatial dependence (DSD), we employed the thresholds provided by Cambardella et al. (1994), defined as the ratio between the nugget effect and the sill, i.e. DSD = (C0/C0+C1)*100.

To estimate the values in non-sampled sites, we applied the Kriging method to interpolate the values without trend and with minimal variance, spatially correlating the neighboring samples for later contour maps generation (Grego et al., 2014). According to Webster and Oliver (2007), the function Z(x) for any position x consists of two components

$$Z(\mathbf{x}) = u(\mathbf{x}) + \varepsilon(\mathbf{x}) \tag{6}$$

Where u(x) is the main trend of the data and ε(x) is the residual error for each x position. Therefore, the semivariance is based on the residuals of the trend, and the spatial trend is represented by the following equation: 7, which can be represented by a low-order polynomial over the observed positions (eq. 8).

$$Z(\mathbf{x}) = u(\mathbf{x}) + \varepsilon(\mathbf{x}) = \sum_{k=0}^{K} \beta_k f_k(\mathbf{x}) + \varepsilon(\mathbf{x}) \tag{7}$$

$$Z(\mathbf{x}) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \varepsilon(\mathbf{x}) \tag{8}$$

Where βk, k = 0, 1,…, K, are unknown coefficients and fk(x) are known functions of the selected variable (x). Using the IswR package's Pearson correlation test, we evaluated the relationship between the variables under consideration (Dalgaard, 2008). We applied Warrick & Nielsen's (1980) parameters to analyze the variability of the data.

III. RESULTS AND DISCUSSION

We confirmed modest variance (CV < 12%) for the corn yield components (Table 1). According to the mean results, the first ear insertion heights ranged from 0.64 to 1.45 m, the ear lengths ranged from 8 to 18 cm, the average ear diameter was 4.19 cm, there were 14.28 rows per ear, and 18 to 35 grains per row per ear.

Table 1 - Descriptive statistics for ear insertion height (EH), ear length (EL), ear diameter (ED), number of kernels per ear (NKR), number of kernel rows per ear (NR) in the integrated crop-livestock and crop-livestock-forest systems.

Variable	**N**	**Min.**	**Max.**	**Average**	**Median**	**SD**	**CV**	**Skew.**	**Kurt.**
EH (cm)	104	0.64	1.45	1.19	1.21	0.13	10.74	-1.60	4.23
EL (cm)	104	8.00	18.00	15.65	16.00	1.56	9.98	-1.61	5.16
ED (cm)	104	3.20	4.70	4.19	4.20	0.26	6.30	-0.89	1.43
NKR (unit)	104	18.00	35.00	29.88	30.00	2.90	9.69	-1.07	2.22
NR (unit)	104	12.00	16.00	14.28	14.00	0.91	6.36	-0.34	-0.65

N= number of samples, Min. = Minimum, Max. = Maximum, SD = standard deviation, CV = coefficient of variation in %, Skew. = skewness, and Kurt. = kurtosis.

The occurrence of high range values demonstrates greater efficiency of the sampling grid in the detection of the variability of attributes (Artur et al., 2014). The different range values for the same attribute show the presence of horizontal variability, in addition to vertical variability (Zanão Júnior et al., 2010a).

Ear insertion height, number of kernels per row, number of kernel rows per ear, and ear length and diameter were the corn variables that demonstrated spatial dependence (Table 2). Other variables exhibited pure nugget effect (PNE), which may suggest either a lack of spatial structure in the data or a sample distance insufficient to identify the data's variability (Vieira et al., 2011). In this instance, we attributed the variability of soil fertility to the management system that promoted the horizontal homogeneity of soil characteristics through time (Tavares et al., 2012, Feitosa et al., 2019).

Table 2 - Parameters of the fitted semivariograms for ear insertion height (EH), ear length (EL), ear diameter (ED), number of kernels per ear (NGR), number of kernel rows per ear (NR) in the integrated crop-livestock and crop-livestock-forest systems.

Variable	**Model**	**C_0**	**C_1**	**a**	**ME**	**MSE**	**RMSE**	**DSD**
EH	Exponential	$5\ 10^{-3}$	$8\ 10^{-3}$	45.00	$3\ 10^{-4}$	$-1\ 10^{-3}$	0.11	39.52
EL	Wave	0.91	0.59	25.86	$-2\ 10^{-3}$	$-7\ 10^{-4}$	1.23	60.58
NKR	Wave	4.27	2.41	28.40	$7\ 10^{-3}$	$1.5\ 10^{-3}$	2.60	63.91
NR	Spherical	0.57	0.20	97.18	$-7\ 10^{-4}$	$-4\ 10^{-4}$	0.94	73.81
ED	Exponential	0.01	0.03	30.5	$-1\ 10^{-3}$	$-2\ 10^{-3}$	0.21	24.57

Pne = pure nugget effect, C0 = nugget effect, C1 = partial sill, a = range, ME = mean error, MSE = mean square error, RSME = root mean square error, DSD = degree of spatial dependence.

The variables that were modeled by the wave model did not exhibit detectable spatial correlation when evaluated in the crop-livestock and crop-livestock-forest systems separately, except for the number of kernels per row (C0 = 3.02, C1 = 0.69, a = 14.73), which showed periodic variation at this scale. In this system, the range value for ear length varied from 25.86 meters (Figure 2). Taking into account the sampling design, the range of spatial dependence is a parameter that allows us to see the spatial continuity and horizontal variability of the attributes (Silva et al., 2008; Silva et al., 2010a; Bottega et al., 2013).

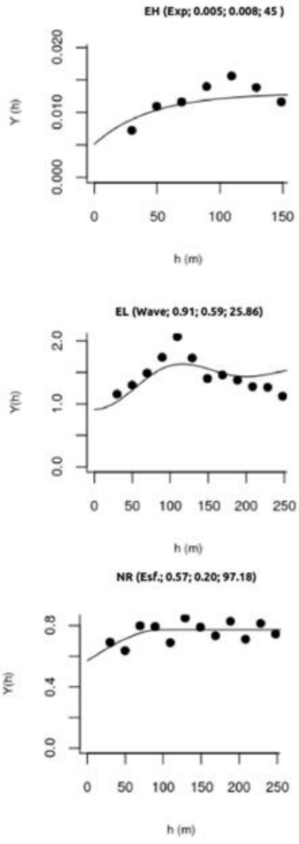

Fig.2 – Empirical (dots) and fitted semivariograms (lines) for ear insertion height (EH), ear diameter (ED), ear length (EL), number of kernels per row (NKR) and number of kernel rows per ear (NR) in the integrated crop-livestock and crop-livestock-forest system. Exp = exponential model, Sph = spherical model, C0 – nugget effect, C1 – partial sill, and a – range.

The spherical, exponential, and wave models provided the best fit for the semivariograms of variables with spatial dependence. These models indicate, respectively, the low, median, and periodic spatial variability in the data (Bottega et al., 2013). There was strong spatial dependence (DSD < 25%) for ear diameter. The degree of spatial dependence was considered moderate (25% < DSD <75%) for 81% of the variables, according to Cambardella et al. (1994), indicating moderate spatial continuity of these variables, which in turn depends on the depth and management of the soil (Silva et al., 2010a; Zanão Júnior et al., 2010a).

The contour maps produced using universal Kriging enabled us to observe the spatial distribution of the corn plants' attributes. Consequently, we can identify the variability of plants with spatialization, wherein the areas with the smallest ear insertion heights also had the smallest ear diameters, ear length, and number of kernels per row (Figure 3). These factors were concentrated within the 18-meter-wide eucalyptus lane

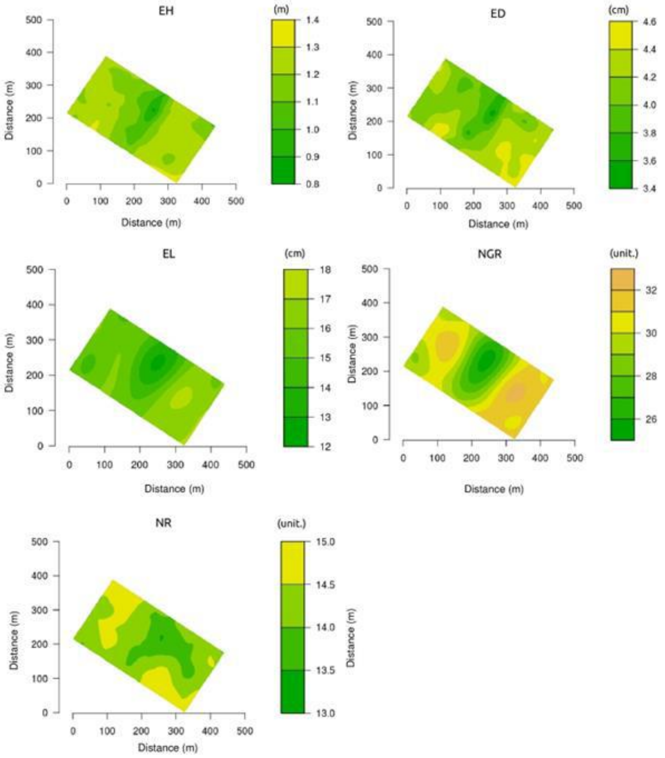

Fig.3 - Kriging maps of ear insertion height (EH), ear diameter (ED), ear length (EL), number of kernels per row (NGR), and number of kernel rows per ear (NR) in the integrated crop-livestock and crop-livestock-forest systems.

The interaction impact between the arboreal component and corn is determinant to affect the physiological mechanisms of the plant due to the lower contribution of photosynthetically active radiation, which is unfavorable to the crop's full growth and development (Oliveira et al., 2016). Several authors have showed that models of integrated systems with an interval between tree strips of 15, 20, and 25 meters are detrimental to the crop and pasture (Silva et al., 2004, Luiz et al., 2015; Mascarenhas et al., 2017). Currently, among the components of integrated systems, annual crops are currently the most profitable, and we must consider the use of wider spacing to maximize the crop-livestock-forest system's economic viability.

Regarding the number of kernels per row, analysis of the integrated systems in isolation revealed microvariability in the crop-livestock-forest system alone, with a spatial structure spanning 14.73 m, whereas it was 28.3 m when both systems were considered together (whole study area). From the semivariogram, we can identify the wavelike pattern (Figure 4), which demonstrates the impact of the eucalypt trees on the variable in the kriged map.

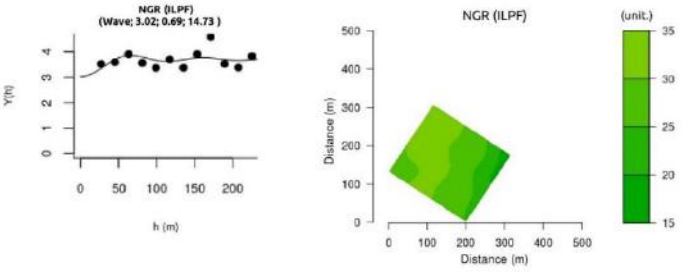

Fig.4 – Empirical (dots) and fitted wave semivariogram (line) and kriged map for the number of kernels per row only in the crop-livestock-forest system (ILPF).

Highlighting the variability of the soil conditions in the area (Feitosa et al., 2019), we can confirm the inherent problems with the use of average levels in the management of the soil's fertility, especially regarding the over- or under-application of fertilizers and correctives in fields with significant spatial variability in the chemical attributes (Silva et al., 2010a). Given the heterogeneity of soil nutrients, it is crucial to understand their spatial distribution in order to limit the effects of soil variability on crop yields (Dalchiavon et al., 2012, Feitosa et al., 2019).

In this sense, when considering existing management areas, we can enhance the efficacy of fertilization and liming practices to achieve higher crop yields, but a smaller sample size and number will misrepresent the fertility of the soil (Zano Jnior et al., 2010b). Therefore, for variables with significant spatial dependence, we recommend sampling at a distance of up to 30 meters, which can be dropped to reduce the area's variability effects.

IV. CONCLUSION

Corn plants exhibits spatial dependence for ear insertion height, number of kernels per row, kernel rows per ear, and ear length and diameter in the crop-livestock-forest systems. The wavy behavior pattern of ear length and number of kernels per row indicates sensitivity to eucalyptus presence.

Among the evaluated crop-livestock-forest systems, the system with 18 m between tree strips has the lowest observed corn crop grain yield indicators.

The crop-livestock system rewards the best agronomic attributes in maize.

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