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Specific Management Areas as a Function of Dendrometric Properties of Eucalyptus and Physical-Chemical Attributes in an Oxisol

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Abstract

Eucalyptus cultivation has expanded considerably in Brazil, especially in regions where soils have low fertility, as in the Brazilian Cerrado (Brazilian Savannah). In order to achieve high yield, it is necessary to know the appropriate time and place to perform the soil management, and to assist in this decision-making process, mathematical and computational models has been used and are a promising alternative. The objective of this study was to model the influence of plant and soil physical-chemical attributes on *Eucalyptus camaldulensis* cultivation in an Oxisol (Latossolo Vermelho distrófico), with clayey texture with the purpose of demonstrating specific management areas closely associated with eucalyptus development. An experimental grid of approximately 2 hectares (ha) containing 40 sampling points were installed and later soil and plant attributes were collected for the determination of physical and chemical attributes in the 0-0.20 m and 0.20-0.40 m layers in Selvíria, MS, Brazil. The results were analyzed using classical and geostatistical statistics. The spatial dependence varied according to the physical attribute evaluated and the depth of sampling. In addition to the vertical variability, there was also horizontal variability between depths, since for the same attribute the range was different between the sampled layers.

Keywords: soil management, forest sustainability, forestry, geostatistics

1. Introduction

The cultivation of *Eucalyptus* spp. in Brazil has increased due to rapid growth, diversification in wood use and ease of adaptation to different soil and climatic conditions. This fact makes the productivity of commercial eucalyptus plantations quite variable (Lima et al., 2017a). According to the Brazilian Forestry Service (2016), the country obtains the best technologies in eucalyptus forestry, reaching average productivity of 60 m^3 ha^{-1} in seven-year rotations.

Because of its potential and diversity of use, *Eucalyptus camaldulensis* is a species of great economic interest, being one of the first cultivation that was planted successfully in regions outside the origin continent (Lima et al., 2010a). The literature has indicated that its main characteristics are given by the ability to grow well in relatively poor soils (frugal species), resistance to long periods of drought, tolerance to excessive rainfall, resistance to frost and production of hard, heavy and dark wood, when compared to the species *E. grandis* and *E. globulus* (Lima et al., 2010a). However, its growth can be influenced by some physical-chemical characteristics of soil, mainly in Brazilian Cerrado, which, among other factors, is commonly poor in nutrients and with high soil acidity (Toledo et al., 2015).

Forestry enterprises have sought an efficiency of both planning and management processes involving practices of reforestation execution and demanded specific knowledge on the species cultivated as well as the site for their production (Lima et al., 2017b). However, the traditional methods used to assess both the development and the productivity of the forests is the measure of central tendency, which is generally average, in addition to a measure of dispersion, such as variance, without considering the affinities existing between surrounding samplings (Lima et al., 2017c). Therefore, with an increase in the necessity of further information on a production area, the use of accuracy instruments is it used applied to forestry (Pelissari et al., 2012).

In addition, highly weathered Cerrado soils have low fertility, low cation exchange capacity (CTC), high aluminum saturation and high acidity (Barbosa et al., 2012). Without correcting these soils, eucalyptus, like other crops, has its development impaired, since it finds impediments to the growth of the root system, responsible for the absorption of water and nutrients necessary for the crop cycle, thus affecting productivity (Costa et al., 2015). Lima et al. (2013) showed that the physical and chemical attributes of the soil, as well as those related to plants, present spatial variability and that the distance between the samples should be taken into account in the study of these attributes, as recommended by geostatistics. Knowing the spatial distribution of the granulometric fractions allows to analyze correctly the availability of the chemical elements in the soil, as reported by Silva et al. (2010).

The new technologies used in the agrarian sector have improved the determination of the spatial and temporal variability of certain attributes, from the mapping even in their correlations, analyzing the distance between the samples in order to represent with more precision the factors that affect the crops profitability (Lima et al., 2010a; Lima et al., 2010b).

In this context, the combination of forestry and geostatistics aims to analyze the spatial dependence of georeferenced data, which are adjusted in semivariograms according to the distances between the observations. From the semivariogram, kriging maps can be create for each attribute searched for, soil and plant, which represents the spatial variability of the data and then obtain the specific areas of soil management for the attribute (Carvalho et al., 2012).

In view of above, the objective of this study was to analyze the linear and spatial correlations of individual development of *Eucalyptus camaldulensis* trees as a function of plant attributes and soil physical-chemical in an Oxisol, in order to show specific management areas closely associated to the development of Eucalyptus, assisting in soil management and decision making in a sustainable manner to the environment.

2. Methods

2.1 Field Sites and Material Description

The study was carried out during the 2016 year at the Education and Research Farm of São Paulo State University (20°20′53″ S and 51°24′02″ W) located in the municipality of Selvíria, MS, Brazil, with an altitude of 335 m (Figure 1). The soil was classified as typical Oxisol, with clayey texture (Latossolo Vermelho distrófico típico) (Santos et al., 2013). According to the Köppen classification, the climate of the region is Aw, tropical climate with dry winter season, with an average annual rainfall of 1,313 mm, with maximum annual temperature of 31 °C and minimum annual temperature of 19 °C (Galindo et al., 2016), annual relative air humidity between 70% and 80% (Centurion, 1982). Precipitation, and maximum, average, and minimum temperatures recorded during the experimental year period are shown in Figure 2.

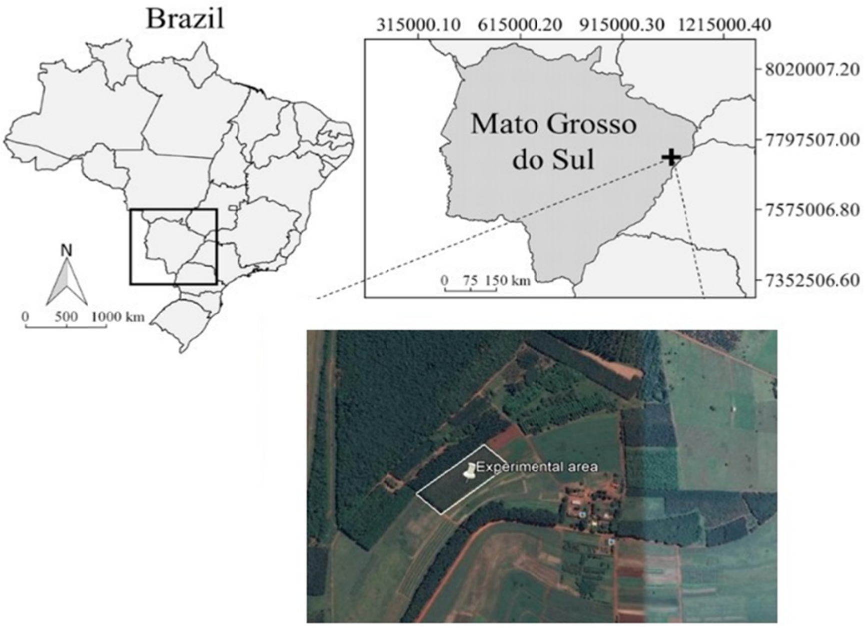

Figure 1. Study area at the Selvíria, Mato Grosso do Sul, Brazil (20°22′ S, 51°22′ W, altitude of 335 m)

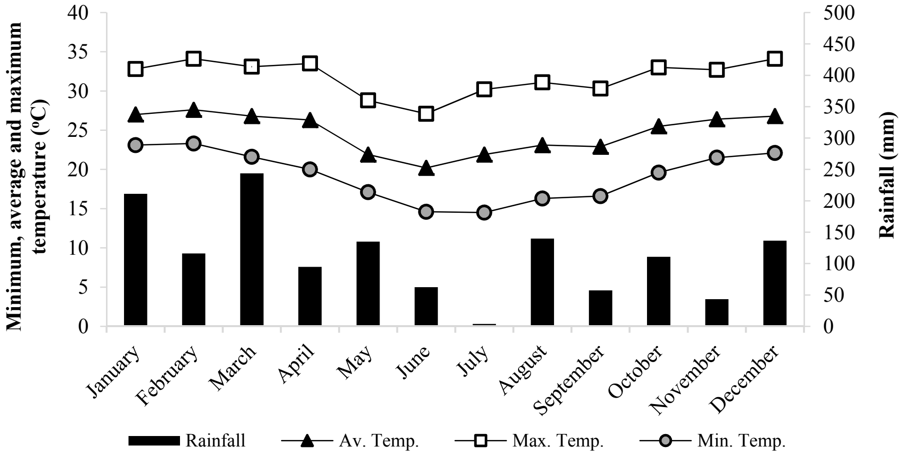

Figure 2. Rainfall, and maximum, average, and minimum temperature obtained from the weather station located on the Education and Research Farm of FE/UNESP during eucalyptus research in the year of 2016

2.2 Experimental Design and Evaluations

The test-plant was *Eucalyptus camaldulensis*, with field installed on 10/10/2008, and spacing of 3.0 m × 1.8 m. Sampling points were determined by cartesian coordinates in the planted area with Eucalyptus. An experimental mesh with 40 points was performed. The transects were spaced 9 m apart, with sample points in the form of 9 × 9 m.

The following evaluations were carried out: Plant height (ALT); Diameter at breast height (DAP); soil penetration resistance (RP); gravimetric humidity (UG); volumetric humidity (UV); soil density (DS); particle density (DP) and total porosity (PT), soil organic matter (MO); hydrogen potential (pH) in $CaCl_2$, and acidity potential (ACPOT), collected at two depths: 0.0-0.2 and 0.2-0.4 m. Therefore, 14 attributes were analyzed: ALT, DAP, RP1, RP2, UG1, UG2, UV1, UV2, DS1, DS2, DP1, DP2, PT1, PT2, pH1, pH2, MO1, MO2, ACPOT1, ACPOT2.

Plant and soil attributes were individually collected around each sampling point. The mechanical resistance was evaluated with the impact penetrometer (Stolf, 1991) and calculated according to the following equation:

$$RP = \{\{5.581 + 6.891\cdot\{[N/(P - A)]\cdot 10\}\}\cdot 0.0981 \quad (1)$$

where, RP is the mechanical resistance of the soil to penetration (MPa); N, the number of impacts made with the penetrometer hammer to obtain the reading; and A and P, the readings before and after the impacts (cm).

The pH was determined potentiometrically in 0.01 mol L^{-1} $CaCl_2$ solution, and the organic C by the wet combustion method, via colorimetric, the organic matter content of the soil being calculated by the following equation (Raij et al., 2001):

$$MO = C\cdot 17.24 \quad (2)$$

where, MO is the organic matter content (g dm^{-3}) and C is the carbon content (g dm^{-3}).

All analyzes were performed at the Laboratory of Physics and Soil Chemistry of the Faculty of Engineering of Ilha Solteira, UNESP. The attributes of the evaluated plant in the field were diameter at breast height, in centimeters (DAP), and the plant height, in meters (ALT). The devices used were, respectively, a measure tape and a dendrometer vertex.

For the determination of DS, undisturbed samples were collected using the volumetric ring method. Gravimetric humidity was obtained using an analytical balance and for the volumetric humidity the ring volume was taken into account. The volumetric flask method was used to determine the particle density (kg dm^{-3}), and for the total porosity the bulk density and the actual density were used Embrapa (1997).

2.3 Analytical Procedures

Laboratory analyzes were performed at the Soil Physical Analysis Laboratory of the Faculty of Engineering of Ilha Solteira, UNESP. Descriptive analysis of all attributes was performed using the SAS statistical program (Schlotzhaver & Littell, 1997). Thus, the mean, median, minimum and maximum values, standard deviation, coefficient of variation, kurtosis, asymmetry and frequency distribution were obtained. It was also found outliers that were properly disposed.

For the normality hypothesis test, we used the statistics of Shapiro and Wilk (1965) at 5% probability. In addition, the correlation matrix was made in order to present the regression analyzes, two for two, between the attributes. From this analysis, we selected the attributes that presented the highest linear correlation, to perform the cross-semivariogram and the cokriging. The spatial dependence, for each isolated attribute, was verified using the simple semivariogram.

Since the attributes that presented spatial interdependence, the cross-semivariograms were realized, with the aid of the package Gamma Design Software (Robertson, 2004). Some factors were taken into account to adjust the simple and crossed semivariograms, as the smaller sum of the squares of the deviations (SQD); higher determination coefficient (R^2) and higher assessed spatial dependence (ADE).

Were related the nugget effect (C_o), range (A_o) and the threshold ($C_o + C$) for each attribute studied. To determine the spatial dependence estimator, the equation $ADE = [C/(C + C_o)]\cdot 100$ was used, in which ADE is the spatial dependence estimator; C is the structural variance and $C + C_o$ is the threshold, respectively.

Cross-validation is used to estimate alternative models of both simple and crossed semivariograms. Thus, the real values obtained are eliminated and values are estimated in the spatial domain, being able to obtain graphs relating the estimated and observed values. Thus, the adjustment is determined by the correlation coefficient (r), obtained by summing the squares of the deviations. Therefore, the regression coefficient equal to 1 would provide a perfect fit, with the linear coefficient being zero and the angular value equal to 1 (Robertson, 2004). The kriging and cokriging maps were obtained to evaluate the spatial dependence and interdependence of the attributes studied.

3. Results and Discussion

3.1 Descriptive Analysis

According to Pimentel Gomes and Garcia (2002), the variability of an attribute is classified according to the magnitude of the CV (coefficient of variation). In this way, Table 1 presents the descriptive analysis of the studied attributes.

Table 1. Descriptive analysis of eucalyptus production components and attributes of an Oxisol

Attribute $^{(a)}$	Descriptive statistical measures									
	Mean	Median	Value		Standart deviation	Coefficient			Probability of the test $^{(b)}$	
			Minimum	Maximum		Variation (%)	Kurtosis	Asymmetry	Pr < w	DF
Plant attributes										
ALT (m)	17.8	18.3	10.2	27.0	4.140	23.3	-0.882	0.008	0.250	NO
DAP (cm)	12.8	13.1	7.5	18.2	2.931	22.9	-0.810	-0.018	0.404	NO
Soil physical attributes										
RP1 (MPa)	4.533	3.857	1.649	10.687	2.416	53.3	0.420	1.084	0.001	IN
RP2 (MPa)	6.480	6.100	1.474	13.471	3.090	48.4	-0.165	0.740	0.011	IN
UG1 (kg kg^{-1})	0.122	0.122	0.109	0.149	0.009	7.2	1.356	0.977	0.033	TN
UG2 (kg kg^{-1})	0.119	0.118	0.106	0.137	0.006	5.4	1.600	0.899	0.015	IN
UV1 (m^3 m^{-3})	0.140	0.142	0.075	0.213	0.026	18.3	1.974	-0.042	0.026	TN
UV2 (m^3 m^{-3})	0.153	0.152	0.121	0.208	0.016	10.8	1.987	0.880	0.090	NO
DS1 (kg dm^{-3})	1.164	1.155	0.776	1.364	0.116	9.9	1.893	-0.807	0.074	NO
DS2 (kg dm^{-3})	1.278	1.265	0.976	1.583	0.117	9.2	0.960	0.395	0.228	NO
DP1 (kg dm^{-3})	2.635	2.590	2.378	3.066	0.152	5.8	1.520	1.106	0.003	IN
DP2 (kg dm^{-3})	2.572	2.564	2.332	2.798	0.096	3.7	0.949	0.139	0.134	NO
PT1 (m^3 m^{-3})	0.567	0.560	0.462	0.744	0.061	10.7	1.646	0.924	0.038	TN
PT2 (m^3 m^{-3})	0.504	0.500	0.387	0.611	0.046	9.1	0.680	-0.194	0.644	NO
Soil chemical attributes										
MO1 (g dm^{-3})	19.2	18.0	12	32	5.070	26.36	0.829	1.206	0.0003	IN
MO2 (g dm^{-3})	13.6	13.0	11	20	1.945	14.30	2.045	1.435	< 0.0001	IN
pH1 ($CaCl_2$)	4.2	4.2	3.8	4.8	0.284	6.71	-0.677	0.542	0.018	IN
pH2 ($CaCl_2$)	4.0	4.0	3.9	4.7	0.153	3.77	6.735	2.118	< 0.0001	IN
ACPOT1 (mmol$_c$ dm^{-3})	5.8	5.8	5.4	6.2	0.190	3.27	-0.214	-0.178	0.285	NO
ACPOT2 (mmol$_c$ dm^{-3})	5.7	5.8	5.5	6.1	0.104	1.80	2.138	0.261	0.0008	IN

Note. $^{(a)}$ ALT = Eucalyptus plant height; DAP = Diameter at breast height; RP, UG, UV, DS, DP, PT, MO, pH and ACPOT 1 and 2, are respectively the penetration resistance, gravimetric humidity, volumetric humidity, soil density, particle density, total porosity, organic matter, hydrogen potential and acidity potential, collected in the soil layers; $^{(b)}$ DF = frequency distribution, being NO, TN and IN respectively of normal type, tending to normal and indeterminate.

The plant attributes plant height (ALT) and diameter at breast height (DAP) presented a high variability with CV 23.3% and 22.9% respectively (Table 1), above that reported by Rosa Filho et al. (2011), who had found median value of 14.4% when assessing the productivity and attributes of the soil in a *Eucalyptus urophylla* forest site and Lima et al. (2010), who verified mean values of variation coefficient for the ALT of 12.0%. However, similar results was observed by Lima et al., (2017b) who verified mean values of variation coefficient for the ALT and DAP 18.23 and 23.45%, respectively.

The physical attributes of soil that presented low variability were gravimetric humidity (UG1 and UG2), soil density (DS1 and DS2), particle density (DP1 and DP2) and total porosity (PT2) with respective values; 7.2%, 5.4%, 9.9%, 9.2%, 5.8%, 3.7% and 9.1% (Table 1). The volumetric humidity (UV1 and UV2) and total porosity (PT1) showed CV following order, 18.3%, 10.8% and 10.7% (Table 1), confirming Lima et al., (2017a), who verified mean variations in CV for soil physical attributes between 1.0 and 18.9%. While the penetration resistance attributes (RP1 and RP2) presented very high variability, with CV 53.3% and 48.4% respectively (Table 1), corroborating with the results observed by Carvalho et al. (2012).

The variation coefficient should be used as a parameter to validate the mean values found since, according to Pimentel-Gomes and Garcia (2002), a variation coefficient above 30% reveals that the average has low significance, and values above 60% reflect a very heterogeneous set of data canceling the confidence of the average. However, if below 30%, data are homogeneous and the average is significant and able to be used as representative for the data obtained. Some authors relate the very high variability associated with the distribution of the arrangement of some nutrients, thus increasing the heterogeneity of these parameters (Corá et al., 2004).

For the chemical attributes of the soil, with exception of the organic matter (MO1 and MO2), which presented high and medium variability with respect to CV (26.36% and 14.30%) (Table 1), the other attributes analyzed;

hydrogen potential (pH1 and pH2), and potential acidity (ACPOT1 and ACPOT2) had low variability with CV respectively 6.71% 3.77%, 3.27% and 1.80% (Table 1). According to Arthur et al. (2014), the variations of soil chemical attributes are related to alterations caused by irregular fertilizations and limestones, and due to the high heterogeneity around the average among the chemical attributes in the evaluated area. This heterogeneity can have several causes, among them, the process of soil formation and accumulation and distribution of soil particles as a function of the shape of the relief and the flow of water in the area.

Plant attributes (ALT and DAP) presented normal frequency distribution, with positive asymmetry coefficients for ALT (0.008) and negative for DAP (-0.018) (Table 1). The kurtosis coefficient was negative for both -0.882 and -0.810 respectively (Table 1). As well as the attributes related to soil physics, with normal frequency for UV2, DS1, DS2, DP2 and PT2, with both positive asymmetry coefficient ranging from 0.169 to 0.880 and negative ranging from -0.807 to -0.194 (Table 1). The kurtosis coefficients were positive, varying from 0.680 to 1.987 (Table 1).

The attributes RP1, RP2, UG1, UG2, DP1, as well as all chemical attributes (MO1, MO2, pH1, pH2, ACPOT2) except for ACPOT1 (normal rate) had indeterminate distribution (Table 1). UG1, UV1, PT1 presented a tendency to normal, with positive asymmetry values of 0.924 to 0.977 and negative values of -0.042, and positive kurtosis values ranging from 1.356 to 1.974 (Table 1).

According to Dalchiavon et al. (2011), if a variable has a normal frequency distribution (NO), the measure of central tendency most appropriate to represent it should be the mean, while if its frequency distribution tends to normal (TN), or indeterminate (IN), will be better represented by the median, so the average values found for ALT and DAP were 17.8 and 12.8 cm, respectively. For UV2, DS1 and DS2, DP2, PT2 and ACPOT1 the mean values were 0.153 m^3 m^{-3}, 1.164 and 1.278 kg dm^{-3}, 2.572 kg dm^{-3}, 0.504 m^3 m^{-3} and 5.8 $mmol_c$ dm^{-3}, respectively (Table 1). For the other attributes the median values were considered; (MPa), RP1 and RP2 (3.857 and 6.100 MPa), U1 and UG2 (0.122 and 0.118 kg kg^{-1}), UV1 (0.142 m^3 m^{-3}), DP1 (2.590 kg dm^{-3}), PT1 (0.560 m^3 m^{-3}) MO1 and MO2 (18.0 and 13.0 g dm^{-3}), pH1 and pH2 (4.2 and 4.0 $CaCl_2$) and ACPOT2 (5.7 $mmol_c$ dm^{-3}) (Table 1).

For the plant attribute ALT, mean values were below those verified by Rosa Filho et al. (2011), with mean ALT of 31 m in *Eucalyptus urophylla* and LIMA et al. (2010), who reported for *Eucalyptus camaldulensis*, under similar conditions to the present study ALT of 24 m, however, the values obtained were higher than those reported by Carvalho et al. (2012) for *Eucalyptus camaldulensis* also in an Oxisol with clayey texture in Cerrado condition, with average ALT of 9.2 m. Regarding DAP, the values found are within the range suitable for *Eucalyptus* spp. in the age range of the culture at the time of analysis (8 years), with values between 12 and 14 cm (Simões et al., 1980; Anjos & Fontes, 2017).

Regarding the soil physical results obtained, for soil density, the normal values for clayey soils vary from 0.9 to 1.7 kg dm^{-3} (Costa et al., 2014). DS values associated with the compaction state with high probability of presenting restriction risks to root growth are around 1.45 kg dm^{-3} for clay soils (Costa et al., 2014), so the verified soil density in the present work was adequate in the layers of 0.0-0.2 and 0.2-0.4 m.

With regard to DP, this variable expresses the relationship between the amount of dry soil mass per unit volume of soil solid; therefore, does not include soil porosity and does not vary with soil management (Costa et al., 2014), being therefore a characteristic dependent primarily on the chemical composition and mineralogical composition of the soil. The components that predominate in mineral soils present values of DP of about 2.65 kg dm^{-3}, except when it has organic matter content or high Fe and Al oxides (Costa et al., 2014), as verified in the present work.

The total pores of soils are constituted by the macro and micropores, so that the increase of one will reduce the percentage of the other. In the study of soil density, aggregation and porosity in areas of Cerrado conversion in the Pinus forest, Wendling et al. (2012) verified average total porosity values of 0.6 m^3 m^{-3}, close to those observed in the present study.

As for the penetration resistance, the mean values obtained were very high (Arshad et al., 1996) and were well above the critical limit of 2.5 MPa recommended by Camargo and Alleoni (1997), and Souza et al. (2006) and Marasca et al. (2011), who recommend an acceptable range between 1.5 and 3.0 MPa, indicating that the eucalyptus plants found physical limitations to the growth of the root system. However, it should be considered that the penetration resistance has a potential relation with soil moisture (Busscher et al., 1997; Silveira et al., 2010), which may explain the values found for the amplitude and the coefficient of variation, considering that small changes in the water content determine large variations in the dependent quantity, that is, in the resistance to penetration.

Compaction is a structural alteration that promotes the reorganization of the particles and their aggregates, being able to limit adsorption, gas exchange, nutrient absorption, infiltration and redistribution of water, delay in the emergence of seedlings and impairment of root and shoot development , resulting in decreases in crop productivity (Stone et al., 2002; Modolo et al., 2008). The physical attribute adopted as an indication of compaction has been the soil resistance to penetration, because it has direct relationships with the development of the plants and because it is more efficient in the identification of compaction states compared to the soil density (Silva et al., 2003), in this way, the soil could be considered as compacted for the cultivation of eucalyptus.

The soil pH was very low, providing high acidity in the soil, according to Raij et al. (1997), as well as low M.O., characteristic of Cerrado soils (Marchini et al., 2015). Thus, from the chemical point of view, the limiting factor for the development of the eucalyptus crop would be pH, indirectly providing a high Al content in solution, which influences the development of the root system, and consequently in the absorption of water and nutrients, with reflection on aerial part development and crop productivity.

3.2 Correlation Analysis

Through the study of the Pearson correlation (Table 2), it was possible to observe positive and negative correlations between the attributes of eucalyptus and physical and chemical of soil.

The correlation between the attributes was positive for ALT × DAP (r = 0.717**), UV1 × DP1 (r = 0.358*), MO1 × PH1 (0.754**), MO2 × PH2 (0.609**) and PT2 × ACPOT2 (0.326*) (Table 2, Figures 3 and 4), demonstrating that DAP is height dependent, that is, with eucalyptus height growth there is an increase in DAP, corroborating with Lima et al. (2017b), and further, that the particle density increases with increasing volumetric humidity in the 0.0-0.2 m layer, pH increases with increasing M.O. in the 0.0-0.2 and 0.2-0.4 m layers and that the total porosity increases with the increase in the potential acidity in the 0.2-0.4 m layer.

The correlation between attributes was negative for DAP × UV1 (r = -0.338*), RP1 × MO1 (r = -0.313*) and DP1-MO1 (r = -0.364*) (Table 2, Figures 3 and 4). showing that the higher is DAP, lower is the volumetric humidity in the 0.0-0.2 m layer, possibly due to the development of the root system, justifying the increase in diameter at breast height, and that this way increase the absorption of water and nutrients, thus reducing the volumetric humidity, and higher is the MO content, lower is the penetration resistance and the density of particles in the 0.0-0.2 m layer.

With the predominance of the Oxisols in Cerrado, the soils are strongly weathered and characterized by low natural fertility (Figuereido et al., 2008). Organic matter is fundamental to raise cation exchange capacity and, consequently, favor nutrient cycling, avoid sudden changes in pH and maintain a good aggregation of soil particles (Silva & Resck, 1997). The importance of organic matter in soils is comprehensive. Its performance is as much in the improvement of the physical conditions, as in the aeration, in the greater retention and storage of water, as in the chemical and physical-chemical properties, in the nutrient supply to the plants and in the greater cationic exchange capacity of the soil, besides providing a suitable environment for the establishment and activity of the microbiota (Figueiredo et al., 2008; Silva et al., 2014). Pearson's linear correlation results evidenced the positive influence of the increase in M.O. in the physical properties of the soil RP and DP, besides positively influencing the pH of the soil, which would culminate in greater availability of nutrients, since the average pH obtained in the present study was in the range between 4.0 and 4.2 in $CaCl_2$, and according to Silva et al. (2016), from the nutritional point of view, the adequate range is between 5.6 and 6.2 in $CaCl_2$, culminating in greater availability of nutrients for the eucalyptus crop.

Still with respect to M.O., it was expected that pH reduction with increasing M.O. due to the release of organic acids in the decomposition process of M.O. (Pavinato et al., 2008), however, this result was not verified possibly due to M.O. have not yet presented total decomposition, due to the high C/N ratio and high levels of lignin and polyphenols (Pulrolnick et al., 2009), resulting in slower decomposition.

Table 2. Pearson's linear correlation of eucalyptus production components and attributes of an Oxisol

Attributes[(a)]	*Correlation coefficient* [(b)]																		
	MO2	**MO1**	**ACPOT2**	**ACPOT1**	**PH2**	**PH1**	**PT2**	**PT1**	**DP2**	**DP1**	**DS2**	**DS1**	**UV2**	**UV1**	**UG2**	**UG1**	**RP2**	**RP1**	**DAP**
ALT	0.024	-0.072	0.019	0.140	-0.019	0.045	-0.036	0.050	-0.158	0.035	-0.002	0.027	0.012	-0.285	0.054	-0.177	0.203	**0.383***	**0.717****
DAP	-0.202	-0.051	-0.146	0.025	-0.224	-0.1815	-0.154	0.150	-0.170	-0.031	0.106	-0.177	0.106	**-0.338***	-0.003	-0.125	0.261	0.300	**1**
RP1	0.018	**-0.313***	0.174	0.159	0.049	-0.058	-0.266	-0.168	0.008	-0.032	**0.315***	0.094	0.178	-0.104	-0.091	-0.221	**0.815****	**1**	-
RP2	0.052	-0.255	0.290	0.028	0.043	-0.137	-0.169	0.0123	0.056	-0.007	0.235	0.014	0.164	-0.157	-0.004	-0.145	1	-	-
UG1	0.220	0.242	-0.210	-0.242	0.062	-0.114	-0.179	0.268	-0.147	0.133	0.121	-0.241	0.306	0.224	0.174	1	-	-	-
UG2	-0.030	-0.127	0.144	-0.050	0.073	-0.156	0.112	-0.115	-0.219	0.212	-0.204	0.024	**0.3181***	0.183	**1**	-	-	-	-
UV1	0.054	0.004	-0.072	-0.160	0.097	-0.086	0.084	**-0.594****	0.070	**0.358***	-0.105	**0.552****	0.024	**1**	-	-	-	-	-
UV2	0.155	-0.033	-0.259	0.041	-0.081	-0.032	**-0.806****	0.097	0.006	0.135	**0.823****	-0.230	1	-	-	-	-	-	-
DS1	-0.015	-0.019	0.128	0.017	0.093	0.059	0.273	**-0.669****	0.097	0.241	-0.253	1	-	-	-	-	-	-	-
DS2	0.200	0.042	-0.244	0.202	-0.076	0.1486	**-0.929****	0.152	0.139	0.009	1	-	-	-	-	-	-	-	-
DP1	-0.149	**-0.364***	-0.0937	-0.005	-0.163	-0.089	0.041	0.168	0.178	1	-	-	-	-	-	-	-	-	-
DP2	0.034	-0.244	0.268	0.124	-0.009	0.083	0.012	0.145	**1**	-	-	-	-	-	-	-	-	-	-
PT1	-0.017	-0.030	0.039	0.055	-0.144	-0.015	-0.099	1	-	-	-	-	-	-	-	-	-	-	-
PT2	-0.200	-0.134	**0.326***	-0.159	0.064	-0.126	**1**	-	-	-	-	-	-	-	-	-	-	-	-
PH1	**0.613****	**0.392***	0.1699	**0.754****	**0.537****	**1**	-	-	-	-	-	-	-	-	-	-	-	-	-
PH2	**0.727****	**0.171***	**0.609****	**0.381***	**1**	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ACPOT1	0.266	0.176	0.294	**1**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ACPOT2	0.252	-0.246	**1**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
MO1	**0.428****	**1**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
MO2	**1**		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Note. [(a)] ALT = Eucalyptus plant height; DAP = Diameter at breast height; RP, UG, UV, DS, DP, PT, MO, pH and ACPOT 1 and 2, are respectively the penetration resistance, gravimetric humidity, volumetric humidity, soil density, particle density, total porosity, organic matter, hydrogen potential and acidity potential, collected in the soil layers; [(b)] Pearson's linear correlation coefficient. ** significant at $p < 0.01$; * significant at $0.01 < p < 0.05$.

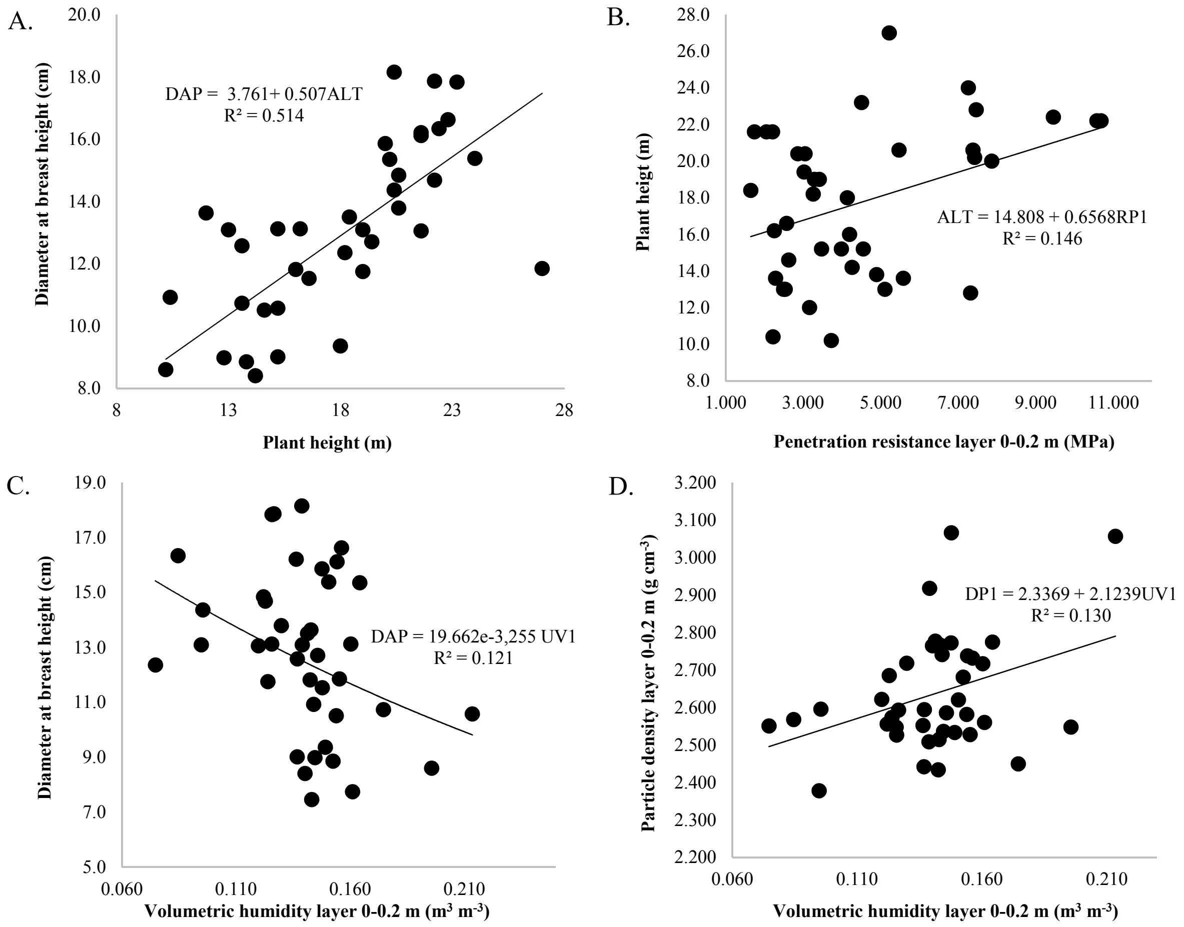

Figure 3. Regression graphs of the correlation between a) ALT × DAP; b) RP1 × ALT; c) UV1 × DAP; and d) UV1 × DP1

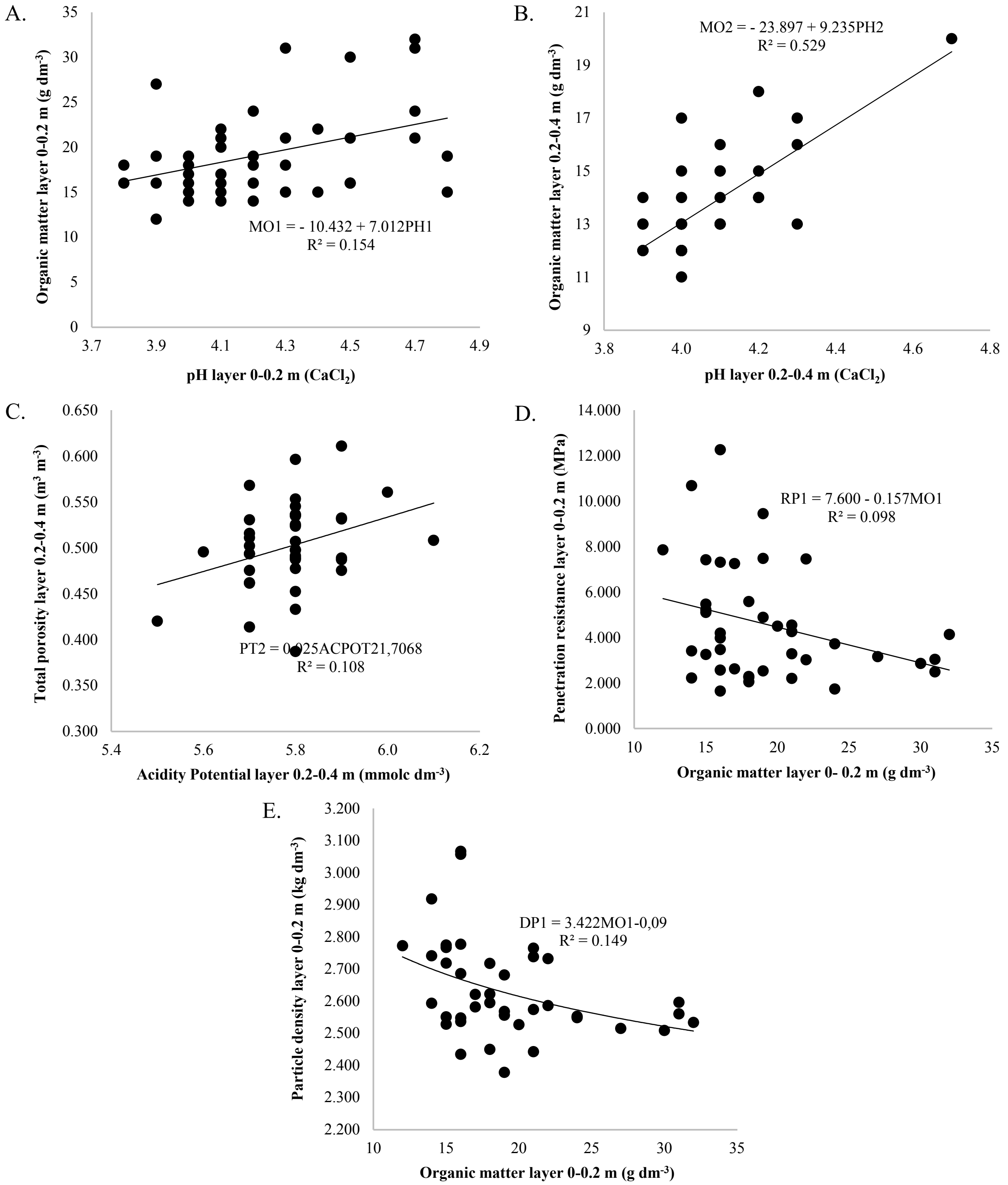

Figure 4. Regression graphs of the correlation between a) pH1 × MO1; b) pH2 × MO2; c) ACPOT2 × PT2; d) MO1 × RP1; and e) MO1 × DP1

3.3 Geostatistical Analysis

In Table 3 and Figure 5 are presented the parameters of the simple semivariograms for the attributes of plant and soil. The attributes that presented spatial dependence were DP1, DP2, DS1, DS2, UV1 and UG1 (Table 3 and Figure 5). All the others attributes did not presented spatial dependence. The lack of dependence is an indication that the value of semivariance is equal to the threshold, for any distance value. The total absence of spatial dependence is called a pure nugget effect, that is, the range (A0) of the data is smaller than the smaller spacing between collected samples. For these data, we have a completely random spatial distribution and the only applicable statistic is the classical statistics (Vieira, 2000).

The pure nugget effect indicates that the spatial distribution of the attribute in the study area is homogeneous, random or the sampling mesh used does not have enough points to detect the dependence that, if it exists, will be manifested at distances smaller than the smaller spacing between samples (Guimarães, 2004). In the present study, the most probable cause of the spatial homogeneity observed may be associated to the Oxisol, whose class presents an advanced process of soil weathering and stability in its formation process.

Regarding the performance of the semivariograms, the highest spatial determination coefficient (r^2) observed for the model adjustment was 0.855 in the spatial dependence modeling for the DP2 and the lowest coefficient was 0.121 in the modeling of the UV1 spatial dependence (Table 3 and Figure 5). All models were selected after cross-validation analysis. The theoretical model that presented the best fit for the empirical semivariance of soil chemical attributes was the exponential followed by the spherical.

According to Bottega et al. (2013), when semivariograms are presented as spherical and exponential, they present simultaneously low and medium continuity of spatial variability. However, the Gaussian model is a high continuation of spatial variability. These adjustments can be explained by the physico-chemical changes made in the soil, mainly by the chemical attributes that change due to the correction and fertilization practices. Thus, MO1 was the attribute of better semivariographic adjustment with a spatial dependency evaluator (ADE) of 67.1%, presenting a high spatial dependence (Table 3 and Figure 5).

The decreasing ratio of the ranges (m) is as follows: DP2 (47.8), DS2 (30.6), UG1 (28.5), DS1 (27.0), DP1 (23.1) and UV1 (17.4) (Table 3). Therefore, in the conditions of the present research, the values of the ranges to be used in the geostatistical packages that will feed the computational packages used in precision forestry, in general, should not be smaller than 17.4 m when under Brazilian Cerrado conditions in a clayey Oxisol.

Analyzing the physical and chemical attributes of the soil, the lowest value for the correlation coefficient found was 0.021 for the DP1 and the highest value of 0.201 was observed for DP2 (Table 3). The low coefficients of correlation are due to the dispersion of the cloud of points around the ideal line, which has an angular coefficient of 1 and cuts the origin of the y-axis (intercept) in the zero value. Thus, from the point of view of the geostatistical analysis, the DP2 was the attribute that presented as plausible quality indicator, in this case, soil physics with angular coefficient (b) of the cross validation of 0.815 (Table 4).

Table 3. Spatial analysis of some components of eucalyptus production and attributes of an Oxisol

Attribute	**Co**	**Co+C**	**Model**	**A**	**SQResidual**	R^2	**ADE (%)**	**DAL**	**IU**
ALT	$1.726*10$	$1.726*10$	EPP	-	-	-	-	68.30	9
DAP	8.530	8.530	EPP	-	-	-	-	68.30	9
DP1	$1.980*10^{-3}$	$1.946*10^{-2}$	Exponential	23.1	$1.280*10^{-5}$	0.509	89.8	68.30	9
DP2	$3.769*10^{-3}$	0.011420	Spherical	47.8	$3.866*10^{-6}$	0.855	67.1	68.30	9
DS1	$2.000*10^{-3}$	$1.38*10^{-2}$	Exponential	27.0	$3.983*10^{-5}$	0.215	85.5	85.38	9
DS2	$2.580*10^{-3}$	$1.456*10^{-2}$	Exponential	30.6	$6.922*10^{-6}$	0.634	82.3	68.30	9
RP1	5.970	5.970	EPP	-	-	-	-	68.30	9
RP2	9.539	9.539	EPP	-	-	-	-	68.30	9
UV1	$6.5*10^{-5}$	$5.12*10^{-4}$	Exponential	17.4	$2.782*10^{-8}$	0.121	87.3	68.30	9
UV2	$2.740*10^{-4}$	$2.740*10^{-4}$	EPP	-	-	-	-	68.30	9
UG1	$1.200*10^{-5}$	$9.100*10^{-5}$	Exponential	28.5	$4.729*10^{-10}$	0.507	86.8	68.30	9
UG2	$5.3*10^{-5}$	$5.300*10^{-5}$	EPP	-	-	-	-	68.30	9
PT1	$3.740*10^{-3}$	$3.740*10^{-3}$	EPP	-	-	-	-	68.30	9
PT2	$2.175*10^{-3}$	$2.175*10^{-3}$	EPP	-	-	-	-	68.30	9
MO1	$2.957*10$	$2.957*10$	EPP	-	-	-	-	68.30	9
MO2	3.756	3.756	EPP	-	-	-	-	68.30	9
PH1	$7.933*10^{-2}$	$7.933*10^{-2}$	EPP	-	-	-	-	68.30	9
PH2	$2.216*10^{-2}$	$2.216*10^{-2}$	EPP	-	-	-	-	68.30	9
ACPOT1	$3.556*10^{-2}$	$3.556*10^{-2}$	EPP	-	-	-	-	68.30	9
ACPOT2	$1.045*10^{-2}$	$1.045*10^{-2}$	EPP	-	-	-	-	68.30	9

Note. [a] ALT = Eucalyptus plant height; DAP = Diameter at breast height; RP, UG, UV, DS, DP, PT, MO, pH and ACPOT 1 and 2, are respectively the penetration resistance, gravimetric humidity, volumetric humidity, soil density, particle density, total porosity, organic matter, hydrogen potential and acidity potential, collected in the soil layers; EPP = nugget effect; ADE = space dependency assessor.

Table 4. Cross-validation of spatial analysis of some components of eucalyptus production and attributes of an Oxisol

Attribute	**Cross-validation**			**Eliminated Points**
	RC = b	**Y = a**	**R^2**	
DP1	0.420	1.52	0.021	(1) → point 3
DP2	0.815	0.48	0.201	(1) → point 9
DS1	-0.503	1.74	0.032	(2) → points 7 and 18
DS2	0.955	0.06	0.179	(2) → points 16 and 23
UG1	0.441	0.07	0.042	(1) → point 38
UV1	-0.770	0.25	0.034	(2) → points 4 and 30

Note. (a) ALT = Eucalyptus plant height; DAP = Diameter at breast height; RP, UG, UV, DS, DP, PT, MO, pH and ACPOT 1 and 2, are respectively the penetration resistance, gravimetric humidity, volumetric humidity, soil density, particle density, total porosity, organic matter, hydrogen potential and acidity potential, collected in the soil layers; RC = regression coefficient, a = angular coefficient.

In relation to the kriging maps (Figure 6), a spatial distribution arrangement of well-defined physical attributes can be observed in the evaluated area, which allowed the identification of homogeneous and soil-specific zones, which are very distinct for most of the attributes of plants and chemicals studied. It was found that the maps with high spatial similarity for the practical effect of soil management were those of DP1 (Figure 6A), DP2 (Figure 6B), DS1 (Figure 6C) and DS2 (Figure 6D). The relative similarities between these kriging maps occurred in the Center-South region, where the highest particle density concentrate (> 2.658 - > 2.774 kg dm^{-3} and > 2.614 - > 2.672 kg dm^{-3}) and soil density (>1.13 - > 1.22 kg dm^{-3} and > 1.23 - > 1.32 kg dm^{-3}) in 0.0-0.2 and 0.2-0.4 m layers, respectively, indicating that possibly this region presents a tendency of greater soil compaction, demanding a different management from the physical point of view.

The isolines maps obtained by means of data interpolation, kriging method, are fundamental in precision forestry. These data are then analyzed and worked with the purpose of planning new samplings and performing more accurate soil management, with lower cost/benefit ratio, according to the spatial variability of the values of each evaluated attribute.

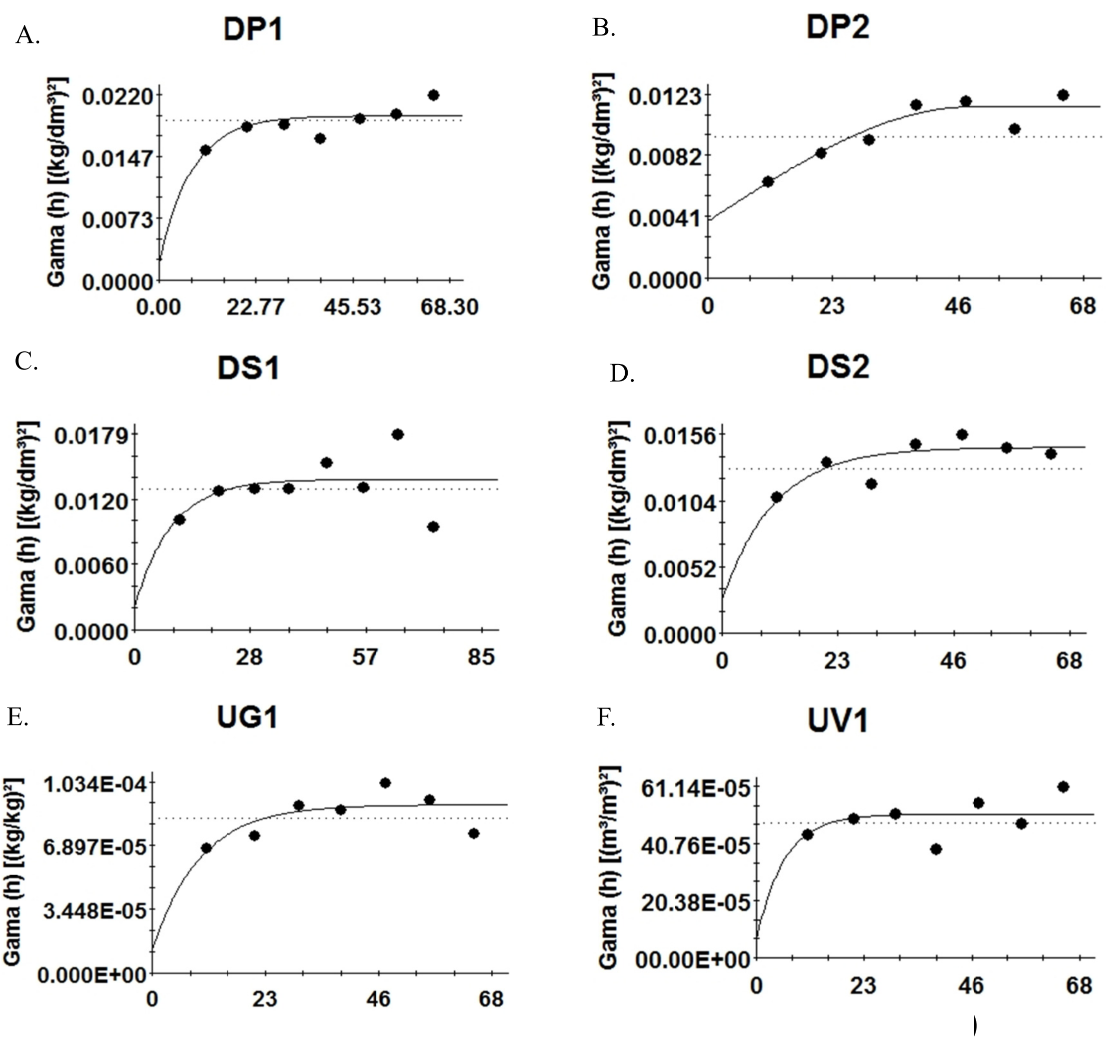

Figure 5. Semivariogram of a) Particle density in the layer 0-0.2 m (kg dm^{-3}); b) Particle density in the layer 0.2-0.4 m (kg dm^{-3}); c) Soil density in the layer 0-0.2 m (kg dm^{-3}); d) Soil density in the layer 0.2-0.4 m (kg dm^{-3}); e) Gravimetric humidity in the layer 0-0.2 m (kg kg^{-1}); and f) Volumetric humidity in the layer 0-0.2 m (m^3 m^{-3})

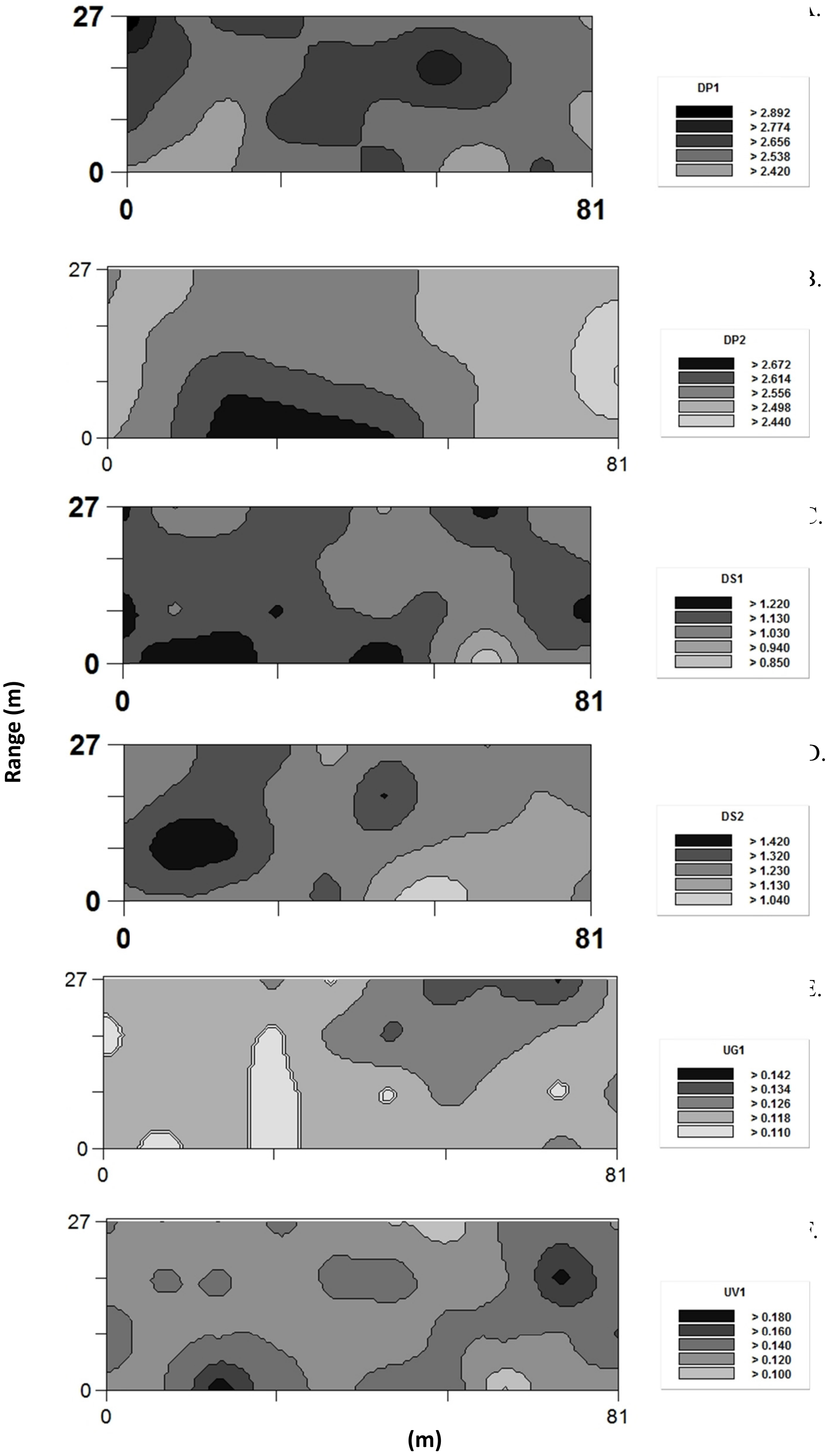

Figure 6. Kriging map of a) Particle density in the layer 0-0.2 m (kg dm^{-3}); b) Particle density in the layer 0.2-0.4 m (kg dm^{-3}); c) Soil density in the layer 0-0.2 m (kg dm^{-3}); d) Soil density in the layer 0.2-0.4 m (kg dm^{-3}); e) Gravimetric humidity in the layer 0-0.2 m (kg kg^{-1}); and f) Volumetric humidity in the layer 0-0.2 m (m^3 m^{-3})

4. Conclusions

The plant attributes of *Eucalyptus camaldulensis* showed high variability, while for the soil physical and chemical attributes the variability was low and medium.

Spatially, the dendrometric attributes of *Eucalyptus camaldulensis* and soil chemical attributes showed pure nugget effect and the great majority of soil physical attributes presented spatial dependence, which varied according to the evaluated attribute and depth of collection. In addition to the vertical variability, there is also horizontal variability between depths, since for the same attribute the range was different between the sampled layers.

The Kriging maps allowed a visualization of the distribution of the soil physical attributes representing an important instrument to its management.

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