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Spatial and temporal variability of soil and plant attributes after application of cellulose residue

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ABSTRACT: The industries of cellulose and paper have generated large amounts of solid waste and effluents which have been used as soil conditioners and source of nutrients to improve physical and chemical attributes of areas growing forest species. This study analyzes the spatial and temporal variability of *Eucalyptus urograndis* regarding the chemical attributes of soil treated with cellulose residue. The fertilization of an experimental area in the Três Lagoas county used a lime sludge/Oxyfertil® compound with a 2 ha. experimental grid containing 50 sampling points set up over it. Plant and soil samples were collected during three consecutive years (2014/2015, 2015/2016; 2016/2017). The assessment encompassed the following chemical attributes organic matter (OM); potential of hydrogen (pH); phosphorus (P), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}) and aluminum (Al^{3+}) contents; potential acidity ($H^+ + Al^{3+}$), sum of the bases (SB), cation exchange capacity (CEC), base saturation (V%), and aluminum saturation (m%), at the 0.00-0.20 m layer. Classical statistical analysis was performed using SAS software while geostatistical analysis used GS+. Low P, K^+, Ca^{2+}, and Mg^{2+} contents were indicated along the assessment period. OM and Al were the attributes that presented spatial and temporal dependence for all evaluated years. Also, the measured levels are considered sufficient for eucalyptus to establish in sandy soils. We also verified the space-temporal variability since nutrient ranges changed during the assessed period.

Key words: effluents; eucalyptus; fertility; geoestatistics; solid waste

Variabilidade espacial e temporal do solo adubado com resíduos de celulose

RESUMO: As indústrias de celulose e papel têm gerado elevadas quantidades de resíduos sólidos e efluentes, que vem sendo utilizados como condicionadores do solo e como fonte de nutrientes para melhorar os atributos químicos e físicos das áreas que vem sendo cultivadas com espécies florestais. O objetivo deste estudo foi analisar a variabilidade espacial e temporal do *Eucalyptus urograndis* em função dos atributos químicos do solo sob aplicação de resíduo da celulose como fertilizante agrícola. O solo foi adubado com o composto Lama de Cal + Oxyfertil, em seguida instalou-se uma malha experimental de 2 ha, contendo 50 pontos amostrais e posteriormente foram coletados atributos de planta e solos em três anos consecutivos no município de Três Lagoas. Os atributos químicos avaliados foram matéria orgânica (MO), potencial hidrogeniônico (pH), teores de fósforo (P), potássio (K^+), cálcio (Ca^{2+}), magnésio (Mg^{2+}), acidez potencial ($H^+ + Al^{3+}$), alumínio (Al^{3+}), valores de soma de bases (SB), capacidade de troca catiônica (CTC), saturação por bases (V%) e saturação por alumínio (m%) na camada de 0,00-0,20. A análise estática clássica foi realizada por meio do software SAS e a geoestatística pelo GS+. Os atributos de solo P, K^+, Ca^{2+} e Mg^{2+} apresentaram baixos teores nos anos avaliados, no entanto, esses teores são suficientes para que a cultura de eucalipto se estabeleça em solos arenosos. Por outro lado, houve variabilidade espaço-temporal entre os anos avaliados, visto que para um mesmo nutriente o alcance foi diferente entre os anos.

Palavras-chave: efluentes; eucalipto; fertilidade; geoestatística; resíduos sólidos

Introduction

Plantations of Eucalyptus species in Brazil it's among the most productive forests in the world. Brazilian tree planting industry employs a total area of 7,840,000 hectares accounting for 91% of all industrial timber in the country and 6.2% of gross domestic product (GDP). This makes Brazil one of the biggest timber producers in the world and the second largest cellulose producer. Most of the total area, 5.7 million hectares, is reserved for the cultivation of *Eucalyptus* sp.

The Eucalyptus plant rapid growth and development is a possible explanation to this increase as well as the varied uses of timber and the easy adaption of the tree to different edaphoclimatic conditions. Even so, productivity of commercial eucalyptus farms in Brazil is still quite variable, averaging 60 m^3 ha^{-1}, over seven-year rotations (Galindo et al., 2018).

The production of paper and cellulose has generated large amounts of solid residues, which has been the cause of significant environmental and economic concern, since for every 100 tons of cellulose produced, around 48 tons of waste are generated. The main residues are the sludge from effluent treatment plants, wood ash from auxiliary energy generation boilers and lime sludge; all of which are available for use in forest farming (Maeda et al., 2015).

An alternative for the use of residues from the cellulose and paper industry can be its application in agricultural soils, using as soil conditioners and source of nutrients that allows to maintain or restore soil quality, reducing the need for inorganic fertilizers, resulting in the improvement of soil characteristics that are necessary for the economic development of forest plantations (Alvarenga et al., 2015).

Lime sludge is a byproduct of wood cooking liquor clarification derived from the cellulose extraction process and contains high calcium (Ca) contents, similarly to those found in calcitic limestone. According to Simonete et al. (2013) and Maeda et al. (2015), when applied to soil, it reduces acidity and aluminum (Al) levels while elevating calcium (Ca) and sodium (Na).

The reduced magnesium content (Mg) present in lime sludge is a limitation for the use of this material, as evidenced by Simonete et al. (2013) in a study carried out with *Eucalyptus saligna* cultivated in Quartzarenic Neosol.

Cultivation of forest species for wood production occurs predominantly in areas with low agricultural aptitude, both due to topographical conditions unsuitable for mechanized farming and low fertility of the soil – characterized by low levels of Ca, Mg, potassium (K), and phosphorus (P) (Rubilar et al., 2018). Such a scenario has undermined eucalyptus productivity. However, nutritional deficiencies limiting the development of eucalyptus plants can be minimized by recycling organic waste produced by the cellulose and paper industries themselves (Abreu-Junior et al., 2017).

Evaluating changes in the soil productive capacity and associating them to eucalyptus plant development constitute processes which require precision silviculture using geostatistics as a tool to assess the spatial variability of production and its subjacent factors (Hegde et al., 2015). Spatial dependence analysis of georeferenced data requires its adjustment to semivariograms as a function of the distance between samples subsequently compiling kriging maps for each soil and plant attribute in question, leading to the achievement of specific soil management zones for the given attribute (Gomes et al., 2017).

The search for alternative uses of cellulose and paper residue provides new research opportunities and can be applied in forestry cultivation to help reduce environmental impacts. This study analyzes spatial and temporal variability of *Eucalyptus urograndis* regarding the soil chemical attributes treated with cellulose residue.

Material and Methods

Site characterization

The study was carried out in the experimental area located in the Três Lagoas county (MS), between latitude 20°27' S and longitude 52°29' W, at an altitude of approximately 318 meters. The area had been cultivated for about 50 years as a *Brachiaria decumbens* pasture for beef cattle and was degraded before the preparation of the ground for the implantation of the forest system.

Climate

The climate of the region is classified as A_w: tropical humid with a rainy summer and a dry winter season according to Alvares et al. (2013). Precipitation and mean annual temperatures range 1.600-1.900 mm and 22-24°C, respectively.

Soil type

Soil in the experimental area was characterized as Quartzarenic Neosol (Embrapa, 2013). In March 2014, a soil correction was performed by applying 2.0 Mg ha^{-1} dolomitic limestone containing 30% CaO and 12% MgO with effective calcium carbonate equivalent (ECCE) of 85% to raise base saturation to 50%. In June 2014, 20 deformed soil samples were randomly collected from (at the 0.00-0.20 m and 0.20-0.40 m layers) for soil chemical characterization according to methodology proposed by Raij et al. (2001). Results are shown in Table 1.

In June 25, 2014, the experimental grid received 2.0 Mg ha^{-1} of the lime sludge (60%)/Oxyfertil® (40%) corrective compound (Table 2). Oxyfertil® 6030F is a simple mineral fertilizer. In contact with water, it initiates an exothermic reaction forming $Ca(OH)_2$ hydroxides and partial $Mg(OH)_2$ hydroxides, releasing approximately 210 cal g^{-1} heat. Its solubility is approximately 0.8 g L^{-1}, with a pH of 12.4 (25° C solution). Particle size distribution is 0.0-3.0 mm before and 0.0-0.2 mm after reacting with water.

Distribution of the *Eucalyptus urograndis* seedlings, clone E13, followed a 3 m row spacing and a 2.5 m individual plant spacing.

Table 1. Chemical characterization of soil attributes.

Prof. (m)	OM (g dm^{-3})	pH $CaCl_2$	P (mg dm^{-3})	K^+	Ca^{2+}	Mg^{2+}	$H^+ + Al^{3+}$	Al^{3+}	SB	CEC	V (%)
				(mmol$_c$ dm^{-3})							
0.00-0.20	12	4.1	8	0.9	1	2	36	8	3.9	39.9	10
0.20-0.40	14	4.1	4	0.9	2	0	26	12	2.9	20.9	10

OM = organic matter; pH = potential of hydrogen; P = phosphorus; K^+ = potassium; Ca^{2+} = calcium; Mg^{2+} = magnesium; H^++Al^{3+} = potential acidity; Al^{3+} = aluminum; SB = sum of the bases; CEC = cation exchange capacity; V = base saturation index; m = aluminum saturation index; Prof = depth.

Table 2. Characteristics of the chemicals used for soil correction and fertilizing.

Chemicals	CaO	MgO	TRNP
		(%)	
Lime sludge	24	0.1	-
Oxyfertil®	60	30	175

CaO = calcium oxide; MgO = magnesium oxide; TRNP = total relative neutralization power.

Sampling

We defined the *X* and *Y* directions in the UTM coordinate system and performed the experimental grid overall staking according to plant spacing. The experimental grid had five transects containing 50 sample points. Eucalyptus lines followed ground topography to improve soil conservation. Sample spacing was 7.5 x 6.0 m.

Samples for analysis of soil and plant attributes were collected in the surroundings of each plant selected for testing. The first analysis occurred three months after having applied the lime sludge/Oxyfertil® compound, while the second analysis was performed six months after the planting of the eucalyptus trees.

Assessments

Plant attributes assessed: tree height (TH) through a graduated ruler and diameter at breast height (DBH) at a height of 1.30 m above ground using a digital caliper.

Soil attributes assessed: phosphorus (P); organic matter (OM); potential of hydrogen values (pH); levels of potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and aluminum (Al^{3+}). All sampling points occurred at the 0.00-0.20 m layer.

Statistical analysis

A descriptive analysis was performed for each attribute using classical statistical methods. SAS (Statistical Analysis System) software was applied for calculation of the following statistical parameters: mean, median, mode, minimum, and maximum values, standard deviation, coefficient of variation, kurtosis, and asymmetry.

We also carried out data frequency distribution analysis and a Shapiro-Wilk test (at 1%) to test the normality of the attributes. A correlation matrix for all the researched attributes was set up containing all possible paired combinations in order to detect significant correlations between plant attributes (dependent variables) and soil attributes (independent variables).

Geostatistical analysis was performed using the GS$^+$ 7.0 software (Gamma Design Software, 2004). Spatial dependence was analyzed by calculating semivariograms based on the stationarity premises of the intrinsic hypothesis.

According to the models, an adjustment of simple semivariograms was carried out primarily by initial selection of: a) the highest determination coefficient (r^2); b) the lowest residual sum of squares (RSS); c) the highest spatial dependence estimator (SDE). Each attribute had the estimation of nugget effect, range, and sill. Spatial dependence estimator (SDE) analysis followed the expression below (Gamma Design Software, 2004):

$$\mathrm{SDE} = \frac{\mathrm{C}}{(\mathrm{C} + \mathrm{Co})} \times 100 \quad (1)$$

where SDE = spatial dependence estimator; C = structural variance; C + Co = sill.

The proposed SDE interpretation was the following: For the spherical semivariogram: ≤ 7% → weak spatial dependence; ≤ 15% → moderate spatial dependence; > 15% → strong spatial dependence. For the exponential semivariogram: ≤ 6% → weak spatial dependence; ≤ 13% → moderate spatial dependence; > 13% → strong spatial dependence. For the Gaussian semivariogram: ≤ 9% → weak spatial dependence; ≤ 20% → moderate spatial dependence; > 20% → strong spatial dependence (Seidel & Oliveira, 2016).

Results and Discussion

Coefficients of variation (CV) for tree height (TH) values were 18.23%, 10.20% and 14.34%, while coefficients of variation for diameter at breast height (DBH) values were 23.45%, 23.94% and 16.98%, respectively for each cultivation year (Table 3).

TH values obtained in this study can be considered of medium variability, while DBH values can be regarded as medium to high variability. Pimentel-Gomes & Garcia (2002) suggest that a CV over 30% shows a too heterogeneous data series, which makes the mean unreliable. However, a CV below 20% points to homogeneous data and a significant mean, representing the obtained data.

During a experiment with *Eucalyptus camaldulensis*, Galindo et al. (2018) conducted a spatial variability analysis of dendrometric properties of eucalyptus and physical attributes of a Latosol and found average CV variabilities of 23.3 and 22.9%, respectively. In a similar study, Lima et al. (2010) found average TH and DBH values ranging from 12 to 11.8%, respectively. These *Eucalyptus urophylla* studies registered values below the ranges obtained in our study.

The soil attributes of phosphorus variability were high over the three experimental years, with coefficients of

Table 3. Descriptive statistics for eucalyptus in Quartzarenic Neosol.

Attributes	Descriptive statistics measurements									
	Mean	Med	Value		SD	Coefficient			Probability	
			Min	Max		Var (%)	Kur	Asy	Pr	FD
2014/2015										
TH (m)	3.51	3.60	1.70	4.50	0.64	18.23	0.03	-0.63	0.0759	NO
DBH (m)	0.027	0.028	0.010	0.036	0.006	23.45	0.20	-0.83	0.0120	UN
P (mg dm^{-3})	2.98	3.000	2.00	5.00	0.69	22.98	1.83	0.82	0.0001	UN
OM (g dm^{-3})	11.52	11.00	11.00	15.00	1.29	11.13	1.09	0.98	0.0001	UN
pH	4.14	4.00	2.90	6.00	0.46	11.00	5.77	1.51	0.0001	UN
K (mmol$_c$ dm^{-3})	0.60	0.50	0.20	1.40	0.29	48.65	0.13	0.79	0.0049	UN
Ca (mmol$_c$ dm^{-3})	3.28	2.00	1.00	11.00	2.84	86.46	0.71	1.17	0.0001	UN
Mg (mmol$_c$ dm^{-3})	4.20	3.00	1.00	18.00	3.53	84.15	5.80	2.23	0.0001	UN
Al (mmol$_c$ dm^{-3})	10.30	12.00	0.00	16.00	4.91	47.69	-0.57	-0.73	0.0004	UN
2015/2016										
TH (m)	10.57	10.70	7.20	12.20	1.078	10.20	1.497	-1.166	0.0019	UN
DBH (m)	0.097	0.102	0.056	0.122	0.016	16.98	0.441	-1.003	0.0012	UN
P (mg dm^{-3})	4.66	5.00	2.00	9.00	1.318	28.30	1.625	0.732	0.0011	UN
OM (g dm^{-3})	13.00	13.00	10.0	17.0	1.714	13.18	-0.567	0.350	0.0377	TN
pH	4.18	4.10	3.90	4.90	0.237	5.67	1.532	1.300	0.0001	UN
K (mmol$_c$ dm^{-3})	0.63	0.60	0.20	1.30	0.248	39.38	0.255	0.824	0.0045	UN
Ca (mmol$_c$ dm^{-3})	3.61	3.00	1.00	11.00	2.354	65.12	1.631	1.400	0.0001	UN
Mg (mmol$_c$ dm^{-3})	3.74	3.00	1.00	9.00	1.827	48.9	0.765	0.967	0.0001	UN
Al (mmol$_c$ dm^{-3})	6.12	6.00	0.00	10.00	2.471	40.4	-0.281	-0.617	0.0005	UN
2016/2017										
TH (m)	15.96	16.05	11.80	20.60	2.29	14.34	-0.98	-0.10	0.1642	NO
DBH (m)	0.134	0.135	0.068	0.184	0.03	23.94	-1.08	-0.18	0.0752	NO
P (mg dm^{-3})	2.32	2.00	5.00	1.00	0.68	29.45	4.54	1.89	0.0001	UN
OM (g dm^{-3})	15.06	15.00	11.00	27.00	2.69	17.87	7.07	1.98	0.0001	UN
pH	4.06	4.00	3.70	5.40	0.33	8.13	4.72	1.80	0.0001	UN
K (mmol$_c$ dm^{-3})	1.30	1.20	0.50	2.60	0.50	38.17	0.71	0.94	0.0100	UN
Ca (mmol$_c$ dm^{-3})	3.20	3.00	1.00	6.00	1.40	43.74	-0.12	0.65	0.0003	UN
Mg (mmol$_c$ dm^{-3})	3.18	3.00	1.00	7.00	1.53	48.25	0.11	0.85	0.0003	UN
Al (mmol$_c$ dm^{-3})	6.8	8.00	0.00	11.00	2.98	43.77	-0.75	-0.51	0.0060	UN

TH = tree height; DBH = diameter at breast height; P = exchangeable phosphorus; OM = organic matter content; pH = potential of hydrogen; K = exchangeable potassium; Ca = exchangeable calcium; Mg = exchangeable magnesium; Al = aluminum; SD = standard deviation; FD = frequency distribution; NO = normal; UN = undetermined; TN = tending to normal. Min = Minimum; Max = Maximum; Var = Variation; Kur = Kurtosis; Asy = Asymmetry.

variability between 19.45 and 22.98%. OM showed medium variability with values between 11.13 and 17.87%; pH had medium variability along the first year, and low variability over consecutive years, ranging from 5.67 to 11.00%. K, Ca, Mg and Al contents showed very high variability, encompassing from 38.17 to 86.46%. It is worth noting that in these cases variability decreased over the experimental period. According to Reis et al. (2018), variations of chemical soil attributes are related to irregular fertilization and liming. Statistically, it can be translated into high heterogeneity around the average for chemical attributes in the assessed area. Such heterogeneity is associated with the formation, accumulation, and distribution of soil particles as a function of topography and water flow and, mainly, by the application of lime sludge.

Average levels of phosphorus (2.98, 4.66, and 2.32 mg dm^{-3}), OM (11.52, 13.00, and 15.06 g dm^{-3}), K (0.60, 0.63, and 1.30 mmol$_c$ dm^{-3}), Ca (3.28, 3.61, and 3.20 mmol$_c$ dm^{-3}), and Mg (4.20, 3.74, and 3.18 mmol$_c$ dm^{-3}) found during the first, second and third experimental years (respectively) could be considered low. These values are below the levels recommended by Raij (2011) for agricultural crops and by Gonçalves et al. (2002) for the eucalyptus cultivation. These are congruent, however, according to the recommendations of Silveira et al. (2001), the following average levels were established as ideal to develop eucalyptus in sandy soils: phosphorus (5.6 mg dm^{-3}), OM (12.00 g dm^{-3}), pH (3.8), K (0.4 mmol$_c$ dm^{-3}), Ca (2.8 mmol$_c$ dm^{-3}), and Mg (0.9 mmol$_c$ dm^{-3}).

Clonal eucalyptus does not require as much nutrition as most agricultural crops and even as many other fast-growing tree species, such as *Pinus* spp. (Rodrigues et al., 2016). Even so, it is necessary to correct soil fertility when critical nutrients levels dip below the suitable value for the species (Guimarães et al., 2015).

Organic matter (OM) levels increased from 11.52 g dm^{-3} along the first to 15.06 g dm^{-3} over the third year. This increase in OM can be explained by the high contribution of litter deposited on the soil in areas under eucalyptus plantation, which cause positive changes in the physical, chemical and biological attributes, favoring the nutrient cycling and the maintenance of greater soil moisture in the area (Barreto et al., 2011). Pereira et al. (2018) evaluating organic fractions in the soil for eucalyptus plantations, observed that there was a high decomposition rate of the litterfall when compared to other tree species. According to Alvarenga et al. (2015), another factor that can contribute to increase the OM content is that the residues generated from cellulose and paper production have high OM content, which potentiates high changes in the organic matter content of the soil.

Before applying the lime sludge/Oxyfertil® compound, levels of Ca and Mg at the 0.00-0.20 and 0.20-0.40 m layers were low (Table 1), which is in accordance to data obtained by Maeda et al. (2015), who observed low levels of these nutrients in a Regolitic Neosol area reserved for forestry cultivation. This nutrient dynamic is exacerbated by the sandy texture and consequently high macroporosity of Quartzarenic Neosols. However, it can be improved – given the soil's low cohesion between particles and low levels of cementing agents (Reis et al., 2018). In any case, according to the authors, such low levels of Ca and Mg would be sufficient to reach average annual increments of up to 20 m^3 ha^{-1} $year^{-1}$ in timber production.

The application of the compound led to an increase in the levels of Ca (3.28, 3.61 and 3.20 $mmol_c$ dm^{-3}) and Mg (4.20, 3.74 and 3.18 $mmol_c$ dm^{-3}) in relation to the initial soil characterization (Tables 1 and 3). This balance between Ca and Mg is important to promote the proper development of plants, which makes it necessary for any corrective agents to contain both nutrients in adequate proportions. A correct balance allows adequate adsorption and absorption of these nutrients. Simonete et al. (2013) and Maeda et al. (2015) observed significant increases in Ca and Mg levels after applying lime sludge to a Quartzarenic Neosol eucalyptus cultivation area.

During the experimental period, we verified a decrease in the amount of aluminum (Al) in the soil after applying the compound (10.00, 6.12 and 6.8 $mmol_c$ dm^{-3}), however, no increase in pH was observed (4.14, 4.18, and 4.06) (Table 3). The application of 2.0 Mg ha^{-1} lime sludge/Oxyfertil® compound caused no pH change but decreased exchangeable Al and increased exchangeable Ca and Mg, resulting in decreased aluminum saturation.

The high levels of Al and low pH in the soil are associated with intense rainfall over the years, which leads to large lixiviation, remaining in the exchange complex, predominantly, the cations H and Al (Reis et al., 2018). Kochian et al. (2015) reports that, in tropical regions, acid soils are generally heterogeneous with respect to pH and aluminum saturation, where pH may have great variability in small areas. In addition to the natural processes, some agricultural practices such as the withdrawal of the vegetal cover, the leaching of nitrogen and indiscriminate use of fertilizers acidify even more the agricultural soils (Sade et al., 2016).

According to Gmach et al. (2018), areas used to produce eucalyptus in Brazil are generally acidic soil, poor in nutrients and organic matter. Species of the genus *Eucalyptus* are more tolerant to high levels of Al^{+3} in the soil than most agricultural crops in addition to requiring levels of Ca and Mg below those established as critical for most cultures (Rodrigues et al., 2016). This allows planting of eucalyptus trees to be carried out in low agricultural aptitude soils, such as Quartzarenic Neosol (Gmach et al., 2018).

Positive and negative correlations occurred between the assessed nutrients. Negative correlations pointed out to a linear relationship between soil acidity measurements in the following cases: Al x Ca (r = -0.836**, -0.625**, -0.363*), Al x Mg (r = -0.803**, 0.6012**, -0.363*), and Al x pH (r = -0.712**, -0.797**, -0.887**). Therefore, the levels of a nutrient increase only upon the decrease of another (Table 4). Such an inverse correlation shows that calcium and magnesium levels reduce due to a substantial increase in aluminum (Al) levels, harmful to plant development. Toxicity by aluminum is one of the limiting factors to forestry production in acid soils (Marques Junior et al., 2014).

The largest direct correlations were the following: Ca x pH (0.567**), OM x Mg (0.580**) and Ca x Mg (r = 0.670**) for 2014/2015; K x OM (r = 0.529**), Ca x pH (0.636**) and Mg x pH (0.690**) for 2015/2016; Mg x OM (0.472*), Mg x Ca (0.496*), and P x OM (0.666**) for 2016/2017 (Table 4). These direct correlations indicated that with the increase of calcium and magnesium contents from the soil correction, there is a substantial increase in pH, which provides greater availability of nutrients in the soil solution for the plants. With increase of calcium and magnesium contents leads

Table 4. Correlation matrix for eucalyptus attributes and chemical attributes of a Quartzarenic Neosol at the 0.00-0.20 m layer, for the three experimental years.

Att.	TH	DBH	P	OM	pH	K	Ca	Mg
				2014/2015				
DBH	0.624**							
P	0.098	0.111						
OM	0.007	-0.216	-0.237					
pH	-0.060	0.083	0.310*	0.263				
K	-0.005	0.026	0.174	0.483**	0.216			
Ca	-0.123	-0.142	0.108	0.537**	0.567**	0.386**		
Mg	-0.192	-0.242	0.313	0.580**	0.427**	0.305**	0.670**	
Al	0.094	0.126	-0.283*	-0.414**	-0.712**	-0.295	-0.836**	-0.803**
				2015/2016				
DBH	0.847**							
P	0.062	0.125						
OM	-0.211	-0.094	0.216					
pH	-0.071	-0.119	-0.194	0.067				
K	-0.218	-0.193	0.058	0.529**	0.140			
Ca	0.075	-0.050	-0.128	0.208	0.636**	0.306*		
Mg	-0.127	-0.145	-0.079	0.166	0.690**	0.183	0.483*	
Al	0.038	0.127	0.193	-0.142	-0.797**	-0.343*	-0.625**	-0.601**
				2016/2017				
DBH	0.912**							
P	-0.339	-0.273						
OM	-0.338	-0.327	0.666**					
pH	-0.157	-0.119	0.236	0.300				
K	0.061	0.018	0.116	0.260	0.150			
Ca	-0.126	-0.120	0.111	0.121	0.249	0.013		
Mg	-0.225	-0.175	0.275	0.472*	0.302	0.113	0.496*	
Al	0.038	0.024	-0.219	-0.329	-0.887**	-0.228	-0.363*	-0.417*

Att. = Attributes; TH = tree height; DBH = diameter at breast height; P = exchangeable phosphorus; OM = organic matter content; pH = potential of hydrogen; K = exchangeable potassium; Ca = exchangeable calcium; Mg = exchangeable magnesium; Al = aluminum; SD = standard deviation; FD = frequency distribution; NO = normal; UN = undetermined; TN = tending to normal. ***** Significant at 5%, ****** Significant at 1%.

to a better development of eucalyptus plants in height and diameter.

For Bordron et al. (2018), applying fertilization as potassium, calcium, magnesium and phosphorus at planting in Eucalyptus areas established in sandy soil increases nutrient concentrations in soil solutions down to a depth of 3 m over the first 2 years after planting.

Calcium availability is important for improving eucalyptus development because it is associated to the cell signaling process, determination of membrane permeability, composition of the cell wall and cell division and development, as highlighted by Ali et al. (2017). Similarly, magnesium is essential to formation of chlorophyll, protein synthesis, cellular pH regulation and equilibrium of cations and anions.

According to the parameters of the simple semivariograms for plant and soil attributes measured during the three experimental years, the attributes that showed spatial dependence were: OM, K, Ca, Mg and Al (first year); TH, P, OM and Al (second year); and OM, pH, K, Mg, and Al (third year) (Table 5).

A dependence absence indicates that the semivariance value is equal to the sill for any distance value, in other words, nugget effect. Total absence of spatial dependence is known as pure nugget effect, which occurs when data range is smaller than the smallest spacing between collected samples. For that type of data, spatial distribution is completely random, and the only applicable form of statistics is classical statistics (Vieira, 2000).

Table 5. Estimated semivariogram models and parameters regarding eucalyptus attributes and chemical attributes of a Quartzarenic Neosol to the 0.00-0.20 m layer over the three experimental years.

Att.	Model	Nugget C_o	Sill $(C_o + C)$	Range (m)	r^2	RSS	SDE[(d)] (%)	Class
			2014/2015					
TH	PNE	0.335	-	-	-	-	-	-
DBH	PNE	$5*10^{-4}$	-	-	-	-	-	-
P	PNE	0.467	-	-	-	-	-	-
OM	Exp (51)	0.001	1.803	20.55	0.864	0.104	99.9	SSD
pH	PNE	0.184	0.184	-	-	-	-	-
K	Exp (51)	0.012	0.088	19.8	0.556	$6.92*10^{-4}$	86.4	SSD
Ca	Exp (62)	1.490	7.750	30.3	0.470	11.60	80.8	SSD
Mg	Exp (66)	1.340	13.380	22.8	0.762	19.3	89.7	SSD
Al	Exp (67)	3.70	25.030	10.8	0.124	66.5	85.2	SSD
			2015/2016					
TH	Sph (17)	0.187	0.631	16.8	0.585	0.704	70.4	SSD
DBH	PNE	$2.850*10^{-4}$	$2.850*10^{-4}$	-	-	-	-	-
P	Gau	0.139	1.162	11.6	0.827	0.911	88.0	SSD
OM	Exp (76)	1.315	3.068	26.7	0.545	0.385	57.1	SSD
pH	PNE	0.055	0.055	-	-	-	-	-
K	PNE	0.064	0.064	-	-	-	-	-
Ca	PNE	5.682	5.682	-	-	-	-	-
Mg	PNE	3.286	3.286	-	-	-	-	-
Al	Exp (16)	0.470	5.145	14.1	0.623	1.57	90.9	SSD
			2016/2017					
TH	PNE	5.140	5.140	-	-	-	-	-
DBH	PNE	$9.74*10^{-4}$	$9.74*10^{-4}$	-	-	-	-	-
P	PNE	0.435	0.435	-	-	-	-	-
OM	Exp (35)	2.510	7.432	30.00	0.719	2.99	66.2	SSD
pH	Exp (51)	0.065	0.131	88.8	0.319	$4.441*10^{-3}$	50.4	SSD
K	Exp (35)	0.032	0.223	16.2	0.714	$1.350*10^{-3}$	61.7	SSD
Ca	PNE	1.920	1.920	-	-	-	-	-
Mg	Exp (10)	1.084	2.832	87.7	0.810	0.225	61.7	SSD
Al	Exp (10)	1.070	7.721	17.4	0.373	18.8	86.1	SSD

TH = tree height; DBH = diameter at breast height; P = exchangeable phosphorus; OM = organic matter content; pH = potential of hydrogen; K = exchangeable potassium; Ca = exchangeable calcium; Mg = exchangeable magnesium; Al = aluminum; Sph = spherical; Exp = exponential; Gau = Gaussian; PNE = Pure Nugget Effect; RSS = residual sum of squares; SDE = spatial dependence estimator (WSD = weak spatial dependence, MSD = moderate spatial dependence and SSD = strong spatial dependence).

According to Isaaks & Srisvastava (1989), pure nugget effect indicates that the spatial distribution of the attribute in the study area is homogeneous, random or the sampling grid used does not have sufficient points to detect the dependence.

Parameters of the adjusted semivariograms showed the highest coefficients of spatial determination (r^2): r^2 = 0.864 (2014/2015) for modeling of OM spatial dependence; r^2 = 0.827 (2015/2016) for P; and r^2 = 0.810 (2016/2017) for Mg. Lowest coefficients were r^2 = 0.124 (2014/2015) for modeling of Al spatial dependence; r^2 = 0.373 (2016/2017) for OM; and r^2 = 0.319 (2016/2017) for pH.

The exponential model was the theoretical model used containing the best adjustment to empirical semivariance of the soil chemical attributes followed by the Gaussian spherical model (Table 5). These adjustments can be explained by physicochemical changes carried out in the soil, especially to chemical attributes, which change according to fertilization and correction practices. Thus, the OM attribute had the best semivariographic adjustment with a spatial dependence estimator (SDE) of 99.9% during the first year (strong spatial dependence) followed by Al over the second and third years, with 90.9 and 86.1% SDEs, respectively (both classified as strong spatial dependence).

The highest ranges were found in the following attributes: Ca (30.3 m) and Mg (22.8 m) [2014/2015]; OM (27.7 m) and TH (16.8 m) [2015/2016]; pH (88.8 m) and Mg (87.7 m) [2016/2017] (Table 5 and Figure 1). Range values fed to geostatistical software packages used in precision silviculture should not be lower than 10.8 m (distance value for Al obtained in experimental year one) when utilizing the lime sludge + Oxyfertil® corrective. For year 2, the smallest distance value was 11.6 m (P) and for year 3, 16.2 m (K).

Range is an important measure in experimental planning and evaluation since it represents the distance at which the sample points are correlated and can assist the definition of the sampling procedure and this parameter is an indicator of the semivariogram model adjustment. Sampling radius can be defined from the spatial dependence range. Attributes studied here showed different range values across the years; these values were above the stipulated by the experimental grid (Marques Junior et al., 2014).

Kriging maps showed a well-defined spatial distribution of chemical attributes, which allowed the identification of homogeneous and soil-specific areas, very distinguishable regarding the most studied attributes (Figure 1). Maps showing high spatial similarity for the years of 2014/2015 and 2016/2017 concerned the following attributes: OM (Figures 1A and 1J), K (Figures 1B and 1L), Ca (Figure 1C), Mg (Figure 1D and 1M), Al (Figures 1E and 1N), and pH (Figure 1K).

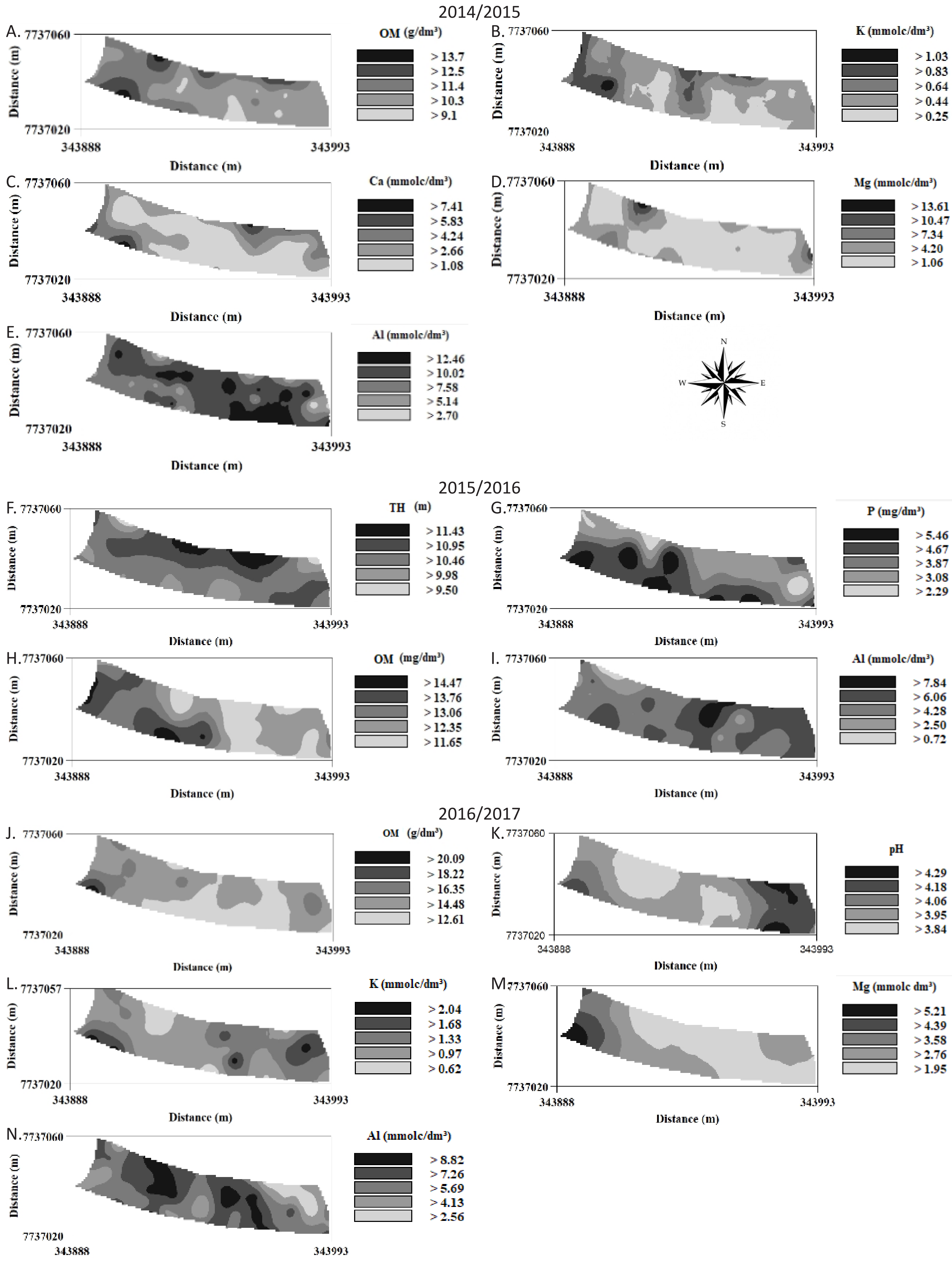

Figure 1. Kriging maps of plant and soil attributes for the three years studied.

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The eastern area indicated similarities between kriging maps with the highest concentrations of organic matter (13.68 and 20.09 mg dm^{-3}) and consequently the highest concentrations of K (1.03 and 2.04 $mmol_c$ dm^{-3}), Ca (7.41 $mmol_c$ dm^{-3}), and Mg (13.61 and 5.21 $mmol_c$ dm^{-3}). This occurred because organic matter is the main soil nutrient conditioner, especially for sandy soils. The same eastern region of the kriging maps also presented the highest pH value (4.29) (Figure 1K) as well as the lowest levels of Al (2.70 and 2.56 $mmol_c$ dm^{-3}) (Figures 1E and 1N).

The attributes that presented spatial and temporal variability were OM (Figures 1A, H and J) and Al (Figures 1E, I and N). The behavior and the amplitude of the variability were different in the experimental area over the years (2014/2015; 2015/2016; 2016/2017), demonstrating that OM increased from 13.7 to 20.1 g dm^{-3} and Al decreased from 12.46 to 8.82 $mmol_c$ dm^{-3}. In both cases there was difference between the kriging maps.

Isoline maps elaborated from data interpolation and kriging are fundamental in precision silviculture for the possibility to be analyzed and processed to plan new samplings and carry out more accurate fertilizing and soil correction with a better cost/benefit relationship according to the spatial variability of each attribute assessed.

Conclusions

Application of the lime sludge/Oxyfertil® compound as a sustainable fertilizer promoting improvements to levels of calcium and magnesium in the soil, making it a viable limestone alternative.

Pure nugget effect was demonstrated through the spatial analysis of dendrometric properties of eucalyptus. Soil attributes had spatial dependence, which varied vertically and temporally, across the experimental years, since, for the same nutrient, the range was different between the years.

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