

ASPECTS OF THE SILVOPASTORAL SYSTEM CORRELATED WITH PROPERTIES OF A TYPIC QUARTZIPSAMMENT (ENTISOL) IN MATO GROSSO DO SUL, BRAZIL

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ABSTRACT

In Brazil, grazing mismanagement may lead to soil and pasture degradation. To impede this process, integrated cropping systems such as silvopasture have been an effective alternative, allied with precision agriculture based on soil mapping for site-specific management. In this study, we aimed to define the soil property that best sheds light on the variability of eucalyptus and forage yield. The experiment was conducted in the 2011/12 crop year in Ribas do Rio Pardo, Mato Grosso do Sul State, Brazil. We analyzed linear and spatial correlations between eucalyptus traits and physical properties of a Typic Quartzipsamment at two depths (0.00-0.10 and 0.10-0.20 m). For that purpose, we set up a geostatistical grid for collection at 72 points. Gravimetric moisture in the 0.00-0.10 m layer is an important index of soil physical quality, showing correlation to eucalyptus circumference at breast height (CBH) in a Typic Quartzipsamment. With an increase in resistance to penetration in the soil surface layer, there is an increase in eucalyptus height and in neutral detergent fiber content in the forage crop. From a spatial point of view, the height of eucalyptus and the neutral detergent fiber of forage can be estimated by co-kriging analysis with soil resistance to penetration. Resistance to penetration values above 2.3 MPa indicated higher yielding sites.

Keywords: geostatistics, resistance to penetration, soil management, agricultural sustainability.

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RESUMO: ASPECTOS DO SISTEMA SILVIPASTORIL CORRELACIONADOS COM ATRIBUTOS DE UM NEOSSOLO QUARTZARÊNICO EM MATO GROSSO DO SUL

No Brasil, pastagens com manejo inadequado conduzem à degradação tanto das pastagens como do solo. Para frear esse processo, uma alternativa eficaz tem sido a exploração de sistemas integrados, como os sistemas silvipastoris, aliados à agricultura de precisão, que tem como base o mapeamento de zonas específicas de manejo do solo. Este trabalho teve por objetivo definir o atributo físico do solo que melhor explique a variabilidade da produtividade do eucalipto e dos componentes da produtividade da forragem. Este estudo foi desenvolvido no ano agrícola de 2011/2012, no município de Ribas do Rio Pardo, Mato Grosso do Sul. Foram analisadas as correlações lineares e espaciais entre atributos do eucalipto e de alguns atributos físicos de um Neossolo Quartzarênico, em duas profundidades (0,00-0,10 e 0,10-0,20 m). Para isso, foi instalada uma malha geoestatística, onde foram coletados 72 pontos. A umidade gravimétrica, na camada de 0,00-0,10 m, é indicadora da qualidade física do solo, apresentando correlação para a circunferência à altura do peito na cultura do eucalipto em um Neossolo Quartzarênico. Com o aumento da resistência à penetração na camada superficial, ocorre o aumento da altura do eucalipto e da fibra em detergente neutro do cultivo da forragem. Do ponto de vista espacial, a altura do eucalipto e a fibra em detergente neutro podem ser estimadas por meio da co-krigagem com a resistência à penetração. Assim, valores da resistência acima de 2,3 MPa indicaram sítios com as mais elevadas produtividades.

Palavras-chave: geoestatística, resistência à penetração, manejo do solo, sustentabilidade agrícola.

INTRODUCTION

In Brazil, soil degradation and low yield indices of grazing areas merit special attention from agronomists and farmers (Montanari et al., 2013). In the Cerrado (Brazilian tropical savanna), grazing areas under inadequate management have led to soil degradation by compaction and loss of fertility. Thus, degradation of grazing areas is an evolving process of loss of vigor, yield, and natural recovery capacity, rendering the area unable to sustain the forage production and quality required by animals, and to overcome to damaging effects of pests, diseases and weeds (Andreotti et al., 2008).

To slow this process and recover already degraded pastures, the search for soil management systems such as those that integrate crops and livestock for the purpose of recovering or maintaining soil quality have been fundamental for sustainable crop and livestock management (Bono et al., 2013). Midwestern Brazil has significant potential for application of agroforestry systems, and silvopastoral systems in particular. Silvopastoral systems decrease environmental impacts inherent to conventional cattle raising systems by favoring ecological restoration of degraded pastures, diversifying farm production, generating profits and additional products, reducing dependence on external inputs, and enhancing sustainable land use, among other benefits (Pezarico et al., 2013).

Trees within the beef cattle production system may play an important role in the formation of a microclimate favorable to grazing since they reduce stress and provide greater animal welfare, with positive effects on weight gain, milk production,

and birth rate, and trees also serve as windbreaks (Trecenti et al., 2008).

Analysis of the relationship between yield capacity of *Eucalyptus* spp. and soil properties favors rational forest and soil management, preventing degradation of physical properties, with a view toward sustainable production (Ortiz et al., 2006), and, above all, contributing to precision forestry techniques. As reported by Vettorazzi and Ferraz (2000), precision forestry is based on collection and analysis of geospatial data for site-specific interventions with adequate precision and accuracy.

Soil physical quality for plant growth can be determined by the degree of mechanical resistance of the soil to root growth, for it limits root elongation and thereby reduces plant yield. Some current studies have concluded that these properties are interdependent, e.g., resistance to penetration exhibits an inverse variation with moisture, and a positive variation with soil bulk density. Interaction among these physical properties determines soil quality (Montanari et al., 2010).

Among the most advanced technologies currently used in farming, precision agriculture is a fundamental tool for monitoring crops in real time and, thus, enhancing production by developing activities according to local soil fertility, in association with soil classes and respective optimal management systems. Tools such as geostatistics are fundamental for scientific agricultural research, allowing georeferencing of locations in terms of their soil physical and chemical properties and their relationship to crop yield. Therefore, in geostatistics, co-kriging examines the spatial dependence between neighboring samples, expressed in cross

semivariograms, estimating a primary variable of interest through a secondary one (Silva et al., 2003).

The current study aims to define the soil physical property that best sheds light on the variability of eucalyptus and forage yields.

MATERIAL AND METHODS

This study was carried out in 2011/12 crop year in Ribas do Rio Pardo, Mato Grosso do Sul - MS, Brazil at 20° 26' 34" S latitude and 53° 45' 32" W longitude with average annual rainfall of 1,500 mm, and average temperature throughout the year ranging from 19 to 25 °C. According to the Köppen classification, the climate is Aw type, characterized by a humid tropical climate with a rainy summer and dry winter.

Initial characterization of soil fertility and classes of evaluation according to Raij (1991) are presented for the respective soil depths of 0.00-0.20 and 0.20-0.40 m as follows: OM (11; 8 mg dm⁻³), pH (4.0; 4.1), P (8; 3 mg dm⁻³); K⁺ (0.2; 0.1 mmol_c dm⁻³); Ca²⁺ (1; 0 mmol_c dm⁻³), Mg²⁺ (1; 0 mmol_c dm⁻³), H+Al (28; 23 mmol_c dm⁻³), Al³⁺ (9; 6 mmol_c dm⁻³), BS (19; 9 mmol_c dm⁻³), CEC (47; 32 mmol_c dm⁻³), V (40; 28 %), and m (32; 42 %). In initial characterization of physical properties, we verify that soil resistance to penetration at the depths of 0.00-0.10, 0.10-0.20, 0.20-0.30, and 0.30-0.40 m were 1.054, 1.445, 1.558, and 1.513 MPa and soil moisture at those depths were 0.035, 0.030, 0.030, and 0.040 kg kg⁻¹, respectively.

An area of approximately one hectare was prepared according to the farming routine for commercial eucalyptus, i.e., desiccation of *braquiária* (signalgrass) with glyphosate and, 15 days later, subsoiling to 0.6 m with furrow opening and fertilization. Saplings were then planted using seedlings commercially produced in the Reflorestadora Ramires nursery.

Planting occurred from April 29 to May 15, 2008 in a degraded signalgrass (*Brachiaria decumbens* cv. Basilisk) grazing area established for more than 20 years in a Quartzipsamment (Entisol) soil with a flat topography. Three different forages were sown in March 2011: *Brachiaria brizantha* cv. Marandú, *Brachiaria brizantha* cv. Piatã, and *Panicum maximum* cv. Massai.

Sampling of dendrometric properties, dry matter, and forage bromatological properties was conducted according to a 72-point grid with irregular spacing. The eucalyptus plant properties studied were circumference at breast height (CBH) and plant height (PH); forage properties studied were total dry matter (TDM), leaf dry matter (LDM), stem dry matter (SDM), dry matter of dead material (DMDM),

crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), and organic matter digestibility *in vitro* (IVOMD).

Grass availability was assessed through sample collection in April 2012 up to a 1-m distance from trees. The sampling area was 0.5 × 0.5 m and grass was cut at ground level. Sampling material was weighed in the field and taken to the laboratory of Embrapa Gado de Corte (Embrapa Beef Cattle Research Center) in Campo Grande, MS, Brazil. They were then separated into the components of leaf blade, stem with sheath, and dead material of weeds and grasses (other types of signalgrass). These components were then placed in an air circulation laboratory oven at 55 °C until reaching constant weight for determination of dry matter. Only the leaves were ground and analyzed to estimate nutritional value. Crude protein (CP), neutral detergent fiber (NDF), acid Detergent Fiber (ADF), and *in vitro* organic matter digestibility (IVOMD) contents were determined by near infrared reflectance spectroscopy (NIRS), as proposed by Marten et al. (1985). Sample NIRS data in the 1,100 to 2,500 nm wavelength range were stored by a NR5000 spectrometer coupled to a microcomputer.

Trees were measured by the Reflorestadora Ramires team following standard procedure. Plant height (PH) was measured by a hypsometer, and circumference at breast height (CBH) by a measuring tape at 1.30 m above the ground.

Soil physical analyses were performed in the laboratory of the Universidade Estadual de Mato Grosso do Sul, Unidade de Aquidauana. The properties studied were soil resistance to penetration (SRP) in MPa, gravimetric moisture (GM), soil bulk density (SBD), volumetric moisture (VM), particle density (PD), and total porosity (TP) of soil samples from around eucalyptus trees nearest the sample points, collected at the depths of 0.00-0.10 and 0.10-0.20 m.

Soil resistance to penetration (SRP) was evaluated by an impact penetrometer (Stolf, 1991) and calculated according to the equation in Rosa Filho et al. (2009) (Equation 1):

$$RP = \{5.581 + 6.891 \times \{[N/(PA)] \times 10\}\} \times 0.0981 \quad \text{Eq. 1}$$

where SRP is soil resistance to penetration (MPa), N is the number of impacts of the penetrometer hammer for a reading, and A and P are readings before and after impact. The disturbed soil sample used for determination of gravimetric moisture (GM) was collected at same time as the sample of resistance to penetration using a bailer-boring auger. Soil bulk density (SBD) was measured by the volumetric ring method, whereas particle density (PD) was measured according to the alcohol-method (graduated flask). Thus, soil total porosity (TP) was determined according to equation 2, proposed by Embrapa (1997):

$$TP = [1 - (SBD \times PD^{-1})] \quad \text{Eq. 2}$$

where TP is total porosity ($\text{m}^3 \text{m}^{-3}$), SBD is soil bulk density (kg dm^{-3}), and PD is particle density (kg dm^{-3}).

Equation 3, cited by Kiehl (1979), obtained volumetric moisture (VM):

$$VM = GM \times SBD \quad \text{Eq. 3}$$

where VM is volumetric moisture [$\text{m}^3 \text{m}^{-3}$], GM is gravimetric moisture [kg kg^{-1}], and SBD is soil bulk density [kg dm^{-3}]. Disturbed soil samples collected with a soil probe were used to obtain GM values.

For each property under consideration, descriptive analysis was performed with the aid of classical statistics using SAS (Schlotzhaver and Littell, 1997). Frequency distribution analysis was also performed using the Shapiro-Wilk test at 1 % probability.

Geospatial modeling was performed through GS+ 7.0 software (GS+, 2004). Kriging, as an unbiased linear estimator, was used to estimate values at non-sampled locations. Once these values were determined, isoline maps were constructed with the same program (GS+, 2004). The program uses the same kriging values for isoline determination and localization; thus, the maps represent well-defined lines based on a linear regression algorithm, as described by Siqueira et al. (2008).

RESULTS AND DISCUSSION

According to Pimentel-Gomes and Garcia (2002), the magnitude of the coefficient of variation (CV) can classify the variability of a property. The classes were established as low ($CV \leq 10\%$), medium ($10\% < CV \leq 20\%$), high ($20\% < CV \leq 30\%$), and very high ($CV > 30\%$). Soil bulk density (SBD) had low variability (6.06 and 5.69 %) at the 0.00-0.10 and 0.10-0.20 m depths, respectively (Table 1). Cavallini et al. (2010) and Lima (2007) also found low variability for this property.

Total porosity (TP) (7.05 and 8.29 %) and particle density (PD) (1.63 and 1.40 %) also exhibited low variability (Table 1). In contrast, gravimetric moisture (GM) (20.03 and 15.48 %) and volumetric moisture (VM) (20.92 and 16.90 %) had medium to high CV, and soil resistance to penetration (SRP) had high variability (25.64 and 29.17 %) (Table 1). In contrast, Lima et al. (2010a) found data with low to medium variability. Montanari et al. (2013), studying Ultisols under signalgrass pasture, found CV values for gravimetric moisture from 10.9 to 13.8 %, which corroborates our study.

Circumference at breast height (CBH) and plant height (PH) showed medium variability (13.8 and, 11.5%), which is similar to results of Rosa Filho et al. (2011) who found values of 15.4 and 14.4 %,

respectively. Forage properties had CV values ranging from low to very high, neutral detergent fiber (NDF) had a lower value (4.4 %), and dry matter of dead material (DMDM) had the highest value (63.6 %).

As reported by Butolo (2002) and Martins Netto and Durães (2005), crude protein (CP) varies with plant type, age, part of the plant, and fertilizer content. Therefore, comparing our results with other studies may lead to erroneous interpretations. If forage were used for animal grazing, a CP value of 6.80 % (Table 1) would be low. As stated by van Soest (1994), forages with less than 7 % CP have reduced digestibility due to inadequate N availability for rumen microorganisms, which also negatively affects dry matter intake. Therefore, higher CP content is necessary to meet the protein requirements of animals. However, this fact can be explained by the forage sampling period, which was April. From March to September, CP values tend to decrease due to the scarcity of rain. Euclides et al. (2008), comparing CP values for Massai grass in different seasons, found higher values in the rainy season compared to the dry season - 9.7 and 8.0 %, respectively.

The reason for this difference is probably due to the fact that this forage had a greater quantity of stem ($1,345.11 \text{ kg ha}^{-1}$) compared to leaf ($1,078.00 \text{ kg ha}^{-1}$), which may have influenced the CP value since this analysis was performed with leaves only.

Mean values of SRP at the soil depths evaluated indicated increased soil compaction in the 0.10-0.20 m layer (Table 1), in which the highest value was obtained ($SRP2 = 4.13 \text{ MPa}$). However, with regards to SBD, values were similar at the different depths ($SBD1 = 1.44$ and $SBD2 = 1.45 \text{ kg dm}^{-3}$). This was different from the study developed by Pezarico et al. (2013), who studied Nitosols and found values ranging from 1.05 to 1.31 kg dm^{-3} .

With respect to SPR (Table 1), the mean values at depths were ranked by Arshad et al. (1996) as high (SRP1) and very high (SRP2), and were thus in agreement with the values observed by Montanari et al. (2013) at the second depth. Since the soil surface layer has intense water loss through evaporation and sand content is high in the assessed soil, low values for gravimetric moisture (GM) were expected and proved to be similar to those found by Montanari et al. (2013).

Correlations between soil and plant properties (Table 2) were significant for $SDM \times VM1$ ($r = 0.316^{**}$), $CP \times TP1$ ($r = 0.229^*$), $PH \times SRP1$ (0.261^*), $DMDM \times PD2$ ($r = -0.245^*$), and $PH \times PD2$ ($r = 0.290^*$). The direct relationship between $PH \times SRP1$ showed that along with an increase in SRP there was an increase in PH, brought about by the low degree of soil compaction in the surface layer (0.00-0.10 m) in the presence of high sand content. Thus, a high SRP is believed to improve soil aggregation, which would favor greater soil/root contact, enhancing the efficiency of water and nutrient uptake.

Table 1. Initial descriptive analysis of dendrometric properties of *Eucalyptus urograndis*, yield and bromatological properties of forage, and physical properties of Quartzipsamment (Entisol) soil in a silvopastoral system in Ribas do Rio Pardo, MS, Brazil

Property ⁽¹⁾	Average	Median	Value		Standard deviation	Coefficient			Test probability ⁽²⁾	
			Maximum	Minimum		Variation	Kurtosis	Asymmetry	Pr <w	FD
%										
Eucalyptus properties										
CBH (cm)	46.38	46.06	66.42	29.35	6.40	13.8	1.217	0.118	0.3079	NO
PH (m)	17.25	17.20	19.95	13.66	1.98	11.5	-1.324	-0.281	0.0001	UN
Forage property										
TDM (kg ha ⁻¹)	2,990.67	2,652.00	6,680.00	896.00	1,356.76	45.4	0.682	1.059	0.0001	UN
LDM (kg ha ⁻¹)	1,078.00	1,008.00	2,304.00	260.00	468.12	43.4	-0.159	0.517	0.0966	NO
SDM (kg ha ⁻¹)	1,345.11	1,134.00	3,484.00	348.00	718.98	53.4	1.065	1.249	0.0001	UN
DMDM (kg ha ⁻¹)	494.82	432.00	1,400.00	40.00	314.66	63.6	-0.140	0.679	0.0034	UN
CP (%)	6.80	6.82	8.92	4.61	1.00	14.7	-0.857	-0.069	0.1714	NO
NDF (%)	76.25	76.06	81.85	68.36	3.33	4.4	-0.580	-0.250	0.1718	NO
ADF (%)	39.46	38.67	45.23	31.86	3.76	9.5	-0.966	-0.193	0.0026	UN
IVOMD (%)	48.45	48.95	60.04	37.30	5.89	12.2	-0.839	0.117	0.1787	NO
Soil physical property										
SRP1 (MPa)	2.47	2.36	4.38	1.39	0.63	25.64	0.703	0.839	0.0014	UN
SRP2 (MPa)	4.13	3.93	6.86	1.82	1.20	29.17	-0.720	0.205	0.2718	NO
GM1 (kg kg ⁻¹)	0.06	0.06	0.10	0.04	0.01	20.03	0.888	0.719	0.0552	NO
GM2 (kg kg ⁻¹)	0.06	0.06	0.08	0.04	0.01	15.48	-0.004	-0.689	0.0082	UN
SBD1 (kg dm ⁻³)	1.44	1.44	1.63	1.20	0.09	6.06	0.345	-0.262	0.1742	NO
SBD2 (kg dm ⁻³)	1.55	1.56	1.75	1.29	0.09	5.69	0.300	-0.249	0.6981	NO
VM1 (m ³ m ⁻³)	0.09	0.09	0.15	0.05	0.02	20.92	1.134	0.902	0.0044	UN
VM2 (m ³ m ⁻³)	0.10	0.10	0.13	0.05	0.02	16.90	0.252	-0.606	0.0638	NO
PD1 (kg dm ⁻³)	2.69	2.70	2.82	2.56	0.04	1.63	0.809	-0.128	0.0027	UN
PD2 (kg dm ⁻³)	2.69	2.70	2.78	2.60	0.04	1.40	0.207	-0.455	0.0001	UN
TP1 (m ³ m ⁻³)	0.46	0.46	0.56	0.39	0.03	7.05	0.807	0.315	0.1951	NO
TP2 (m ³ m ⁻³)	0.42	0.42	0.52	0.35	0.03	8.29	0.663	0.546	0.0791	NO

⁽¹⁾ CBH: circumference at breast height; PH: plant height; TDM: total dry matter; LDM: leaf dry matter; SDM: stem dry matter; DMDM: dry matter of dead material; CP: crude protein; NDF: neutral detergent fiber; ADF: acid detergent fiber; IVOMD: *in vitro* organic matter digestibility; SRP: soil resistance to penetration; GM: gravimetric moisture; SBD: soil bulk density; VM: volumetric moisture; PD: particle density and TP: total porosity, sampled in the (1) 0.00-0.10 m, and (2) 0.10-0.20 m layers; ⁽²⁾ FD: frequency distribution, where NO and UN are normal and undetermined types, respectively.

Analyzing the correlation of CP × TP1 (Table 2), it may be concluded that with the higher water content in the soil (TP1), increased N sorption may have occurred, since there is a direct relationship between CP and the N content in plants (Cavallini et al., 2010).

Correlations between plant properties and soil properties exhibited: a) an exponential model represented the regression equation of PH in relation to SRP1 (Equation 4), with a low yet significant coefficient of correlation ($r = 0.265^*$). This low value arose through the large number of

observations used in this study ($n = 72$) (Montanari et al., 2013). Therefore, this PH variation can be explained by only 26.5 % of the variation of the SRP1 data. Thus, when SRP1 varies from 1.39 to 4.38, PH will increase from 16.23 to 18.80 m. However, upon taking the average value of 2.47 for SRP1, a mean PH of 17.16 m can be estimated; b) CP correlation with TP1 ($r = 0.250^*$) exhibited a potential model (Equation 5); therefore, when the minimum value of TP1 occurs ($0.39 \text{ m}^3 \text{ m}^{-3}$), CP will reach 6.14 %. Proportionally, when the maximum value of TP1 occurs ($0.56 \text{ m}^3 \text{ m}^{-3}$), CP will express a maximum value of 7.46 %; c) PH as function of

Table 2. Correlation matrix between some aspects of *Eucalyptus urograndis* dendrometric properties, yield and bromatological properties of forage, and physical properties of a Quartzipsamment (Entisol) soil in a silvopastoral system in Ribas do Rio Pardo, MS, Brazil

Property ⁽¹⁾	TDM	LDM	SDM	DMDM	CP	NDF	ADF	IVOMD	CBH	PH
TDM	1									
LDM	0.726**	1								
SDM	0.952**	0.663**	1							
DMDM	0.529**	0.040	0.440**	1						
CP	0.077	-0.350*	0.092	0.378**	1					
NDF	-0.150	0.362**	-0.253*	-0.524**	-0.672**	1				
ADF	-0.235*	0.392**	-0.255*	-0.674**	-0.734**	0.856**	1			
IVOMD	0.159	-0.364**	0.172	0.575**	0.793**	-0.789**	-0.902**	1		
CBH	-0.035	0.143	-0.084	-0.192	-0.401**	0.434**	0.380**	-0.406**	1	
PH	-0.170	0.078	-0.169	-0.338**	-0.085	0.273*	0.291**	-0.172	0.444**	1
SRP1	-0.078	-0.109	-0.056	0.046	0.042	-0.148	-0.194	0.208	0.138	0.261*
SRP2	-0.028	-0.006	-0.034	0.109	0.017	-0.110	-0.155	0.138	-0.029	0.116
GM1	0.204	0.181	0.225	0.048	-0.110	0.125	0.104	-0.064	0.022	0.006
GM2	0.044	0.044	0.084	-0.094	-0.124	0.054	0.089	-0.099	0.09	-0.217
SD1	0.130	0.154	0.198	-0.095	-0.200	-0.009	0.073	-0.098	0.198	0.080
SD2	-0.020	0.011	-0.019	-0.024	-0.139	-0.039	0.010	0.020	0.071	0.111
VM1	0.283	0.275	0.316**	0.039	-0.209	0.132	0.135	-0.119	0.086	0.042
VM2	0.066	0.082	0.098	-0.083	-0.166	0.043	0.102	-0.097	0.035	-0.157
PD1	0.157	0.095	0.223	0.042	0.081	-0.160	-0.128	0.081	0.100	0.018
PD2	-0.192	-0.118	-0.110	-0.245*	-0.076	0.084	0.170	-0.118	0.164	0.290*
TP1	-0.076	-0.102	-0.113	0.058	0.229*	-0.029	-0.080	0.096	-0.188	-0.042
TP2	-0.010	0.006	-0.002	-0.032	0.141	0.080	0.067	-0.046	-0.014	0.026

⁽¹⁾ CBH: circumference at breast height; PH: plant height; TDM: total dry matter; LDM: leaf dry matter; SDM: stem dry matter; DMDM: dry matter of dead material; CP: crude protein; NDF neutral detergent fiber; ADF: acid detergent fiber; IVOMD: *in vitro* organic matter digestibility; SRP: soil resistance to penetration; GM: gravimetric moisture; SBD: soil bulk density; VM: volumetric moisture; PD: particle density and TP: total porosity, sampled in the (1) 0.00-0.10 m, and (2) 0.10-0.20 m layers; ⁽²⁾ ** and * significant at 1 and 5 %, respectively.

PD2 exhibited a linear model ($r = 0.290^*$), in which PH can be explained by 29.0 % of the variation of PD2 data (Equation 6). Thus, at the minimum value of PD2 (2.60 kg dm⁻³), PH will have a value of 15.852 m.

$$PH = 1.516 \times 10e^{4.911 \times 10^{-2} \times SRP1} \quad \text{Eq. 4}$$

$$CP = 1.018 \times 10PT1^{5.356 \times 10^{-1} *} \quad \text{Eq. 5}$$

$$PH = -2.372 \times 10 + 1.522 \times 10^3 PD2 \quad \text{Eq. 6}$$

Equation 7 expresses the analysis of variance of multiple linear regression fitted to estimate PH as a function of soil physical properties (independent variables). Thus, the independent variables SRP1, GM2, and PD2 are responsible for 17.2 % of the variation of PH, assuming a coefficient of determination (R^2) of 0.1720.

Furthermore, in relation to independent variables, in equation 08, SBD1 is included as a variation factor for CBH, responding for 3.95 %, whose R^2 was 0.0395. In contrast, in equation 9,

we observe that 5.25 % of the CP variation can be explained by the TP1 property, whose R^2 was 0.0525.

However, in equation 10, LDM varied in relation to VM1, which was influenced at the level of 7.59 %, and the R^2 was 0.0759.

The proposed explanation based on multiple linear regression analysis showed the implications of each property acting on the crops under study, taking the values of these properties obtained in the field into account, which allowed the contribution of each of them in the fitted model to be taken into account (Equations 7, 8, 9, and 10).

$$PH = -18.099 + 0.6529^{**}SRP1 - 40.317^{*}GM2 + 13.46^{**}PD2 \quad \text{Eq. 7}$$

$$CBH = 25.378 + 14.538^{*}SBD1 \quad \text{Eq. 8}$$

$$CP = 3.5535 + 7.0353^{*}TP1 \quad \text{Eq. 9}$$

$$LDM = 461.54 + 6969.6^{**}VM1 \quad \text{Eq. 10}$$

where *, ** and *** = significant at 10, 5, and 1 %, respectively.

Table 3. Parameters of single and cross semivariograms fit for some dendrometric properties of *Eucalyptus urograndis*, yield and bromatological properties of forage, and physical properties of a Quartzipsamment (Entisol) soil in a silvopastoral system in Ribas do Rio Pardo, MS, Brazil

Property ⁽¹⁾	Model ⁽²⁾	Nugget effect (C ₀)	Sill (C ₀ +C)	Range (A ₀)	R ²	RSS ⁽³⁾	SDE ⁽⁴⁾	Class
m								
Simple $\gamma(h)$ for forage property								
TDM	Exp.(98)	2.690×10 ⁵	1.547×10 ⁶	12.0	0.464	1.440×10 ¹¹	82.60	Very high
LDM	Exp.(104)	3.1×10 ⁴	2.213×10 ⁵	10.5	0.632	1.220×10 ⁹	86.00	Very high
SDM	Exp.(94)	9.2×10 ⁴	4.851×10 ⁵	15.9	0.686	9.600×10 ⁹	81.00	Very high
CP	Exp.(91)	1.130×10 ⁻¹	8.830×10 ⁻¹	14.7	0.672	4.040×10 ⁻²	87.20	Very high
NDF	Exp.(73)	4.600	1.096×10	23.1	0.653	6.97	58.00	Medium
ADF	Exp.(94)	1.260	1.145×10	14.0	0.852	2.222	89.00	Very high
IVOMD	Exp.(66)	3.970	3.134×10	15.3	0.691	2.775×10 ⁻³	83.50	Very high
Simple $\gamma(h)$ for eucalyptus property								
CBH	Exp.(108)	1.208×10	3.378×10	32.7	0.827	3.650×10	64.20	High
PH	Exp.(114)	4.340×10 ⁻²	2.638×10 ⁻¹	15.3	0.691	2.775×10 ⁻³	83.50	Very high
Simple $\gamma(h)$ for soil physical property								
SRP1	Exp. (91)	4.340×10 ⁻²	2.638×10 ⁻¹	15.3	0.691	2.775×10 ⁻³	83.50	Very high
GM1	Exp. (106)	2.000×10 ⁻⁶	1.810×10 ⁻⁵	16.2	0.732	1.436×10 ⁻⁹	88.10	Very high
Crossed $\gamma(h)$ for plant and soil property								
PH=f(SRP1)	Sph. (64)	1.700×10 ⁻²	3.130×10 ⁻¹	61.7	0.487	1.090×10 ⁻¹	94.60	Very high
CBH=f(GM1)	Sph. (76)	-1.460×10 ⁻³	-7.120×10 ⁻³	8.9	0.053	6.713×10 ⁵	79.50	High
NDF=f(SRP1)	Gau. (61)	1.000×10 ⁻⁴	-3.142×10 ⁻¹	14.4	0.247	1.750×10 ⁻¹	99.90	Very high

⁽¹⁾ TDM: total dry matter, LDM: leaf dry matter, SDM: stem dry matter, CP: crude protein, NDF: neutral detergent fiber, ADF: acid detergent fiber, IVOMD: in vitro organic matter digestibility, CBH: circumference at breast height, PH: plant height, SRP: soil resistance to penetration, and GM: gravimetric moisture, sampled in the 0.00-0.10 m layer; ⁽²⁾ Exp.: exponential, Sph.: spherical, and Gau.: Gaussian, with the respective number of pairs of the first lag in brackets; ⁽³⁾ RSS: residue square sum; ⁽⁴⁾ SDE: spatial dependence evaluator.

Table 3 shows the parameters of single semivariograms fitted to forage and eucalyptus properties and some physical properties of a Quartzipsamment soil. Thus, it was attested that except for LDM, SRP2, GM2, SBD1, SBD2, VM1, VM2, PD1, PD2, TP1, and TP2, which exhibited a pure nugget effect, all other properties showed spatial dependence.

The best semivariogram adjustment was for the R² of ADF, which was 0.852. The spatial dependence evaluator (SDE) value observed was very high (89.00 %); an exponential model was fitted with a range of 14.0 m.

The CBH had an R² of 0.827, which is close to the value found by Lima et al. (2010b), who obtained an R² of 0.771. We observed a high SDE (64.20 %), similar to Lima et al. (2010b) (75.7 %), and Carvalho et al. (2012), who found a very high SDE (91.0 %). The fitted exponential model was the same found by Lima et al. (2010b). However, the range of 32.7 m was lower than the 67.5 m and 71.6 m found by Lima et al. (2010b) and Carvalho et al. (2012), respectively.

The property with the third best semivariogram fit was GM1, with an R² of 0.732, the same order of magnitude observed by Montanari et al. (2013), which was 0.778. In relation to the SDE, we observed

a very high value (88.10 %), corroborating Montanari et al. (2013), who also observed a very high value (86.0 %). The fitted exponential model matched the findings of Montanari et al. (2013), and the range of 16.20 m was close to the value of 15.5 m obtained by Montanari et al. (2010).

In the co-kriging analyses (Table 3, Figure 1), fitting the semivariogram PH = f(SRP1) showed that 48.7 % of spatial variability of eucalyptus height could be explained by SRP1. It is now possible to locate management zones for the eucalyptus crop from the data of this property. It could be seen that where there were the highest SRP1 values, the highest PH values were mapped (Figure 1c). Therefore, it is necessary to carry out conservation practices for the management areas in which SRP1 had lower values so as to increase eucalyptus height. From the spatial perspective, SRP1 proved to be an adequate indicator of the physical quality of the soil under study in regard to eucalyptus height.

For fitting the cross semivariogram CBH = f(GM1), CBH spatial variability can be explained by GM1 variability (5.3 %). Thus, it is possible to recommend conservation practices

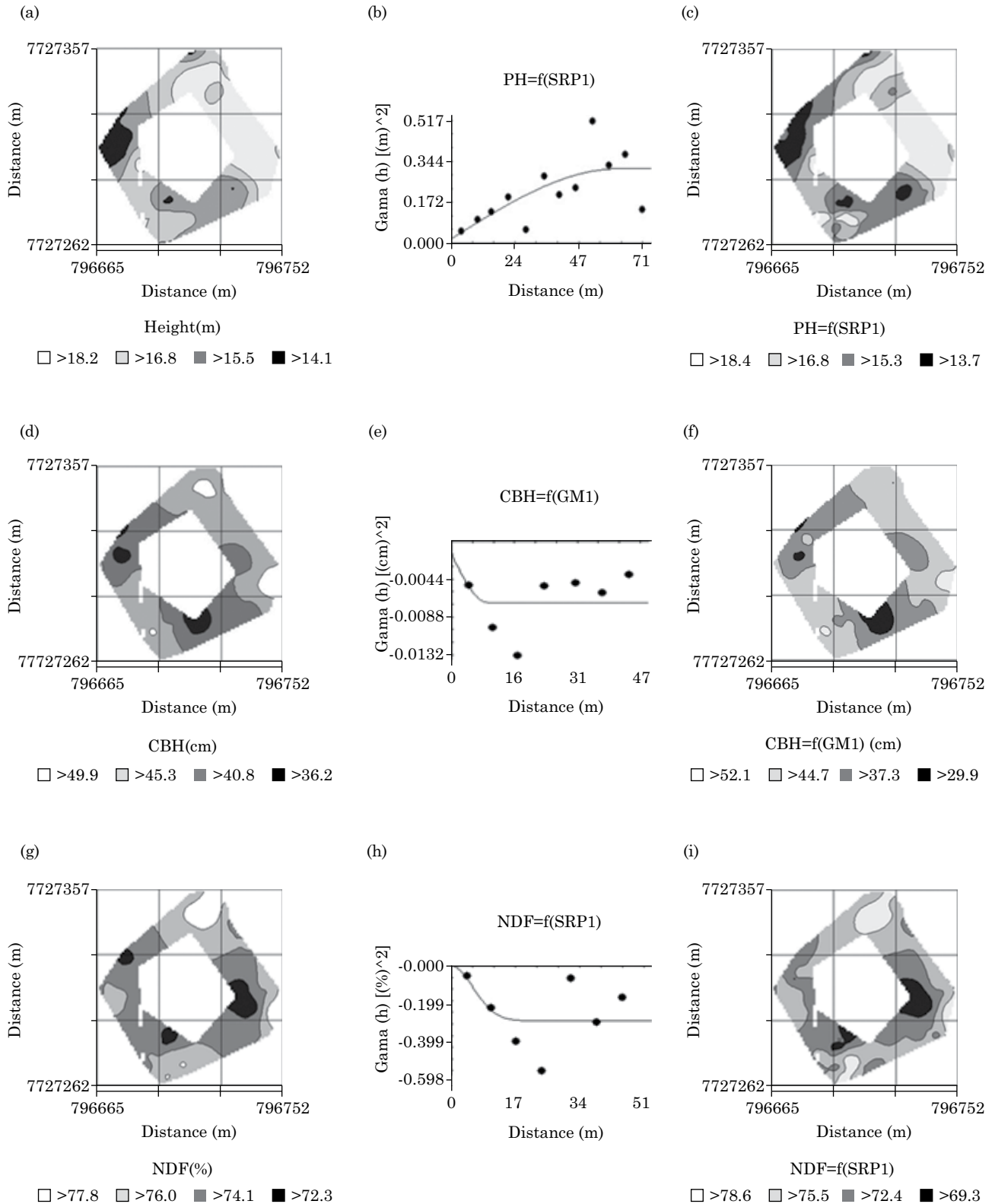


Figure 1. Kriging map, cross semivariogram and co-kriging map for eucalyptus plant height (PH) in relation to resistance to penetration, 0.00-0.10 m (SRP1); circumference at breast height (CBH) in relation to gravimetric moisture, 0.00-0.10 m (GM1), and neutral detergent fiber (NDF) in relation to resistance to penetration, 0.00-0.10 m (SRP1) in a Quartzipsamment (Entisol) soil in a silvopastoral system in Ribas do Rio Pardo, MS, Brazil.

for the management areas in which GM1 had maximum values, aiming to increase eucalyptus CBH in those locations since the lowest GM1 values were correlated with the highest CBH values (Figure 1f).

In regard to NDF = f (SRP1), 24.7 % of the NDF variation can be explained by SRP1. As NDF is inversely proportional to the number of leaves, local management of SRP1 may be recommended so that the NDF values be reduced. thus performing adequate management in the areas with low SRP1. From the spatial perspective, SRP1 was an adequate index of the physical quality of the soil under study in regard to forage fiber production.

CONCLUSIONS

Gravimetric moisture in the 0.00-0.10 m layer was an indicator of soil physical quality, showing correlation to circumference at breast height of eucalyptus plants in a Quartzipsamment.

With increasing resistance to penetration at the soil surface, eucalyptus total height and neutral detergent fiber of the forage crop increase.

From a spatial perspective, eucalyptus height and neutral detergent fiber can be estimated by means of co-kriging with soil resistance to penetration. Thus, resistance values above 2.3 MPa indicate sites with the highest yields.

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