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Soil Attributes and Production of *Eucalyptus* in Monoculture and Silvopastoral Systems in the North of Minas Gerais, Brazil

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Abstract: The objective of this study was to evaluate the chemical and physical attributes of soil, and the productivity of *Eucalyptus* cultivated in monoculture and silvopastoral systems. The experiment started in 2009 and evaluated the following four systems: native vegetation system (Cerrado), a degraded pasture, a *Eucalyptus urograndis* monoculture (*E. urophylla* × *E. grandis*) and a silvopastoral system (*E. urograndis* combined with *Brachiaria brizantha* cv. "Marandu"). The experimental design used was completely randomized. In each system, four soil samples were collected from the 0-20 cm depth layer, and the chemical and physical attributes of the soil were evaluated. The diameters of all *Eucalyptus* trees at 1.30 m above the ground as well as the total height were measured. Subsequently, the trees dimensions were measured and their individual volumes obtained by applying the Smalian formula. The correlation between the parameters for *Eucalyptus* production and soil attributes was established using the Pearson's correlation coefficient method. The planting of *Eucalyptus* in monoculture and silvopastoral systems contributed to the improvement of the soil's chemical and physical attributes, which indicates the potential of these systems for recovery of degraded pastures. The silvopastoral system yielded the highest average volume of wood per tree (0.2228 m^3), with a productivity of 111.4 m^3/ha. The *Eucalyptus* monoculture yielded 0.1895 m^3 per tree and 315.71 m^3/ha due to the higher density of the crop. The growth and productivity of *Eucalyptus* showed highly correlation with the soil attributes, thus suggesting that well-managed crops are an indicator of the soil quality recovery.

Key words: Diameter at breast weight, forest-livestock integration system, forest production, soil quality.

1. Introduction

Increasing environmental degradation is the result of anthropic interventions that negatively alter and modify the environment. Accordingly, agricultural activities can exhaust the productive capacity of the soil, modifying its chemical, physical and biological characteristics [1].

The adoption of integrated production systems constitutes an alternative to maintain or even maximize production, without the need to incorporate new areas into the production process [2]. However, information regarding soil attributes and *Eucalyptus* cultivation in silvopastoral systems (SPS) of the Cerrado regions is scarce.

In agrosilvopastoral and SPS systems, there is an increase in the net area of the tree component, allowing for favorable conditions for an increase in tree trunk volume [3]. In *Eucalyptus* monocultures, however, the spacing between plants was smaller along the planting lines, or multiple rows were planted more densely. This management system aims to increase the number of trees per unit area. In this context, thinning is necessary to produce quality lumber suited for sawmills [4, 5].

The different management systems cause changes in soil organic matter, cation exchange capacity, pH, ion dynamics and soil aggregation. These

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modifications become more evident according to the use of the area over time [6]. According to Carneiro et al. [7], the evaluation of the soil attributes is important to improve management aiming at the sustainability of the system.

Against the above background, the objective of this study was to evaluate the chemical and physical attributes of the soil, and the productivity of *Eucalyptus* cultivated in monoculture system (MCS) and SPS in the north of the state of Minas Gerais.

2. Materials and Methods

2.1 Characterization of the Experimental Area

The experiment was set up at the Professor Hamilton de Abreu Navarro Farm, Federal University of Minas Gerais (MG) with the coordinates of 16°41′ S and 43°50′ W, in the municipality of Montes Claros. The site is located at an altitude of 598 m, and has an average annual temperature of 22.9 °C.

The soil in this area was classified as ustult or “Argissolo Vermelho-Amarelo” in the Brazilian soil classification system [8] with a smooth undulating relief. According to Köppen classification, the local climate is tropical savanna (Aw), hot and dry [9], with an average annual rainfall ranging between 1,000 mm and 1,200 mm. The dry season is well defined, with rainy periods concentrated from October to March. Fig. 1 shows the monthly rainfall of the study area between 2006 and 2015.

The experimental area was established in December 2009, and the systems evaluated were: (1) native vegetation system (NVS), classified as Cerrado stricto sensu, used as the reference for the original condition of the soil without anthropic intervention; (2) degraded pasture of *Panicum maximum* (DPS) in use since 2006, with exposed soil showing laminar and furrow erosion, used as the reference for the soil condition preceding the implantation of trees; (3) monoculture of *E. urograndis* (MCS) (*E. urophylla* S. T. Blake × *E. grandis* W. Hill) at a spacing of 3 m × 2 m, at six years of age, totaling 1,666 trees/ha; (4) SPS of six years’ age, composing of *E. urograndis* cultivated in a single row at a spacing of 10 m × 2 m, and mixed with *Brachiaria* (*B. brizantha* cv. “Marandu”), totaling 500 trees/ha.

The planting of *Eucalyptus* seedlings was carried out in December 2009, in circular pits 40 cm deep, in which 100 g of simple superphosphate had previously been applied. Fertilization was conducted 15 d after

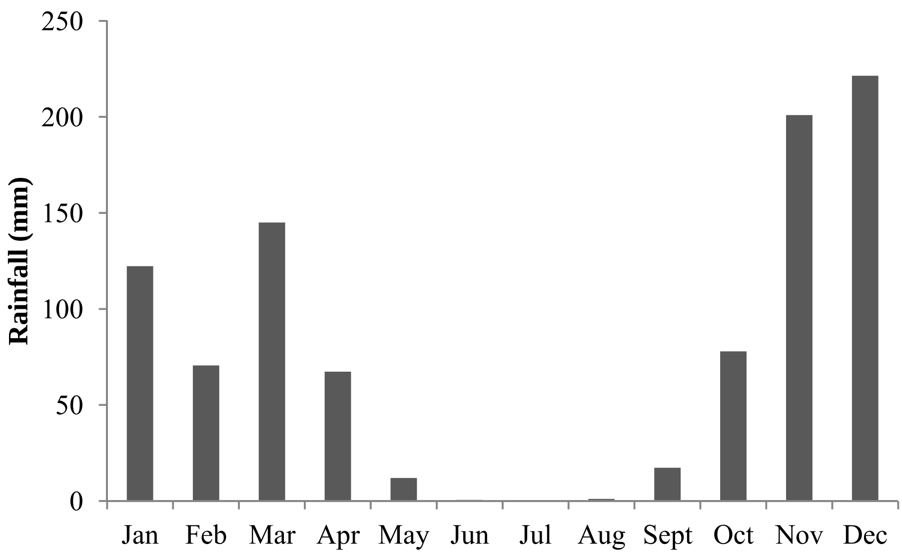

Fig. 1 Monthly rainfall distribution between 2006 and 2015 in Montes Claros, MG, Brazil.
Source: INMET [10].

transplanting the seedlings, using borax of 18 g per pit and NPK (4-30-10) of 100 g per pit as fertilizers. Top-dressing fertilization was carried out 90 d and 150 d after transplanting (DAT) the *Eucalyptus* seedlings using KCl (150 g/plant), and at 270 d after transplanting using NPK (100 g/plant) [11].

In the SPS, the *Brachiaria* seeds were spread on the surface, using 6 kg/ha of pure and viable seeds, immediately before planting the crop *Sorghum bicolor* (L.) Moench. The sorghum plantation was fertilized using 300 kg/ha of NPK (4-30-10) and top-dressed (30 d after emergence) with 80 kg/ha of N (ammonium sulfate).

From the third year (2012), the area was managed as a SPS, and no further fertilization or intervention was undertaken until the date of soil sampling and measurement of the forest.

2.2 Soil Sampling, and Determination of Physical and Chemical Attributes

Soil samples were collected in August 2014. From each study area, samples were collected in the 0-20 cm depth layer using an auger, to evaluate the chemical and physical attributes of the soil. Sampling was carried out randomly in the areas under study, with 16 simple soil samples collected in each evaluated system forming four composite samples.

The collected samples were air dried and passed through a 2 mm aperture sieve to determine the chemical attributes following the method recommended by Brazilian Agricultural Research Corporation (EMBRAPA) [12]. Calcium (Ca^{2+}) and magnesium (Mg^{2+}) were determined using atomic absorption spectrophotometry. Potassium (K^+) and phosphorus (P) were extracted using the Mehlich-1 method, and then determined by flame photometry and colorimetry, respectively. Based on the results, the total exchangeable bases (EB), the effective cation exchange capacity (CEC), the potential cation exchange capacity at pH 7.0 (T), and percent base saturation (BS) of the soil were calculated.

The soil density (SD) was determined in undisturbed samples collected with stainless steel rings 5 cm in diameter and height [13]. The samples were dried in an oven at 105 °C for 24 h to determine soil moisture (SM). The total porosity of the soil (TVP) was estimated using the relationship between soil density and particle density, the latter being determined using the volumetric balloon method [12]. The stability of the aggregates in water was determined by application of a method that classifies the aggregates according to their diameters, using a set of sieves with meshes sized 2, 1, 0.5, 0.25 and 0.105 mm [14]. The mean weight diameter (MWD), geometric mean diameter (GMD) and soil aggregate stability index (ASI) [15] were calculated according to Eqs. (1)-(3), respectively:

$$\mathrm{MWD} = \sum_{i=1}^{n} x_i \cdot w_i \tag{1}$$

$$\mathrm{GMD} = 10^{\sum x_i \cdot \log(w_i)} \tag{2}$$

$$\mathrm{ASI} = \frac{W_s - W_{p=0.105} - \mathrm{sand}}{W_s - \mathrm{sand}} \times 100 \tag{3}$$

where, x_i = arithmetic mean diameter of each size fraction (mm);

w_i = proportion of the total water-stable aggregates in the corresponding size fraction during the weight of sand/gravel particles (upon dispersion and passing through the same sieve);

W_s = dry weight of soil sample (g);

$W_{p\,=\,0.105}$ = aggregate weight of size class < 0.105 mm.

2.3 Evaluation of the Growth and Volumetric Production of Eucalyptus

The evaluation of the growth and volumetric production of *Eucalyptus* cultivated in MCS and SPS was carried out six years after the establishment of these systems. This was undertaken via a forest census of the evaluated systems, in which the tree diameter at breast height (DBH: 1.30 m height) and total height (Ht) were measured. The characterization of the diametrical distribution of the forest stand was established, with four sample trees per DBH class being selected in each system.

In order to determine the volume of the stem of each tree, including the bark, the original geometrical method was applied for standing tree cubic volume [16] using a Bitterlich relascope and calipers. Based on the diameters at 0.3 m (stump), 1.3 m (DBH), as well as the relative height (Hr) and total height (Ht), the angular coefficients of the lines for different segments of the stem were obtained (from 0.3 m until 1.30 m; from 1.30 m until the Hr; from the Hr until the Ht). The angular coefficients of the lines generated taper equations that allowed estimating the diameters in the three distinct segments of the stem. After estimating the tree diameters at the various heights, the profiles were reconstituted and the volumes were calculated, using the Smalian formula [17].

Having obtained the volumes of the trees using the geometric method, adjustments were made for different volumetric models. To select the equations that best approximated the volume estimate of the other trees, for each processing method, volumetric models available in the literature were adjusted and an equation was selected according to the following criteria: graphical analysis of the residues, residual standard error in percentage (*Syx*) and coefficient of determination (R^2) in percentage. Regression analysis allowed to evaluate the best equation for volume determination, for each processing method.

The adopted volumetric model was proposed by Schumacher and Hall [18], according to Eq. (4):

$$V = b_0 \times DBH^{b_1} \times Ht^{b_2} \times e \tag{4}$$

where, V = cubic volume (m^3); DBH = diameter at breast height (1.30 m height) (cm); Ht = total height (m); b_i = parameters; e = random error.

In order to obtain the estimated parameters using the ordinary least squares method, a linear approximation of the Schumacher and Hall model was performed by logarithmic transformation. The following adjustments were found, as Eq. (5) for stem of *Eucalyptus* cultivated in MCS and Eq. (6) in SPS:

$$\ln Y = \text{-}11.3209 + 0.0723 \times \ln(\text{DBH}) + 2.6733 \times \ln(\text{Ht}) \tag{5}$$

where, R^2 = 98.82% and *Syx* = 6.30%.

$$\text{Ln}Y = \text{-}10.6189 + 2.0120 \times \ln(\text{DBH}) + 0.2323 \times \ln(\text{Ht}) \tag{6}$$

where, R^2 = 98.12%; *Syx* = 6.26%.

2.4 Statistical Analysis

To evaluate the chemical and physical attributes of the soil, and the growth and volumetry of *Eucalyptus* trees, the experiment was carried out in a completely randomized design. For comparison of the different processing methods, the variables were analyzed for variance (ANOVA), and the means from each processing method were compared using Tukey's test ($P < 0.05$). Estimates of correlation between *Eucalyptus* growth and production, and the physical and chemical attributes of the soil, were calculated using the Pearson's correlation coefficient method. The analyses were carried out using the System for Statistical Analysis software (SAEG 9.1).

3. Results and Discussion

3.1 Soil Chemical Attributes

The conversion of the native vegetation to different uses of the soil caused modifications in the chemical attributes evaluated (Table 1).

The pH value of soil in NVS was lower than that of the other land use systems evaluated. The result can be attributed to the liming carried out in the cultivation areas, a common practice before the implantation of the crops in Cerrado soils, and by the absence of Al^{3+}. It was observed that soil pH values in all the studied agricultural systems were above 6.0, indicating that crop restrictions can be circumvented with the correct and efficient use of correctives and fertilizers in

Table 1 Soil chemical attributes in different land use and management in the north of Minas Gerais State, Brazil.

Area	pH (H_2O)	Ca^{2+}	Mg^{2+}	K^+	H + Al	P	P-rem	EB	CEC	T	BS (%)
		cmol/dm³				mg/dm³		cmol/dm³			
NVS	6.1^b	8.6^a	2.45^a	472.5^a	2.42^a	4.8^{ab}	36.5^c	11.1^a	11.1^a	11.1^{ab}	100^a
DPS	6.5^a	5.4^b	2.35^a	454.6^a	2.51^a	3.7^b	40.7^b	9.6^b	9.6^b	9.6^b	80.5^b
MCS	6.6^a	6.1^b	2.07^a	432.2^a	2.20^a	6.6^{ab}	45.4^a	8.8^b	8.8^{ab}	11.0^{ab}	80.5^b
SPS	6.4^a	7.2^{ab}	2.43^a	453.4^a	2.33^a	8.7^a	46.5^a	10.8^a	10.8^a	13.3^a	81.5^b

NVS = native vegetation system; DPS = degraded pasture of the maximum *Panicum* system; MCS = monoculture system of *E. urograndis*; SPS = silvopastoril system; EB: exchangeable bases; CEC: cation exchange capacity; T = potential cation exchange capacity at pH 7.0; BS = base saturation.

[a-c] Means following by the same letter did not differ by the Tukey's test ($P < 0.05$).

Cerrado soils. This indicator is directly related to the EB and BS, which presented similarly high values, characterizing soils of high fertility [11].

The Ca^{2+} content was lower in the DPS and MSC, when compared to NVS; however, it was rated as high in all systems [11]. Liming favors the soil's absorption of water and nutrients, and contributes to its structuring, as well as to increasing Ca^{2+} and/or Mg^{2+} levels in the soil's surface layer [19]. The levels of Mg^{2+} and K^+ were high, and did not differ among the various systems evaluated.

The available P content of the soil varied according to its use and management, with the highest values observed in the SPS (8.7 mg/dm^3), and the lowest in DPS (3.7 mg/dm^3). These results can be related to mineral fertilization containing P, used in the implantation and maintenance of the SPS over time. In contrast, the absence of nutrient replacement and acidity correction in the pastures (DPS) contributed to its degradation over time. The low P levels found in the DPS area is in agreement with those found in a oxisol under native Cerrado (NVS) for a range of land use conditions [20].

Remnant P (P-rem) levels, although considered good, were higher in the MCS and SPS areas than those in other systems. This result indicates that the *Eucalyptus* cultivation contributed to the increase of the P-rem content in the most superficial layer of the soil, this fraction being considered labile and available for absorption by the plants [21].

The values obtained for EB in SPS and NVS were higher than in the other evaluated systems. This result concerning the SPS indicates that the combination of species found in the same area contributes to the increase of EB in the soil. This is mainly due to the management of the fertilization for the different components of the system, as well as to the alternation between tilling and livestock related activities.

The high levels of EB in the soil contributed to the high values of CEC and T found in the study areas, especially in the SPS. The evaluated soil was characterized as eutrophic due its low potential acidity (H + Al) and high BS.

Adequate land use creates conditions to improve the availability of nutrients to the plants. It also avoids losses from leaching and volatilization. SPS with deep-rooted trees are a viable option to recover soil fertility, increase biodiversity and improve natural resources, by recycling nutrients and reducing soil erosion [22].

3.2 Soil Physical Attributes

The soil physical attributes underwent modifications under the different systems when compared with the NVS (Table 2). This result is in agreement with previous data [23], in which *Eucalyptus* systems promote an improvement in the physical quality of the soil.

The soil density was higher in the DPS area, with a value of 1.68 g/cm^3. Similar data were found in a study that evaluated the effect of different cropping systems on the physical properties of ustox in the

Table 2 Soil bulk density (SD), total pore volume (TPV), soil moisture (SM), mean weight diameter (MWD), geometric mean diameter (GMD) and aggregate stability index (ASI) in different land use and management in the north of Minas Gerais State, Brazil.

Area	SD (g/cm³)	TVP	SM	MWD	GMD	ASI (%)
		%		mm		
NVS	1.49^{b}	38.84^{a}	10.31^{a}	3.14^{a}	1.85^{a}	87.24^{a}
DPS	1.68^{a}	33.62^{b}	6.72^{b}	2.82^{b}	1.33^{a}	79.11^{a}
MCS	1.53^{b}	39.28^{a}	9.67^{a}	2.64^{b}	1.22^{a}	76.25^{a}
SPS	1.53^{b}	34.63^{b}	8.52^{ab}	2.62^{b}	1.32^{a}	81.08^{a}

[a, b] Means following by the same letter did not differ by the Tukey's test ($P < 0.05$).

Cerrado Biome, where soil density was higher in the pasture area [24]. The use of *Eucalyptus* in MSC and SPS contributed to a decrease in soil density to the levels similar to those observed in NVS. The threshold value for the development of a root system in ustult is 1.5 g/cm^3 [25]. Density higher than this value influences the penetration and emergence of germinated seeds.

The TVP in the MCS area was similar to that in the NVS. However, a small TVP reduction in the SPS can be explained by cattle trampling, whereas in the DPS area, this result could be attributed to incorrect management of grazing over time, which interfered with soil structure. In the MCS area, TVP followed an inverse behavior to that observed for SD, which shows the close relationship between the soil structure and its pore distribution. These results are similar to those reported by Bavoso et al. [26].

The highest SM were also observed in the NVS (10.31%), not different from SPS and MCS areas. The fact may be related to litter deposition leading to an increase in the organic matter content in the soil of these systems. Soil moisture can be used as an indicator of soil type and quality [27]. It also influences water movement, soil compaction, soil aeration and root development, which are important for soil and plant processes [28].

A study carried out in agroforestry systems on oxisol presented MWD results that ranged from 3.29 mm to 4.43 mm, with a higher value in NVS [29]. These values are higher than those found in this study, where the highest value of MWD (3.14 mm) was observed in NVS.

GMD values did not differ between the different evaluated systems. Good values of MWD and GMD had a positive impact on ASI, which was similar in all the study areas analyzed. Aggregate stability is an indicator of the processes involved in soil, as it is related to organic matter indices and consequently to soil degradation [30].

The reduction in the size of aggregates results from the application of pressure on the soil and from the reduction of the soil cover. The continuous supply of organic material contributes to the formation and stabilization of the structure [31], which provides a greater proportion of aggregates larger than 0.25 mm, thus offering greater resistance to erosive processes, gas exchange capacity and water infiltration.

3.3 Growth and Volumetric Production of Eucalyptus

E. urograndis cultivated in the SPS showed a higher growth in total height, diameter at chest height and individual volume per tree when compared to the MCS system at six years of age ($P < 0.05$). However, the highest volume of wood per hectare was observed in the MCS area (315.89 m^3/ha), as it had a larger tree population per unit of area (Table 3). These results are similar to those of a survey that evaluated the dendrometric characteristics of *E. urophylla* in SPS at 3 m × 2 m, 6 m × 4 m and 10 m × 4 m spacing from 48 to 66 months after planting, in the fields of the Minas Gerais meso-region slopes, with a larger volume/plant at wider spacing [32].

Choosing less dense spacing between trees implies

Table 3 Parameters of growth and production of *Eucalyptus* cultivated in monoculture (MCS) and intercropped in silvopastoral system (SPS) in the north of Minas Gerais State, Brazil.

Area	DBH (cm)	Ht (m)	Volume of wood per tree (m^3/tree)	Volume of wood per ha (m^3/ha)
MCS	16.67^b	14.30^b	0.1895^b	315.89^a
SPS	20.98^a	18.51^a	0.2228^a	111.40^b

DBH = diameter at breath weight; Ht = total height.

a-b Means following by the same letter did not differ by the Tukey's test ($P < 0.05$).

Table 4 Pearson's correlation coefficient of the parameters of growth and production of *Eucalyptus* and soil attributes under monoculture (MCS) and silvopastoral system (SPS) in the north of Minas Gerais State, Brazil.

Parameters	EB	CEC	T	BS	SD	VTP	SM	ASI
SPS								
DBH	0.8554	0.8554	0.9482	0.7569	-0.7021	0.7163	0.6241	0.8863
Ht	0.7422	0.7422	0.8352	0.7852	-0.6897	0.6077	0.5983	0.8721
V per tree	0.8011	0.8011	0.893	0.7724	-0.7823	0.6409	0.653	0.8199
MCS								
DBH	0.9169	0.9169	0.8788	0.7509	-0.6531	0.707	0.5805	0.8937
Ht	0.9169	0.9169	0.8472	0.8476	-0.6661	0.6209	0.6111	0.9124
V per tree	0.9171	0.9171	0.8632	0.8025	-0.754	0.6401	0.6341	0.8473

DBH = diameter at breath weight; Ht = total height; V = cubic volume; EB: exchangeable bases; CEC: cation exchange capacity; T = potential cation exchange capacity at pH 7.0; BS = base saturation; SD = soil bulk density; TVP = total volume of pores; SM = soil moisture; ASI = aggregate stability index.

larger individual volumes, as there is less competition for water, sunlight and soil nutrients [33].

In densely planted *Eucalyptus* plantations, the competition stimulates tree growth in height [34], differing from that in the present study. In mixed plantations, tree growth conditions may be influenced by higher soil moisture and fertility, and also by the effect of vegetative extracts [35]. This may have occurred with six-year-old *Eucalyptus* in the SPS, where favorable conditions benefited the trees in terms of height and DBH, when compared to the MCS system. Another factor that can be considered is the stagnation of growth that occurs earlier in high-density plantations, with individuals showing lower increments of volume over time.

In the initial period of stand growth (until the formation of the tree tops), *Eucalyptus* benefits from mixing with forage species, as there is a resultant increase in soil nutrient availability, mainly due to the decomposition of fine roots and nodules [36].

When estimating the volumetric production, the SPS yielded the highest average volume of wood per tree (0.2228 m^3), with a productivity of 111.4 m^3/ha. The *Eucalyptus* in MCS yielded a low volume per tree (0.1895 m^3) and a higher productivity per hectare (315.71 m^3/ha) due to the higher density of the crop (Table 3). This result is directly related to height and DBH, which showed the same tendency, proving that larger layouts result in greater individual volume, due to the larger area available for each plant [37].

These results are in agreement with existing research that analyzed the growth dynamics of a *Eucalyptus* clone implanted at various spacing (3 m × 2 m, 6 m × 2 m, 6 m × 3 m, 6 m × 4 m and 12 m × 2.5 m, respectively) in the northwestern region of Minas Gerais, showing higher values of DBH, Ht and volume/plant for spacing with a ground surface equal to or greater than 18 m^2, and a highest volume/tree at the 12 m × 2.5 m spacing. However, the smaller the land surface per plant (as is the case for the MCS area), the larger is the number of plants per hectare, and consequently, higher is the volume of wood per hectare [38].

3.4 Correlation between Soil Attributes and Eucalyptus Production

DBH, Ht and volume/tree were, in general, highly correlated to the values of SB, CEC, T, BS, SD, TVP, SM and ASI in SPS and MCS (Table 4).

The predominance of high values for correlations can be considered an indicator that the growth and production of *Eucalyptus* are sensitive to soil quality, with better performances in soils of greater fertility, and that are physically well structured, proving the importance of vegetative and edaphic conservation practices that aim at maintaining soil fertility.

4. Conclusions

Recovering areas of degraded pastures by planting *Eucalyptus* using MCS and SPS contributed to the improvement of the soil's chemical and physical attributes. Soil density and cation exchange capacity were the quality indicators which are most sensitive to interference in soil use and management.

The higher production of *Eucalyptus* in the SPS suggests the possibility of using wide spacing between plants to produce trees with larger diameters along the stem, allowing the wood to be used for economically more attractive purposes; however, the greater number of trees in the MCS yields a higher volume of wood per hectare.

The high correlations between the parameters of growth and production of *Eucalyptus*, and the chemical and physical attributes of the soil, confirm the importance of maintaining soil fertility to obtain good productivity indices of *Eucalyptus* in different spatial arrangements.

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