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CROP PRODUCTION

Soil preparation systems and type of fertilization as affecting physical attributes of cohesive soil under eucalyptus in Northeastern Brazil

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ABSTRACT. Cohesive Oxisols are widely used for cultivating eucalyptus in the Coastal Tablelands of the northeastern region of Brazil. However, mechanization and plant cultivation in these soils are difficult because of their cohesive layers. Therefore, the objective of this study was to identify better combinations between tillage systems and types of fertilization to improve the physical attributes of cohesive soil, with the aim of improving eucalyptus growth. The experimental design was completely randomized in a 4 × 2 factorial scheme (soil preparation × fertilization). The tillage systems tested were: i) conventional tillage (CT) - one plowing combined with two harrowings, ii) minimum tillage (MT) - subsoiling down until 0.57 m depths in the planting line, iii) no-tillage type 1 (NT1) - planting in 0.3 m-deep pits, and iv) no-tillage type 2 (NT2) - planting in 0.6 m-deep pits. The types of fertilization tested were mineral (MF) and organic fertilization (OF). The diameter of the soil aggregates was reduced after being subjected to any combination of cohesive soils. Furthermore, OF provided the best levels of plant-available water, attenuating the adverse conditions of the cohesive layer. MT, NT1, and NT2 improved the soil physical attributes when compared to CT. Therefore, the combination of either NT1 or NT2 with OF, followed by the combination of either NT1 or NT2 with MF, was determined to be the best way to cultivate eucalyptus on cohesive soils.

Keywords: coastal tablelands; soil quality; root growth; forest systems; Oxisols.

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Introduction

Cohesive soils are common in the Brazilian Coastal Tablelands. They are formed on sandy sediments that reach the coastal zone. The presence of cohesive layers constrains root growth and plant productivity. These landscapes include the coastal wetlands of the southeast, north, and northeastern regions of Brazil, encompassing a small part of the semi-arid coastal zone, between the states of Rio Grande do Norte and Piauí (Silva et al., 2019).

These soils, popularly denominated “cohesive soils,” have characteristics that restrict the development of root systems (Cavalcanti et al., 2019). The combination of high bulk density (BD), low water permeability, and high resistance to root penetration are the primary causes of these restrictions (Gomes et al., 2017). Furthermore, these soils also have chemical limitations that restrict plant development, such as low pH, high aluminum toxicity, low cation exchange capacity, and low base saturation (Cunha, Fontes, & Lani, 2019).

Despite their agricultural limitations, these soils are extensively used in agribusiness and are essential for maintaining the agricultural trade balance of this region. In Brazil, the production of eucalyptus accounts for 72% of the productivity in forests, with a planted area of approximately 5.7 million hectares, of which 16% is in the northeastern region of the country (Ibá, 2020).

In eucalyptus production systems, most producers use minimum tillage (MT) as a standard preparation system. This system consists of subsoiling cultivation lines and maintaining plant residues on the soil surface (González Barrios, Pérez, & Gutiérrez, 2015). However, due to the lack of qualified technical information, there are disagreements among eucalyptus farmers in Northeastern Brazil regarding the quality of the cohesive soil of the Coastal Tablelands, when subjected to MT. Therefore, some farmers alternatively use the conventional tillage (CT) system (plowing and harrowing) or the method which involves directly planting in pits, also called no-tillage (NT), in forest systems, because they believe that these systems are more efficient in establishing eucalyptus (Prevedello et al., 2013).

In addition to the above-mentioned tillage systems, the type of fertilization used is also of concern in cohesive soils. There is still a lack of consensus among eucalyptus farmers on the adoption of mineral fertilization (MF) or organic fertilization (OF), considering the intrinsic characteristics of cohesive soils. Both MF and OF are known to have positive effects on improving the chemical quality of the soil, such as increasing nutrient availability in the soil. However, both types of fertilization also affect the physical attributes of the soil differently. Among these effects, they may increase the dispersion of soil particles (Bi, Yao, & Zhang, 2015; Andrade et al., 2016), and reduce the stability and size of the aggregates (Blanco-Canqui, Ferguson, Shapiro, Drijber, & Walters, 2014; He, Xu, Gu, Wang, & Chen, 2018; Sithole, Magwaza, & Thibaud, 2019), as well as reduce soil permeability and water retention (Bassouny & Chen, 2015; He et al., 2018).

In this sense, the combination of tillage systems and the types of fertilization is a fundamental step when the objective is the sustainable management of cohesive soils under eucalyptus cultivation in the Coastal Tablelands of Northeastern Brazil. Thus, the objective of this study was to evaluate the effect of combinations of tillage systems and the types of fertilization to improve the physical attributes in cohesive soil, with the aim of improving eucalyptus growth.

Material and methods

The experiment was carried out in a cohesive Yellow Oxisol of the Coastal Tablelands in Cruz das Almas, Bahia State, Brazil (39°05'28'' W and 12°41'50,44'' S; altitude of 226 m). According to the Köppen classification, the region’s climate is tropical hot and humid, with a dry summer, mainly from September to February, and rainy winter in the rest of the year. The average annual rainfall in the rainy season is 1224 mm distributed between March and August, ranging from 900 to 1,300 mm, with 80% relative humidity, and an average annual temperature of 24.5°C.

The soil was classified as a typical dystrophic cohesive Yellow Oxisol (Santos et al., 2013), equivalent to Stagnic Densic Acrisol (Differentic, Hyperdystric) according to an international soil classification system (WRB, 2014), with a sandy-clay-loam texture, and the cohesive layer beginning at 0.15 m deep. Table 1 shows the physical and chemical characteristics of the soil during the experiment.

Table 1. Chemical and physical characterization of a dystrophic cohesive Yellow Oxisol, under eucalyptus cultivation in different types of tillage and fertilization, in the region of the Coastal Tablelands of the state of Bahia, Brazil.

Attributes[1]	0 - 0.2 m	0.2 - 0.4 m
pH (H_2O)	5.58	5.24
P (mg dm^{-3})	2.80	1.20
K^+ (mg dm^{-3})	40.00	17.00
Ca^{2+} ($cmol_c$ dm^{-3})	0.45	0.35
Mg^{2+} ($cmol_c$ dm^{-3})	0.35	0.19
Al^{3+} ($cmol_c$ dm^{-3})	0.20	0.68
H^++Al^{3+} ($cmol_c$ dm^{-3})	3.10	3.90
SB	0.90	0.58
t ($cmol_c$ dm^{-3})	1.10	1.26
T ($cmol_c$ dm^{-3})	4.00	4.48
V (%)	22.54	13.01
m (%)	18.14	53.82
Sand (g kg^{-1})	701.90	660.23
Silt (g kg^{-1})	47.83	40.51
CDC (g kg^{-1})	250.28	299.26
WDC (g kg^{-1})	208.03	240.60
DF (%)	16.88	19.60

[1]pH in water = 1:2.5 ratio, P and K = Mehlich extractor, Ca, Mg, and Al = KCl 1 mol L^{-1} extractor, H+Al = SMP extractor, SB = Sum of exchangeable bases, t = Effective cation exchange capacity, T = Cation exchange capacity at pH 7.0, V = Percentage of base saturation at pH 7.0, m = Percentage of aluminum saturation, CDC = Chemically dispersed clay, WDC = Water dispersed clay, DF = Degree of flocculation.

Before planting the eucalyptus, the soil was covered with degraded *Brachiaria decumbens* grass, with no mechanical intervention or fertilization. For the experiment, the area was desiccated using glyphosate herbicide at the dose recommended by the manufacturer. Four tillage systems were tested in this study combined with two types of fertilization, which were: i) CT - consisting of one plowing combined with two harrowings, and planting in 0.30-m deep pits that were 0.53 m in diameter; ii) MT - consisting of a single-shaft subsoiler at 0.57-m depths in the planting line; iii) NT1 - consisting of planting in 0.3-m depths, with 0.53-m diameter pits, on the dried pasture; and iv) NT2 - consisting of planting in 0.6-m deep pits that were 0.53 m in diameter.

The tractor used for this field work was an extra front-wheel drive, with a nominal power of 90 kW (122 hp) in the engine at 2,200 rpm and a maximum torque of 490 Nm at 1,400 rpm. The total weight was 5462 kg, including the operator, with 2,992 kg on the front, and 2,470 kg on the rear axle. The pits were dug with a drill 0.53 m in diameter and pulled by an agricultural tractor with a nominal power of 75 hp.

Furthermore, a reversible three-disc plow with a working depth of 0.22 m and a 22-disc leveling harrowing pulled by a 75 hp tractor, was used for the CT treatment. Meanwhile, for the MT treatment, we had used a trailing subsoiler with a smooth cutting disc that is 0.5 m in diameter, with a mass of 1,130 kg, a rod, and a working depth of 0.57 m in the planting line, pulled by a 122 hp tractor.

The MF treatment consisted of 136 g of NPK (10-30-10) per pit (N = 15.11 kg ha^{-1}, P_2O_5 = 45.33 kg ha^{-1}, and K_2O = 15.11 kg ha^{-1}). Subsequently, the fertilization was covered with 84 g (two doses of 42 g) of 20-0-20 per pit (N = 18.66 kg ha^{-1}, K_2O = 18.66 kg ha^{-1}). The OF treatment consisted of 6.38 L of cattle manure per pit (3.6 Mg ha^{-1}) (P≈1.25%, N≈1.16%, K≈0.77%, S≈0.2%, Ca≈1.93%, Mg≈0.88%, H_2O≈28.8%), estimated based on the phosphorus content, with a manure density of 0.51 g cm^{-3}.

The eucalyptus seedlings (a clonal hybrid of *Eucalyptus grandis* × *Eucalyptus urophylla*) were produced in polycarbonate tubes with 50 cm^3 of substrate, aged 78 days. All treatments received 0.6 L of hydrogel per plant.

The experimental design was completely randomized with four replicates, resulting in a 4 × 2 factorial assay (tillage × fertilization). The experimental plots consisted of an area of 180 m^2 with 20 plants, spaced 3 × 3 m, distributed in four lines of five trees, in addition to two borderlines.

For physical analysis of the soil, samples were collected in the planting line, at depths of 0.0–0.10 m, 0.10–0.20 m, 0.20–0.40 m, and 0.40–0.60 m. Undisturbed soil was sampled from each layer using metallic cylinders of 0.05 m × 0.05 m. The samples were taken from a trench in each experimental plot, 0.60 m deep, 0.50 m wide, and at 0.20 m from the plants.

Macroporosity (Ma), microporosity (Mi), total pore volume (TPV), bulk density (BD), field capacity (FC), permanent wilting point (PWP), and available water (AW) were determined for each sample. Samples of undisturbed clods were collected to analyze aggregate stability and expressed as the weighted average diameter (WAD). Deformed samples were collected using a Dutch-type auger at three points within the plot for granulometric analysis.

The grain size and water dispersed clay (WDC) were determined as described by Donagema, Campos, Calderano, Teixeira, and Viana (2011). Aggregate stability was achieved through wet sieving, according to Yoder (1936). The samples were air-dried, subjected to breakage at their points of weakness, and passed through sieves with 4.76 and 2.00 mm meshes. For this test, 30 g of aggregate samples, saturated in water by capillarity, was placed on a filter paper overnight and sieved for 15 min. in a sieve set with 2.0, 1.0, 0.5, 0.25, and 0.105 mm mesh. This was done with a stirring amplitude of 5.6 cm in water and a frequency of 46 rpm. The weighted average diameter was calculated according to the method of Kemper and Rosenau (1986):

$$DMP = \sum_{i=1}^{n} (xi \times wi)$$

where *xi* = % of aggregates retained in each sieve and *wi* = average diameter of the fraction (mm).

The available water (AW) was defined as the difference between field capacity (FC), soil moisture corresponding to the tension of 10 kPa, and permanent wilting point (PWP), with soil moisture corresponding to the tension of 1,500 kPa, using a Richards extractor. The collar diameter of the plants was measured using a graduated tape and the height of the plants was measured using a laser device. The six plants located at the center of each plot were sampled.

The results were initially subjected to the Shapiro-Wilk normality test. Once the normality was verified, the data were subjected to analysis of variance and the Scott-Knott test to compare the average results at a 5% probability level, using the Sisvar statistical program (Ferreira, 2014). After analyzing the variables, Spearman's correlation coefficients and their significance were tested with the Student's t-test, at 1% and 5% probabilities, using the "R" statistical software (R Development Core Team, 2018).

Results and discussion

Bulk density (BD) was not different in any combination of tillage systems and types of fertilization (Table 2). Prevedello et al. (2013) also found similar results when evaluating different soil preparation systems for planting eucalyptus.

Table 2. Bulk density in a typical dystrophic cohesive Yellow Oxisol, under eucalyptus cultivation with different types of tillage and fertilization, in the region of the Coastal Tablelands of the state of Bahia, Northeastern Brazil.

Fertilization	Tillage systems[1]				
	CT	MT	NT1	NT2	Means
			Bulk density (mg m^{-3})		
			0-0.1 m		
Mineral	1.46 aA	1.52 aA	1.57 aA	1.54 aA	1.52 A
Organic	1.52 aA	1.59 aA	1.59 aA	1.58 aA	1.57 A
Means	1.49 a	1.56 a	1.58 a	1.56 a	
CV (%)		4.26			
			0.1-0.2 m		
Mineral	1.53 aA	1.58 aA	1.58 aA	1.61 aA	1.58 A
Organic	1.62 aA	1.56 aA	1.64 aA	1.62 aA	1.61 A
Means	1.56 a	1.57 a	1.61 a	1.61 a	
CV (%)		5.99			
			0.2-0.4 m		
Mineral	1.61 aA	1.58 aA	1.57 aA	1.65 aA	1.60 A
Organic	1.45 aB	1.52 aA	1.56 aA	1.58 aA	1.52 BB
Means	1.54 a	1.55 a	1.57 a	1.62 a	
CV (%)		4.00			
			0.4-0.6 m		
Mineral	1.50 aA	1.53 aA	1.60 aA	1.55 aA	1.54 A
Organic	1.54 aA	1.55 aA	1.59 aA	1.52 aA	1.55 A
Means	1.52 a	1.54 a	1.59 a	1.53 a	
CV (%)		4.02			

[1]Means followed by the same lowercase letter in the lines and uppercase letters in the columns do not differ between each other by the Scott-Knott test at 5%. CT = conventional tillage, MT = minimum tillage, NT1 = no-tillage type 1and NT2 = no-tillage type 2. CV = coefficient of variation.

Nevertheless, there was a difference in the 0.20-0.40 m layer within the types of fertilization where OF provided a lower BD (1.52 Mg m^{-3}) than MF (1.60 Mg m^{-3}). There was especially a difference seen in the CT, in which the BD ranged from 1.61 Mg m^{-3} to 1.45 Mg m^{-3} under the OF treatment. As described in previous pieces of research, organic matter is directly related to the decrease in BD, mainly due to the improvement in soil structure by functioning as a binding agent (Reichert, Bervald, Rodrigues, Kato, & Reinert 2014; Cherubin et al., 2015), as well as because it has a lower density.

The TPV, Mi, and Ma did not differ among treatments in the 0-0.1 m layer (Table 3), except in the NT1 system, where a reduction in Mi was observed when compared to other systems.

There was a significant interaction between soil preparation and fertilization systems in the 0.2-0.4 m layer, showing higher TPV and Ma in the OF treatment. NT2 provided the lowest TPV in the MF. In contrast, the MT, NT1, and NT2 systems presented the lowest values under OF, which also negatively affected the Ma in the NT2 system. Furthermore, the BD had an inverse relationship with the TPV, which led to a greater Ma. Other authors attributed their results in the field to the effect of organic matter on the soil structure (Suzuki, Lima, Reinert, Reichert, & Pillon, 2014; Bi et al., 2015; León et al., 2019; Sithole et al., 2019). For the NT2 system, the reduction of Ma to values below 10%, that is, below the critical limit of 10 m^3m^{-3} (Richart, Tavares Filho, Brito, Llanillo, & Ferreira, 2005), is a limiting factor for soil aeration, affecting root development and biological activity (Azam, Grant, Murray, Nuberg, & Misra, 2014).

Soil resistance to penetration (SRP) (Figure 1) was different only when comparing among soil tillage systems (Table 4). The MT system was highlighted, which, regardless of the type of fertilization, provided the lowest SRP in the 0.1-0.2 m layer. The MT system was efficient when compared to the others, down to the 0.3-0.4 m layer. Therefore, it shows that the cohesive layer is below 0.2 m. At this depth, a cohesive layer was also observed during the morphological characterization of the soil profile in the field.

According to Tormena, Barbosa, Costa, and Gonçalves (2002), critical SRP values can range from 1.5 to 4.0 MPa, depending on the culture under study. However, values close to 2.0 MPa are generally accepted as constraints to root growth. Thus, regardless of the type of fertilization, only the MT system contributed to lowering the SRP values below the limit recommended by the literature (2.0 MPa) (Tormena et al., 2002). The SRP values obtained in the other treatments were higher than 2.0 MPa, starting at 0.2 m, in the humidity range of soil in this study. Silva, Silva, Giarola, Tormena, and Sá (2012) also found increasing values of SRP, starting at 0.2 m, when considering the same soil and management systems with no subsoiling.

Table 3. Total pore volume (TPV), and Micro- (Mi) and Macroporosity (Ma) of a typical dystrophic cohesive Yellow Oxisol, under eucalyptus cultivation with different types of tillage and fertilization, in the region of the Coastal Tablelands of the state of Bahia, Northeastern Brazil.

Fertilization	Tillage systems[1]														
	CT	MT	NT1	NT2	Means	CT	MT	NT1	NT2	Means	CT	MT	NT1	NT2	Means
	TPV (m^3 m^{-3})					Mi (m^3 m^{-3})					Ma (m^3 m^{-3})				
	0 - 0.1 m														
Mineral	42.41 aA	40.27 aA	35.86 aA	39.38 aA	39.43 A	20.93 aA	22.93 aA	17.62 aA	18.71 aA	19.71 A	22.03 aA	17.33 aA	18.23 aA	20.67 aA	17.61 A
Organic	39.67 aA	37.77 aA	36.81 aA	38.88 aA	38.23 A	21.08 aA	21.27 aA	18.14 aA	21.97 aA	20.62 A	18.59 aA	16.27 aA	18.66 aA	16.91 aA	19.71 A
Means	41.04 a	38.71 a	36.33 a	39.13 a		20.73 a	21.98 a	17.88 b	20.34 a		20.31 a	16.71 a	18.45 a	18.79 a	
CV (%)			8.04					12.47					23.54		
	0.1 - 0.2 m														
Mineral	39.82 aA	40.27 aA	35.85 aA	36.85 aA	37.96 A	22.38 aA	23.39 aA	21.34 aA	20.87 aA	21.90 A	17.43 aA	16.88 aA	14.51 aA	15.61 aA	16.06 A
Organic	39.41 aA	38.04 aA	37.29 aA	36.83 aA	36.82 A	24.39 aA	22.69 aA	22.05 aA	21.81 aA	22.47 A	15.02 aA	15.35 aA	15.24 aA	15.02 aA	15.16 A
Means	39.62 a	39.15 a	36.57 a	36.66 a		23.03 a	23.04 a	21.69 a	21.34 a		16.23 a	16.11 a	14.87 a	15.32 a	
CV (%)			7.47					9.86					20.90		
	0.2 - 0.4 m														
Mineral	35.93 aB	37.98 aA	36.31 aA	32.27 bA	35.85 B	24.28 aA	26.28 aA	24.15 aA	23.16 aA	24.56 A	11.65 aB	11.70 aA	12.16 aA	9.12 aA	11.29 B
Organic	43.83 aA	38.86 bA	37.80 bA	36.43 bA	39.43 A	26.10 aA	23.29 bA	21.01 bA	25.76 aA	23.83 A	17.72 aA	15.57 aA	16.80 aA	10.17 bA	15.51 A
Means	39.32 a	38.42 a	36.95 a	33.94 b		25.06 a	24.78 a	22.80 a	24.20 a		14.25 a	13.63 a	14.14 a	9.54 b	
CV (%)			5.91					9.37					25.19		
	0.4 - 0.6 m														
Mineral	39.16 aA	39.93 aA	38.87 bA	37.53 aA	37.39 A	23.43 aA	22.33 aA	26.64 aA	23.47 aA	23.97 A	17.60 aA	15.73 aA	15.79 bA	14.05 aA	13.42 A
Organic	38.64 aA	38.36 aA	38.07 aA	38.09 aA	38.29 A	24.23 aA	24.92 aA	23.25 aA	25.46 aA	24.47 A	14.12 aA	13.17 aA	14.81 aA	13.17 aA	13.82 A
Means	39.01 a	38.76 a	38.50 b	38.08 a		23.83 a	23.62 a	24.94 a	24.47 a		15.38 a	14.92 a	15.30 b	13.61 a	
CV (%)			6.60					10.01					26.23		

[1]Means followed by the same lowercase letter in the lines and uppercase letters in the columns do not differ between each other by the Scott-Knott test at 5%. CT = conventional tillage, MT = minimum tillage, NT1 = no-tillage type 1and NT2 = no-tillage type 2. CV = coefficient of variation.

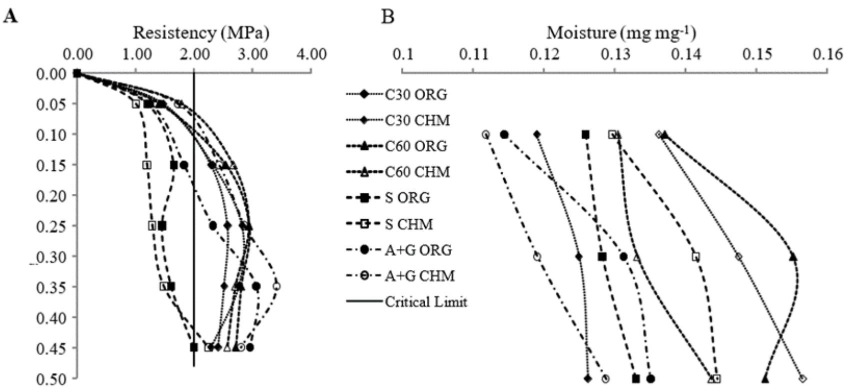

Figure 1. Soil resistance to penetration (SRP) (A) and gravimetric humidity at the time of reading in the field (B) of a typical dystrophic cohesive Yellow Oxisol, under eucalyptus cultivation with different types of tillage and fertilization, in the region of the Coastal Tablelands.

Reichert, Kaiser, Reinert, and Riquelme (2009) stated that SRP is the property that best characterizes the differences among management systems. The authors found layers with different degrees of resistance to penetration even under different sampling periods. Thus, the impact of the MT system after two years proved to be efficient for this attribute at various depths by breaking the cohesive layer and providing a lower SRP.

The CT treatment and the treatment with organic fertilization showed no difference when compared to the treatment with MT and SRP, down to a depth of 0.2 m. Below this layer, the implements used went no deeper into the soil, which was associated with the effect of the cohesive layer, which increased the SRP. Leon et al. (2019) found similar behavior in cohesive soils with the same preparation, as did Prevedello et al. (2013) and Ibiapina et al. (2014), when evaluating different types of tillage systems for eucalyptus cultivation.

The SRP of the NT1 and NT2 found in this study are consistent with that of the literature, in which there is a natural increase in SRP of the soil in either no tilling or in natural conditions, when there is the presence of cohesive horizons (Fonseca, Figueiredo, & Martins, 2011; Silva et al., 2012; Cherubin et al., 2015; Leon et al., 2019).

Table 4. Soil resistance to penetration of a dystrophic cohesive Yellow Oxisol, under eucalyptus cultivation with different types of soil preparation and fertilization, in the Coastal Tablelands of the state of Bahia, Brazil.

Fertilization	Tillage systems				
	NT1	NT2	MT	CT	Means
Soil Resistance to Penetration (MPa)					
0 - 0.1 m					
MF	1.44 aA	1.79 aA	1.00 aA	1.73 aA	1.49 A
OF	1.48 aA	1.41 aA	1.20 aA	1.25 aA	1.33 A
Means	1.46 a	1.60 a	1.10 a	1.49 a	
CV (%)			47.66		
0.1 - 0.2 m					
MF	2.33 aA	2.68 aA	1.20 aA	2.43 aA	2.16 A
OF	2.29 aA	2.55 aA	1.65 aA	1.83 aA	2.08 A
Means	2.31 b	2.61 b	1.42 a	2.13 b	
CV (%)			31.31		
0.2 - 0.3 m					
MF	2.83 bA	2.95 bA	1.29 aA	2.87 bA	2.48 A
OF	2.58 bA	2.95 bA	1.45 aA	2.32 bA	2.33 A
Means	2.70 b	2.95 b	1.37 a	2.59 b	
CV (%)			25.89		
0.3 - 0.4 m					
MF	2.77 bA	2.71 bA	1.49 aA	3.42 bA	2.60 A
OF	2.52 bA	2.81 bA	1.61 aA	3.07 bA	2.50 A
Means	2.65 b	2.76 b	1.55 a	3.24 b	
CV (%)			24.84		
0.4 - 0.5 m					
MF	2.30 aA	2.57 aA	2.25 aA	2.81 aA	2.48 A
OF	2.42 aA	2.72 aA	2.00 aA	2.97 aA	2.53 A
Means	2.36 a	2.65 a	2.13 a	2.89 a	
CV (%)			26.61		

Means followed by the same lowercase letter in the lines and uppercase letters in the columns do not differ between each other by the Scott-Knott test at 5%. CT = conventional tillage, MT = minimum tillage, NT1 = no-tillage type 1and NT2 = no-tillage type 2. MF = mineral fertilization, OF = organic fertilization. CV = coefficient of variation.

When studying the growth and morphology of the root system of eucalyptus plants, Misra and Gibbons (1996) found that increasing the SRP not only reduces the growth of the primary root and the emergence of lateral roots, but also increases the radial expansion of the roots and the number of root hairs. According to Azan et al. (2014), this is a plant response to the in-depth restriction of root growth.

The higher SRP, imposed by the cohesive layer of the Coastal Tableland soils, is the main limiting factor for crop development. This layer restricts the effective depth penetration and the superficial development of the root system. Because of this and the variations in rainfall, crops undergo significant periods of water deficit, as the volume of soil to be explored by the plant roots is reduced as a result (Souza, Sobrinho, Ribeiro, Souza, & Ledo, 2004a; Souza, Souza, & Ledo, 2004b; Santana, Souza, Souza, & Fontes, 2006).

The WAD in the 0.0-0.10 m layer (Table 5) highlighted one of the main effects of soil preparation in the CT (conventional) treatment. The typical intensive use of machines, plows, and harrows acts by fractioning and pulverizing soil aggregates, destroying the soil structure (Rocha et al., 2015). Among the soil preparation treatments, the CT differed from the other treatments, regardless of the type of fertilization, presenting the smallest weighted diameter of all aggregates. For the 0.1-0.2 m layer, the CT system was not enough to mitigate the negative effect on the WAD, even with OF. When studying different areas and types of tillage, Prevedello et al. (2014) concluded that in areas not tilled, or that had minimum preparation, the aggregates remain large.

For the 0.2-0.4 m layer, there is a specific effect of fertilization on the WAD. The diameters of the OF treatment were smaller than those in the MF. This temporary reduction in WAD results from the electrostatic effect of organic matter on soil aggregation. This effect takes longer to occur, unlike its effect on TPV and Ma, due to the reduction in Ds immediately after application and the porosity of the organic material used.

The treatments involving tillage and fertilization were capable of changing the FC and PWP, having a direct effect on plant-available water (AW) (Table 6). There was a specific effect on FC in the 0-0.1 m layer, with higher values in OF. At the depths of 0.1-0.2 m and 0.2-0.4 m, the effect showed an interaction between tillage systems and types of fertilization, with a prominence of the treatment under OF in the 0.1-0.2 m layer. This fact contributes to raising FC, especially in the CT system, when compared to the treatment under MF.

The effect of OF in the 0.2-0.4 m layer is also noteworthy, with higher FC values in the MT and NT2 systems, and higher values of PWP in the NT2 treatment.

Table 5. Weighted average diameter (WAD) of a typical dystrophic cohesive Yellow Oxisol, under eucalyptus cultivation with different types of tillage systems and fertilization, in the region of the Coastal Tablelands of the state of Bahia, Northeastern Brazil.

Fertilization	Tillage systems[1]				
	CT	MT	NT1	NT2	Means
	Weighted average diameter (mm)				
	0 - 0.1 m				
Mineral	2.32 aA	2.70 aA	2.76 aA	2.88 aA	2.67 A
Organic	2.29 aA	2.72 aA	2.52 aA	2.68 aA	2.54 A
Means	2.30 b	2.71 a	2.70 a	2.71 a	
CV (%)			10.16		
	0.1 – 0.2 m				
Mineral	2.58 aA	2.32 aA	2.55 aA	2.55 aA	2.50 A
Organic	1.82 bB	2.31 aA	2.46 aA	2.70 aA	2.32 A
Means	2.20 a	2.32 a	2.50 a	2.62 a	
CV (%)			13.67		
	0.2 – 0.4 m				
Mineral	2.22 aA	2.01 aA	2.29 aA	2.22 aA	2.18 A
Organic	1.95 aA	2.00 aA	1.87 aB	1.99 aA	1.95 B
Means	2.10 a	2.01 a	2.08 a	2.06 a	
CV (%)			12.68		
	0.4 – 0.6 m				
Mineral	1.97 aA	1.88 aA	1.70 aA	2.02 aA	1.85 A
Organic	1.69 aA	1.66 aA	1.93 aA	1.35 aA	1.65 A
Means	1.86 a	1.77 a	1.81 a	1.48 a	
CV (%)			16.52		

[1]Means followed by the same lowercase letter in the lines and uppercase letters in the columns do not differ between each other by the Scott-Knott test at 5%. CT = conventional tillage, MT = minimum tillage, NT1 = no-tillage type 1and NT2 = no-tillage type 2. CV = coefficient of variation.

Table 6. Field capacity (FC), permanent wilting point (PWP), and available water (AW) of a typical dystrophic cohesive Yellow Oxisol, under a eucalyptus crop in different types of tillage systems and fertilization, in the Coastal Tablelands of the state of Bahia, Northeastern Brazil.

Fertilization	Tillage systems[1]														
	CT	MT	NT1	NT2	Means	CT	MT	NT1	NT2	Means	CT	MT	NT1	NT2	Means
	FC ($m^3\ m^{-3}$)					PWP ($m^3\ m^{-3}$)					AW ($m^3\ m^{-3}$)				
	0 - 0.1 m														
Mineral	0.145 aA	0.145 aA	0.123 aA	0.129 aA	0.135 B	0.091 aA	0.087 aA	0.082 aA	0.067 bA	0.081 A	0.053 aB	0.058 aA	0.041 aB	0.061 aA	0.053 B
Organic	0.157 aA	0.155 aA	0.138 aA	0.153 aA	0.151 A	0.087 aA	0.090 aA	0.077 aA	0.083 aA	0.084 A	0.070 aA	0.064 aA	0.060 aA	0.069 aA	0.066 A
Means	0.151 a	0.151 a	0.130 a	0.141 a		0.089 b	0.089 b	0.076 a	0.075 a		0.065 a	0.062 a	0.051 b	0.062 a	
CV (%)			13.18					14.05					18.30		
	0.1 - 0.2 m														
Mineral	0.142 bB	0.178 aA	0.140 bA	0.153 bA	0.152 B	0.088 aA	0.111 aA	0.085 aA	0.083 aA	0.090 A	0.053 aB	0.066 aA	0.055 aA	0.070 aA	0.061 B
Organic	0.187 aA	0.187 aA	0.157 aA	0.171 aA	0.173 A	0.110 aA	0.107 aA	0.088 aA	0.104 aA	0.101 A	0.079 aA	0.077 aA	0.068 aA	0.067 aA	0.072 A
Means	0.157 b	0.182 a	0.148 b	0.161 b		0.095 a	0.109 a	0.087 a	0.092 a		0.061 a	0.073 a	0.061 a	0.069 a	
CV (%)			10.60					16.88					18.95		
	0.2 - 0.4 m														
Mineral	0.168 aA	0.191 aA	0.184 aA	0.188 aA	0.183 A	0.099 aA	0.123 aA	0.114 aA	0.118 aA	0.113 A	0.068 aA	0.073 aA	0.070 aA	0.064 aA	0.069 A
Organic	0.164 bA	0.200 aA	0.165 bA	0.183 aA	0.176 A	0.099 bA	0.111 bA	0.097 bA	0.127 aA	0.107 A	0.064 aA	0.071 aA	0.068 aA	0.073 aA	0.069 A
Means	0.166 b	0.187 a	0.176 b	0.193 a		0.099 b	0.114 a	0.107 b	0.125 a		0.067 a	0.073 a	0.069 a	0.068 a	
CV (%)			7.03					10.47					10.73		
	0.4 - 0.6 m														
Mineral	0.178 aA	0.191 aA	0.197 aA	0.188 aA	0.188 A	0.113 aA	0.121 aA	0.130 aA	0.123 aA	0.122 A	0.065 aA	0.069 aA	0.067 aA	0.064 aB	0.066 B
Organic	0.181 aA	0.197 aA	0.183 aA	0.200 aA	0.190 A	0.111 aA	0.120 aA	0.110 aA	0.122 aA	0.116 A	0.070 aA	0.077 aA	0.072 aA	0.077 aA	0.074 A
Means	0.179 a	0.193 a	0.190 a	0.193 a		0.112 a	0.120 a	0.120 a	0.123 a		0.067 a	0.073 a	0.070 a	0.070 a	
CV (%)			7.39					11.37					7.39		

[1]Means followed by the same lowercase letter in the lines and uppercase letters in the columns do not differ between each other by the Scott-Knott test at 5%. CT = conventional tillage, MT = minimum tillage, NT1 = no-tillage type 1and NT2 = no-tillage type 2. CV = coefficient of variation.

Fertilization had a positive effect on AW, with the highest values in the 0-0.1 m and 0.1-0.2 m layers of the CT system, as well as in the 0.4-0.6 m layer of the NT2 system. Braida, Bayer, Albuquerque, and Reichert, (2011) and Sithole et al. (2019) highlighted the importance of organic matter in water retention and availability due to the increase in pH-dependent loads and its high specific surface area, which reduces water loss through percolation along the profile (Bocuti, Amorim, Raimo, Magalhães, & Azevedo, 2020). When assessing the AW in different types of land use, Reichert et al. (2014) observed that when FC was higher, a more significant increase in AW occurred. This corroborates the values found in the present study. The results obtained by those authors showed that the effect of OF is more significant on mesopores, which are responsible for retaining water, than on the other pore sizes, thereby making it more available to plants.

This work showed significant correlations in all the depths studied when relating the physical attributes of the soil and eucalyptus parameters (Table 7). According to Callegari-Jacques (2003), the qualitative variations range from strong to very strong between soil attributes (porosity and soil density) and eucalyptus parameters.

Table 7. Pearson linear correlation matrixes for the different depths studied between the physical attributes of a typical dystrophic cohesive Yellow Oxisol and eucalyptus parameters in different tillage systems and types of fertilization in the Coastal Tablelands region.

	AW	H	FC	DGL	WAD	BD	Ma	Mi	PWP
					0-0.1 m				
H	0.20^{ns}	1.00							
FC	0.80*	0.18^{ns}	1.00						
DGL	0.27^{ns}	0.62*	0.16^{ns}	1.00					
WAD	0.06^{ns}	0.39^{ns}	0.07^{ns}	0.29^{ns}	1.00				
BD	0.07^{ns}	-0.32^{ns}	0.02^{ns}	-0.10^{ns}	0.25^{ns}	1.00			
Ma	-0.18^{ns}	0.18^{ns}	-0.13^{ns}	0.02^{ns}	-0.08^{ns}	-0.78*	1.00		
Mi	0.36^{ns}	0.02^{ns}	0.29^{ns}	0.09^{ns}	-0.08^{ns}	0.14^{ns}	-0.67*	1.00	
PWP	0.27^{ns}	0.10^{ns}	0.79*	0.00^{ns}	0.05^{ns}	-0.05^{ns}	-0.01^{ns}	0.08^{ns}	1.00
TPV	0.08^{ns}	0.26^{ns}	0.08^{ns}	0.11^{ns}	-0.18^{ns}	-0.93*	0.74*	0.00^{ns}	0.07^{ns}
					0.1-0.2 m				
H	-0.08^{ns}	1.00							
FC	0.61*	-0.23^{ns}	1.00						
DGL	0.02^{ns}	0.66*	-0.20^{ns}	1.00					
WAD	-0.27^{ns}	0.26^{ns}	-0.41^{ns}	0.15^{ns}	1.00				
BD	0.39^{ns}	0.07^{ns}	0.62*	0.17^{ns}	-0.32^{ns}	1.00			
Ma	-0.50^{ns}	0.09^{ns}	-0.57^{ns}	0.30^{ns}	0.05^{ns}	-0.55*	1.00		
Mi	0.38^{ns}	-0.13^{ns}	0.46^{ns}	-0.38^{ns}	-0.07^{ns}	0.03^{ns}	-0.45*	1.00	
PWP	-0.03^{ns}	-0.22^{ns}	0.77*	-0.26^{ns}	-0.31^{ns}	0.47^{ns}	-0.32^{ns}	0.27^{ns}	1.00
TPV	-0.28^{ns}	0.01^{ns}	-0.31^{ns}	0.06^{ns}	0.01^{ns}	-0.58*	0.78*	0.20^{ns}	-0.16^{ns}
					0.2-0.4 m				
H	0.03^{ns}	1.00							
FC	0.51^{ns}	0.14^{ns}	1.00						
DGL	-0.03^{ns}	0.74*	0.23^{ns}	1.00					
WAD	0.20^{ns}	0.03^{ns}	0.22^{ns}	-0.09^{ns}	1.00				
BD	-0.36^{ns}	-0.12^{ns}	-0.10^{ns}	0.05^{ns}	0.31^{ns}	1.00			
Ma	0.33^{ns}	0.11^{ns}	-0.07^{ns}	-0.16^{ns}	-0.27^{ns}	-0.61*	1.00		
Mi	0.06^{ns}	-0.18^{ns}	0.20^{ns}	0.00^{ns}	0.06^{ns}	0.07^{ns}	-0.73*	1.00	
PWP	0.02^{ns}	0.14^{ns}	0.87*	0.30^{ns}	0.13^{ns}	0.10^{ns}	-0.27^{ns}	0.21^{ns}	1.00
TPV	0.55^{ns}	-0.03^{ns}	0.13^{ns}	-0.23^{ns}	-0.33^{ns}	-0.80*	0.62*	0.08^{ns}	-0.16^{ns}
					0.4-0.6 m				
H	0.32^{ns}	1.00							
FC	0.38^{ns}	0.01^{ns}	1.00						
DGL	0.07^{ns}	0.70*	-0.03^{ns}	1.00					
WAD	-0.43^{ns}	-0.03^{ns}	-0.52^{ns}	0.06^{ns}	1.00				
BD	0.11^{ns}	0.01^{ns}	0.61*	-0.16^{ns}	-0.12^{ns}	1.00			
Ma	-0.02^{ns}	0.02^{ns}	-0.40^{ns}	0.26^{ns}	0.28^{ns}	-0.59*	1.00		
Mi	0.15^{ns}	0.11^{ns}	0.19^{ns}	-0.08^{ns}	-0.26^{ns}	0.19^{ns}	-0.79*	1.00	
PWP	-0.10^{ns}	-0.14^{ns}	0.88*	-0.06^{ns}	-0.34^{ns}	0.58^{ns}	-0.41^{ns}	0.14^{ns}	1.00
TPV	0.07^{ns}	0.11^{ns}	-0.44^{ns}	0.32^{ns}	0.23^{ns}	-0.72*	0.90*	-0.43^{ns}	-0.50^{ns}

AW = Available water, H = Plant height, FC = Field capacity, DGL = Diameter at ground level, WAD = Weighted average diameter, BD = Bulk density, Ma = Macroporosity, Mi = Microporosity, PWP = Permanent wilting point, TPV = Total pore volume.

As for Ma, the results showed a significant and positive correlation with TPV, and a negative correlation with Mi, for all the layers studied. This indicates that there is a dependence between both attributes in the distribution of the porous space within the soil. This behavior was previously observed and discussed (Table 3) with an increase or decrease in either attribute (Ma or Mi). When comparing the bulk density to soil porosity attributes, such as TPV and Ma, all the layers studied had significant negative correlations ranging from moderate to very strong, which indicates the close relationship between BD and soil porosity.

In the 0-0.1 and 0.1-0.2 m layers, FC showed a significant positive correlation with AW, which explains the effects observed in Table 6. The OF influenced the treatments, providing a better FC with a direct reflection on the AW.

The eucalyptus attributes evaluated (H and DGL) showed a significant positive correlation with each other at all depths studied. However, there was no significant correlation between the eucalyptus attributes and any of the soil attributes that were studied. The correlation between H and DGL was expected, and has also been observed by other researchers (Lima, Carvalho, Narimatsu, Silva, & Queiroz, 2010; Rosa Filho et al., 2011; Carvalho et al., 2012).

Conclusion

The reduced preparation and no-till systems yielded better physical conditions in the soil when compared to the conventional preparation (one plowing and two harrowings). Additionally, the conventional system reduced the aggregate diameter. Organic fertilization increased water availability for the eucalyptus trees, regardless of the management system adopted. Furthermore, there were significant correlations between some of the physical attributes of the soil. However, none had a relationship with the collar diameter and the plant height, which presented relationships with each other.

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