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Soil Compressibility under Irrigated Perennial and Annual Crops in a Semi-Arid Environment

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ABSTRACT: In irrigated soils, a continuous state of high moisture reduces resistance of the soil to applied external forces, favouring compaction. The aim of this study was to evaluate the susceptibility to compaction of developed calcareous soils in irrigated annual and perennial cropping systems of the Apodi Plateau, located in the Brazilian semi-arid region. Four areas of irrigated crops were evaluated: banana after two (B2) and 15 (B15) years cultivation, pasture (P), and a corn and beans succession (MB), as well as the reference areas for soil quality and corresponding natural vegetation (NVB2, NVB15, NVP and NVMB). Samples were collected at layers of 0.00-0.10 and 0.20-0.30 m; and for B2 and B15, samples were collected in the row and inter-row spaces. The following properties were determined: degree of compactness (*DC*), preconsolidation pressure (σ_p), compression index (*Cc*), maximum density (ρ_{max}), critical water content (WC_{crit}), total organic carbon (TOC) and carbon of light organic matter (C_{lom}). Mean values were compared by the t-test at 5, 10, 15 and 20 % probability. An increase was seen in *DC* at a layer of 0.20-0.30 m in MB (p<0.15), showing the deleterious effects of preparing the soil by ploughing and chiselling, together with the cumulative traffic of heavy machinery. The TOC had a greater influence on ρ_{max} than the stocks of C_{lom}. Irrigation caused a reduction in *Cc*, and there was no effect on σ_p at field capacity. The planting rows showed different behaviour for *Cc*, ρ_{max}, and WC_{crit}, and in general the physical properties displayed better conditions than the inter-row spaces. Values for σ_p and *Cc* showed that agricultural soils display greater load-bearing capacity and are less susceptible to compaction in relation to soils under natural vegetation.

Keywords: irrigated agriculture, soil quality, load capacity, trampling by animals.

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INTRODUCTION

One of the main causes of reduction in physical quality of agricultural soils is compaction, which increases with machine traffic and trampling by animals under conditions of high soil moisture (Hamza and Anderson, 2005; Michelon et al., 2009). Compaction may compromise the capacity of the soil to carry out its functions since it reduces the storage and availability of water and nutrients, gas exchange and fertilisation efficiency, and the biodiversity of the soil, and increases the rates of leaching and erosion (Soane and van Ouwerkerk, 1995; Saffih-Hdadi et al., 2009).

Soil compaction in agricultural soils is studied to avoid applying loads that exceed the load-bearing capacity of the soil (Alakukku et al., 2003). Therefore, quantification of the response of the soil to an applied stress is essential and this may be achieved by determination of preconsolidation pressure (σ_p), which is an indicator of soil load capacity and the compression index, which expresses soil compressibility (Défossez et al., 2014). When the soil undergoes pressures less than the σ_p, no increase in compaction occurs, but when the pressure is higher than the σ_p, soil compaction will occur, with consequent degradation of soil structure.

In Brazil, soil compression curves have been widely used to evaluate soil response in reference to different soil properties and management practices, such as tillage systems (Silva et al., 2002a,b; Veiga et al., 2007), grazed pasture and eucalyptus forest (Suzuki et al., 2015), orange orchard (Fidalski et al., 2015), Oxisols with different textures (Severiano et al., 2011), sugar cane crop (Pacheco and Cantalice, 2011; Pereira et al., 2015), pastures (Pires et al., 2012), coffee crop (Araujo-Junior et al., 2011; Pais et al., 2013), and agroforestry systems (Watanabe et al., 2016). Other studies have focused on investigating the methods applied in determination of σ_p and pedotransfer functions (Dias Junior and Pierce, 1996; Imhoff et al., 2004; Cavalieri et al., 2008; Suzuki et al., 2008; Severiano et al., 2011; Silva and Lima, 2016).

The Apodi Plateau, located in the semi-arid environment of the Brazilian Northeast, includes a large area with irrigated soil developed from calcareous rocks under different land use systems, where Dantas et al. (2012) and Pereira et al. (2012) have noted a reduction in the physical quality of soils under irrigated crops. However, other studies (Mota et al., 2013, Mota et al., 2015) reported that cultivated soils in the same region have no negative effect on soil physical quality. Literature shows that effects of management practices on soils under irrigated systems are not well understood for the Apodi Plateau region.

In irrigated soils, wetter conditions reduce the resistance of the soil to the application of external forces, which favours compaction (Neiva Júnior et al., 2015), especially in little-developed soils of moderate to weak structure with high-activity clay since the bonds between solids are weak compared to the intergranular forces (Mosaddeghi et al., 2007). Evaluation of the degree of compactness (*DC*) and determination of the σ_p of soils can therefore help in developing management strategies aimed at maintaining soil quality and agricultural productivity. Data on soil compression of soils derived from calcareous rocks of the Apodi Plateau region are still scarce. These data are useful for a better understanding of the soil response to external forces under different management practices, which will contribute to improving soil management.

The hypothesis of this study is that soils of the Apodi Plateau, developed from calcareous materials, have high susceptibility to compaction, regardless of the cropping system. The aim was to evaluate the susceptibility to compaction of developed calcareous soils under irrigated annual and perennial cropping systems in the Apodi Plateau in the Brazilian semi-arid region.

MATERIALS AND METHODS

Site description and soil sampling

This study was carried out in the Jaguaribe-Apodi Irrigated Area in the Apodi Plateau near the town of Limoeiro do Norte in the state of Ceará (CE), Brazil. The topography is flat, with an altitude that ranges from 100 to 130 m. Climate in the region is classified as hot semi-arid, type BSw'h, according to the Köppen classification system. The annual average rainfall is 772 mm and annual average temperature is 28 °C. The soils of the study areas are derived from calcareous rocks and developed from the Jandaira Formation, referred to as the Upper Cretaceous (Brasil, 1981).

Four areas under continuous cropping were selected for this study: a succession of corn and beans (MB), an area under banana for 2 years (B2), an area under banana for 15 years (B15), and pasture (P), and their adjacent areas under native vegetation (NVMB, NVB2, NVB15, and NVP). These areas were selected on the basis of: i) continuous use of cropping practices specific to each crop type (annual, semi-perennial, or perennial); ii) the time over which these practices were likely to have been applied; and iii) the relevance of the management system to the area. The areas under native vegetation (NV) that were selected showed characteristics of steppe-like savannah (*Caatinga*), including the presence of low trees and a seasonal herbaceous stratum with perennial, thorny, and deciduous species (Woodward et al., 2004). The areas under NV belong to the same soil class as their respective agricultural areas, except for MB, which is under an *Argissolo Vermelho-Amarelo Eutrófico típico* (*Typic Paleudults*). A description of these areas, their soil types, and their management history are in table 1.

Table 1. Land use, soil classification, and history of the areas under study in the Jaguaribe-Apodi Irrigated Area, Limoeiro do Norte, CE, Brazil

Land use and geographic coordinates[(1)]	Soil classification	Description and history of the area
Banana (B15) 5° 09' 15" S 37° 59' 55" W	Typic Haplocambid (*Cambissolo Háplico Ta Eutrófico típico*)	Area cultivated with vegetables for five years before planting the banana crop (*Musa sp*) cv. Dwarf Silver in 1998. Banana was fertilised with applications of goat manure (20 L per plant) and by compost prepared from harvest residue (600 L ha^{-1} per week). Mineral fertilisation was carried out monthly using urea, and potassium and magnesium sulphates. Crop residues were left on the soil surface and insects, diseases, and weeds were controlled by the application of chemical pesticides. Machine and equipment traffic in the area included an agricultural tractor and trailer when harvesting, and chisel plough and harrow when renewing. At the time of sample collection, the soil had been used for cultivating bananas for 15 years.
Banana (B2) 5° 09' 29" S 38° 01' 52" W	Typic Haplocambid (*Cambissolo Háplico Tb Eutrófico típico*)	From 1990 to 1999, the area was cultivated with corn and beans in succession, with centre-pivot irrigation. This was followed by guava from 2000 to 2007, but with irrigation by micro-sprinkler. In 2008, the guava trees were removed for cultivation of banana. Soil tillage for planting the crop included chiselling and harrowing. The control of insects, diseases, and weeds was by chemical pesticides. Mineral fertilization was carried out when needed, and machine traffic in the area, associated with harvesting, involved an agricultural tractor and trailer. When soil samples were collected, the banana trees had been in place for two years.
Pasture (P) 5° 12" 54" S 38° 01' 52" W	Typic Haplocambid (*Cambissolo Háplico Ta Eutrófico típico*)	After removal of natural vegetation, the area was planted with corn and beans in succession from 1990 to 2001 under centre-pivot irrigation. Tifton grass (*Cynodon niemfluesis*) was planted in 2001, and the area was used as pasture for feeding 300 cows. The whole area was divided into 16 paddocks of 3 acres, with the animals remaining for 36 h in each paddock, returning to the same paddock after approximately 24 days, on average. Mineral fertilization was carried out with urea (100 kg ha^{-1}) applied at each grazing cycle, and NPK (10:50:00) at 50 kg ha^{-1} for every four applications of urea. Organic fertilization used manure from the animals in the area. During the rainy season the soil became saturated, which could lead to animals being removed. Haymaking was at the end of the rainy season.
Corn/beans (MB) 5° 10' 9" S 37° 58' 58" W	Rhodic Eutrustox (*Latossolo Vermelho Eutrófico cambissólico*)	Since 1990, this area has been cultivated with corn (*Zea mays* L.) in succession with beans (*Vigna unguiculata*) using centre-pivot irrigation. Each year three corn crops are harvested (30,000 ears ha^{-1}) and one of beans (1,600 kg ha^{-1}). The ears and shoots of the corn were removed and sold for silage. Before sowing, ploughing and harrowing were always performed, and chiselling was sometimes performed after ploughing and harrowing. Mineral fertilization used 250 kg ha^{-1} of NPK (10:28:20), and fertigation with micronutrients was also carried out. The control of insects, diseases, and weeds was by chemical pesticides.

(1) Sources: Dantas et al. (2012) and Pereira et al. (2012).

Soil sampling was carried out at layers of 0.00-0.10 and 0.20-0.30 m. In the areas cultivated with banana (B2 and B15), the soil samples were collected in the crop rows ($B2_R$ and $B15_R$) and inter-row spaces ($B2_I$ and $B15_I$). This was not done for the other types of land use due to the difficulty of setting up similar sampling points. For each treatment, four undisturbed samples (2.5 cm high and 7.4 cm in diameter) were obtained using an Uhland sampler, together with four single disturbed samples from each layer. Additionally, a composite sample was obtained from the four sampling points to carry out the Proctor test. The single disturbed samples were used to determine soil particle size, particle density, total organic carbon (TOC), and light organic matter. The undisturbed samples were used to determine the compaction curve and soil bulk density.

Proctor test and degree of compactness

For the Standard Proctor Test (Stancati et al., 1981), undisturbed soil samples were moistened and compacted in a metal ring of 10 cm diameter and 12.73 cm in height, in three layers, each receiving 25 blows of a 2.50 kg hammer dropped from a height of 0.305 m. After application of the blows, a specimen sample was removed to determine the soil moisture (*Ms*). The compaction curve was obtained from three replications and five different values for water content. The degree of compactness was determined in accordance with the equation proposed by Håkansson (1990): $DC = (\rho / \rho_{max}) \times 100$, in which *DC* is the degree of compactness in %, ρ is soil bulk density in Mg m^{-3}, and ρ_{max} is the maximum soil density in Mg m^{-3}.

Uniaxial compaction test

For the uniaxial compaction test, undisturbed samples were used, equilibrated at a matric potential of -10 kPa using Richards chambers (Dane and Hopmans, 2002). The uniaxial compaction test was performed with a pneumatic consolidometer, described by Figueiredo et al. (2011). Successive and continuous applications of increasing loads of 0, 12.5, 25, 50, 100, 200, 400, 600, 800, 1000, and 1200 kPa were applied to the samples for a period of five minutes (Silva et al., 2000). The samples were subsequently dried in an oven at 105 °C for 24 h to determine the soil bulk density (ρ) (Grossman and Reinsch, 2002) and water content (θ) of the sample. The total porosity (*Tp*) and degree of saturation (*Sr*) were estimated using the equations: $Tp = 1 - (\rho/\rho d)$ and $Sr = (\theta/Tp) \times 100$, in which *Tp* is the total porosity in m^3 m^{-3}, ρ is the soil density in Mg m^{-3}, ρ*d* is the particle density in Mg m^{-3}, *Sr* is the degree of saturation in %, and θ is the water content in m^3 m^{-3}.

From soil deformation data in the uniaxial compaction test, the void ratio (*e*) for each load applied (σ’) was calculated in accordance with the equation proposed by McBride and Joosse (1996): $e = (\rho d/\rho) - 1$. Soil compaction curves were constructed from values obtained for *e* and σ’ using the Gompertz equation as suggested by Gregory et al. (2006) and adjusted by the method of least squares: $e = j + k \exp[l((\log 10\ \sigma') - m))]$, in which σ’ is the applied load in kPa and *j*, *k*, *l*, and *m* are coefficients obtained when fitting the data to the model. The compression index (*Cc*) was calculated from the adjusted coefficients using the model of Gregory et al. (2006), which estimates the slope of the virgin compression line, with the modulus of the slope at the inflection point (*m*) estimated by the equation $Cc = lk/exp(1)$ in which *Cc* is the compression index, *l* and *k* are coefficients obtained when adjusting the Gompertz model (Gregory et al., 2006), and *exp(1)* is the exponential function of the number one. The preconsolidation pressure (σ_p) was determined from the compaction curve adjusted by the Gompertz equation (Gregory et al., 2006) using the algorithm proposed by Imhoff et al. (2004) with the Mathcad® software. This method results in slightly lower values of σ_p than Casagrande (1936), but better describes the soil curve because the rate of decrease of the void ratio is lower after the inflection point.

Particle size and organic matter

Particle size analysis was determined by the pipette method (Claessen, 1997) using chemical dispersion with 10 mol L^{-1} NaOH, combined with ultrasonic dispersion using sonication at an energy level of 204 J mL^{-1}. The particle size composition of the soils is given in table 2. Particle density (ρd) was determined by the gas displacement method (Flint and Flint, 2002) with the use of a helium gas pycnometer, AccuPyc Model 1330 from Micromeritics Instrument Corporation®, using soil samples passed through a 2.0 mm sieve and dried at 105 °C.

The light organic matter (*LOM*) was determined for the layer of 0.00-0.10 m. Initially, 500 g of air-dried soil were passed through mesh sieves of 8, 4, 2, and 0.25 mm diameter, with the material retained in each sieve being separated, weighed, and stored. 13-g samples of each soil fraction retained by the 4, 2, and 0.25 mm sieves were subsequently shaken in a NaI solution (density 1.8 kg L^{-1}) and then centrifuged at 3,200 rpm for 15 min, followed by flotation separation of the *LOM* (Sohi et al., 2001). The suspended material was separated using a 0.025 mm sieve, washed with distilled water to remove the NaI, dried at 65 °C, and then weighed.

The concentration of carbon light organic matter (C_{lom}) was determined for each fraction by dry combustion in an elemental analyser. The concentration of total organic carbon (*TOC*) in the soil was determined by wet oxidation of the organic matter in the presence of $K_2Cr_2O_7$, in a sulphuric medium with external heating (Yeomans and Bremner, 1988). The stocks of light organic matter (S_{lom}) and carbon light organic matter (S_{Clom}) were calculated by the expression S_{lom} *or* $S_{Clom} = t \times \rho \times h$, in which S_{lom} or S_{Clom} are the stocks in Mg ha^{-1}; t is the *LOM* or C_{lom} concentration in g kg^{-1}; and h is the thickness of the soil layer in m, in each of the separated soil fractions.

Statistical analysis

Mean values were compared based on variance and average by the F-test and t-test, respectively, comparing the cultivated areas and those under natural vegetation. To check the homogeneity of variance between populations, the unilateral F-test was carried out using the quotient between the largest and smallest variance, $F = S_A^2 / S_B^2$, where S_A^2 is the variance with the greatest value and S_B^2 is the variance with the smallest value.

Evaluation of the difference in variables between the different uses as regards average was carried out using the bilateral t-test. For populations with homogeneity of variance, the t-test was applied as per the equations $t = \left(\bar{Y}_1 - \bar{Y}_2\right) \Big/ \sqrt{S_c^2\left(1/n_1 + 1/n_2\right)}$ and $S_c^2 = \left((n_1 - 1)S_1^2 + (n_1 - 1)S_2^2\right) \Big/ (n_1 + n_2 - 2)$, in which $n_1 + n_2 - 2$ are the degrees of freedom, $\bar{Y}_1 - \bar{Y}_2$ are averages of the variables for the different populations, S_1^2 and S_2^2 are the variances of the two populations used in each comparison, S_c^2 is the common variance among the populations, and n_1 and n_2 are the number of samples for each population (1 and 2) under comparison. In cases where the variance was heterogeneous, the t-test calculation was done using the above equation proposed by Moser and Stevens (1992). For calculating the degrees of freedom (n^*), the equation $n^* = ((S_1^2/n_1) + (S_2^2/n_2)) \Big/ ((S_1^2/n_1)/(n_1 - 1) + (S_2^2/n_2)/(n_2 - 1))$ was used.

Both the Pearson linear correlation and simple linear regression were performed using the Statistica® software (Weiß, 2007), which were used to verify the degree of relationship between the variables. The t-test was carried out at levels of 5, 10, 15, and 20 % probability, considering $p<0.05$ as a statistically significance difference between means, while the remaining probabilities were considered to be trends.

RESULTS AND DISCUSSION

Influence of texture on compressive behaviour

Particle size for the soils under different agricultural uses and their adjacent reference areas (NVs) were statistically similar ($p<0.05$), except for the soil under MB (Tables 2 and 3),

Table 2. Means and standard deviation of the physical and chemical properties of the soil at layers of 0.00-0.10 and 0.20-0.30 m in areas under irrigated cultivation and natural vegetation (NV) in the Jaguaribe Irrigated Area, Apodi, CE, Brazil, n=4

Variable	P[(1)]	NVP	MB	NVMB	$B2_R$	$B2_I$	NVB2	$B15_R$	$B15_I$	NVB15
					0.00-0.10 m					
Clay (g kg^{-1})	459 (50.67)	300 (85.08)	493 (22.43)	305 (20.44)	394 (23.92)	403 (33.37)	420 (31.42)	340 (30.97)	321 (33.90)	379 (41.80)
Silt (g kg^{-1})	111 (6.60)	227 (18.57)	65 (4.79)	70 (4.59)	113 (24.72)	78 (14.86)	88 (5.84)	111 (24.42)	98 (11.14)	106 (28.22)
TS (g kg^{-1})	430 (54.74)	473 (10.12)	442 (18.03)	625 (41.06)	493 (36.58)	519 (32.33)	492 (26.08)	549 (51.06)	581 (29.40)	515 (29.61)
Cc[(2)]	0.31 (0.05)	0.26 (0.01)	0.25 (0.06)	0.31 (0.01)	0.25 (0.06)	-	0.42 (0.09)	0.30 (0.04)	0.24 (0.04)	0.31 (0.02)
σ_p (kPa)	118 (18.35)	127 (8.64)	83 (18.33)	135 (14.82)	110 (7.14)	-	71 (31.79)	137 (30.41)	131 (18.92)	124 (7.25)
e_0	0.74 (0.10)	0.67 (0.04)	0.65 (0.09)	0.69 (0.03)	0.62 (0.06)	0.58 (0.07)	0.95 (0.14)	0.66 (0.07)	0.60 (0.07)	0.70 (0.04)
ρ (Mg m^{-3})	1.52 (0.09)	1.62 (0.04)	1.62 (0.08)	1.59 (0.03)	1.64 (0.06)	1.69 (0.08)	1.36 (0.10)	1.59 (0.07)	1.68 (0.08)	1.57 (0.04)
DC (%)	97 (5.64)	-	94 (4.73)	85 (1.65)	91 (3.55)	96 (4.32)	77 (5.87)	92 (3.84)	97 (4.46)	91 (2.16)
Sr (%)	68.18 (6.74)	65.63 (4.79)	79.05 (12.47)	55.99 (3.14)	74.06 (7.32)	57.28 (6.25)	57.33 (7.36)	65.44 (6.90)	85.49 (7.87)	66.20 (5.59)
Mv	0.29 (0.01)	0.26 (0.02)	0.31 (0.03)	0.23 (0.01)	0.28 (0.02)	0.21 (0.01)	0.28 (0.01)	0.26 (0.03)	0.32 (0.04)	0.27 (0.01)
Ms	0.19 (0.01)	0.16 (0.02)	0.19 (0.01)	0.14 (0.01)	0.17 (0.01)	0.12 (0.01)	0.20 (0.01)	0.16 (0.02)	0.19 (0.03)	0.17 (0.01)
ρ_{max} (Mg m^{-3})	1.56 (0.07)	-	1.73 (0.04)	1.87 (0.03)	1.80 (0.02)	1.76 (0.02)	1.77 (0.02)	1.73 (0.02)	1.72 (0.02)	1.73 (0.03)
WC_{crit} (%)	32.35 (5.32)	-	19.23 (0.81)	13.51 (1.19)	16.46 (0.25)	17.15 (0.41)	16.92 (0.24)	18.09 (0.86)	19.25 (0.44)	17.36 (0.68)
TOC (g kg^{-1})	81.02 (6.78)	38.13 (3.31)	14.05 (2.31)	21.99 (3.45)	15.75 (1.57)	16.43 (3.45)	19.34 (6.58)	16.72 (2.16)	16.03 (3.96)	20.83 (3.57)
					0.20-0.30 m					
Clay (g kg^{-1})	465 (43.85)	245 (71.69)	514 (14.55)	505 (96.86)	460 (27.97)	494 (89.91)	586 (26.37)	538 (2.10)	488 (37.82)	387 (61.22)
Silt (g kg^{-1})	90 (2.66)	163 (21.97)	62 (3.12)	87 (24.86)	85 (12.59)	82 (11.49)	71 (10.90)	66 (3.39)	66 (6.96)	89 (21.20)
TS (g kg^{-1})	445 (46.50)	592 (16.50)	424 (14.50)	408 (43.70)	455 (17.70)	424 (67.54)	343 (26.38)	396 (5.39)	446 (43.75)	524 (42.08)
Cc[(2)]	0.29 (0.02)	0.33 (0.03)	0.35 (0.08)	0.33 (0.03)	0.30 (0.03)	0.32 (0.05)	0.31 (0.01)	0.37 (0.03)	0.30 (0.02)	0.36 (0.02)
σ_p (kPa)	154 (32.80)	219 (45.71)	128 (24.31)	116 (4.16)	126 (25.20)	72 (7.98)	122 (13.14)	64 (7.49)	106 (6.92)	142 (29.96)
e_0	0.72 (0.07)	0.81 (0.06)	0.51 (0.07)	0.84 (0.02)	0.75 (0.11)	0.78 (0.12)	0.85 (0.03)	0.90 (0.03)	0.79 (0.79)	0.83 (0.05)
ρ (Mg m^{-3})	1.54 (0.06)	1.49 (0.05)	1.79 (0.08)	1.46 (0.02)	1.53 (0.10)	1.50 (0.11)	1.46 (0.02)	1.41 (0.02)	1.50 (0.02)	1.47 (0.02)
DC (%)	93 (3.58)	-	108 (4.97)	84 (5.61)	85 (6.29)	87 (1.20)	81 (1.43)	82 (1.41)	84 (1.31)	82 (2.42)
Sr (%)	73.50 (3.79)	69.38 (3.62)	92.70 (10.40)	66.23 (3.38)	72.45 (6.09)	69.72 (4.96)	73.10 (3.87)	57.02 (2.49)	65.89 (1.25)	58.26 (2.03)
Mv	0.31 (0.02)	0.31 (0.01)	0.31 (0.01)	0.30 (0.01)	0.31 (0.04)	0.30 (0.01)	0.33 (0.01)	0.27 (0.01)	0.29 (0.01)	0.26 (0.01)
Ms	0.20 (0.02)	0.21 (0.01)	0.17 (0.01)	0.21 (0.01)	0.20 (0.03)	0.20 (0.01)	0.23 (0.01)	0.19 (0.01)	0.19 (0.01)	0.18 (0.01)
ρ_{max} (Mg m^{-3})	1.65 (0.01)	-	1.64 (0.14)	1.73 (0.01)	1.79 (0.01)	1.72 (0.05)	1.80 (0.01)	1.72 (0.01)	1.78 (0.01)	1.80 (0.01)
WCcrit (%)	21.28 (0.54)	-	17.98 (0.27)	18.01 (0.28)	18.08 (0.16)	19.01 (0.93)	19.36 (0.28)	17.87 (0.48)	17.68 (0.13)	17.28 (0.11)
TOC (g kg^{-1})	22.11 (1.67)	21.89 (1.68)	10.66 (2.23)	11.40 (4.08)	10.05 (2.62)	7.82 (1.42)	13.23 (6.40)	6.52 (1.06)	7.03 (0.91)	10.07 (2.13)

[(1)] P: Irrigated pasture; NVP: natural vegetation close to P; MB: Irrigated corn and beans in succession; NVMB: natural vegetation close to MB; $B2_R$: row of irrigated banana crop after two years of planting; $B2_I$: inter-row space of irrigated banana crop after two years of planting; NVB2: natural vegetation close to B2; $B15_R$: row of irrigated banana crop after 15 years of planting; $B15_I$: inter-row space of irrigated banana crop after 15 years of planting; NVB15: natural vegetation close to B15. [(2)] Clay: <2 μm; Silt: 2-50 μm; TS: total sand 50-2,000 μm; Cc: compression index (adimensional); σ_p: preconsolidation pressure; e_0: void index (adimensional); ρ: soil bulk density; DC: degree of compactness; Sr: degree of water saturation; Mv: volumetric water content; Ms: water content; ρ_{max}: maximum bulk density; WC_{crit}: critical water content; TOC: total organic carbon. -: not estimated.

Table 3. Results of the t-test and F-test for the physical and chemical properties of the soil at layers of 0.00-0.10 and 0.20-0.30 m in areas under irrigated cultivation and natural vegetation (NV) in the Jaguaribe Irrigated Area, Apodi, CE, Brazil

Variable	P vs NVP(1)	MB vs NVMB	$B2_R$ vs NVB2	$B2_E$ vs NVB2	$B2_R$ vs $B2_I$	$B15_R$ vs NVB15	$B15_I$ vs NVB15	$B15_R$ vs $B15_I$
				0.00-0.10 m				
Clay (g kg^{-1})	ns (ns)	*(*)	ns (ns)	ns (ns)	-	ns (ns)	ns (ns)	-
Silt (g kg^{-1})	ns (*)	ns (ns)	ns (*)	ns (ns)	-	ns (ns)	ns (ns)	-
TS (g kg^{-1})	ns (*)	ns (ns)	ns (ns)	ns(ns)	-	ns (ns)	ns (ns)	-
Cc(2)	* (*)	* (*)	* (ns)	-	-	* (ns)	* (ns)	* (ns)
σ_p (kPa)	ns (ns)	ns (ns)	ns (*)	-	-	ns (*)	ns (ns)	ns (ns)
e_0	* (ns)	* (ns)	* (ns)	* (ns)	* (ns)	* (ns)	* (ns)	* (ns)
ρ (Mg m^{-3})	* (ns)	* (ns)	* (ns)	* (ns)	* (ns)	* (ns)	* (ns)	* (ns)
DC (%)	-	ns (ns)	ns (ns)	ns (ns)	ns (ns)	ns (ns)	ns (ns)	ns (ns)
Sr (%)	ns (ns)	ns (*)	ns (ns)	ns (ns)	ns (ns)	ns (ns)	ns (ns)	ns (ns)
Mv	* (ns)	* (*)	* (ns)	* (ns)	* (ns)	* (ns)	* (ns)	* (ns)
Ms	* (ns)	* (ns)	* (ns)	* (ns)	* (ns)	* (ns)	* (*)	* (ns)
ρ_{max} (Mg m^{-3})	-	* (ns)	* (ns)	* (ns)	* (ns)	ns (ns)	* (ns)	* (ns)
WC_{crit} (%)	-	* (ns)	* (ns)	+ (ns)	* (ns)	ns (ns)	* (ns)	* (ns)
TOC (g kg^{-1})	+++(ns)	ns (ns)	ns (*)	ns (ns)	ns (ns)	ns (ns)	ns (ns)	ns (ns)
				0.20-0.30 m				
Clay (g kg^{-1})	ns (ns)	ns (*)	ns (ns)	ns (*)	-	ns (*)	ns (ns)	-
Silt (g kg^{-1})	ns (*)	ns (*)	ns (ns)	ns (*)	-	ns (*)	ns (ns)	-
TS (g kg^{-1})	ns (ns)	ns (ns)	*(ns)	ns (ns)	-	ns (*)	ns (ns)	-
Cc(2)	* (ns)	* (ns)	* (ns)	* (*)	* (ns)	* (ns)	* (ns)	* (ns)
σ_p (kPa)	ns (ns)	ns (*)	ns (ns)	ns (ns)	ns (*)	ns (*)	ns (*)	ns (ns)
e_0	* (ns)	* (*)	* (*)	* (*)	* (ns)	* (ns)	* (ns)	* (ns)
ρ (Mg m^{-3})	* (ns)	* (*)	* (*)	* (*)	* (ns)	* (ns)	* (ns)	* (ns)
DC (%)	-	++ (*)	ns (*)	ns (*)	ns (ns)	ns (ns)	ns (ns)	++ (ns)
Sr (%)	ns (ns)	+ (*)	ns (ns)	ns (ns)	ns (ns)	ns (ns)	* (ns)	* (ns)
Mv	* (ns)	* (ns)	* (ns)	* (ns)	* (*)	* (ns)	* (ns)	* (ns)
Ms	* (ns)	* (ns)	* (*)	* (*)	ns (ns)	* (ns)	* (ns)	* (ns)
ρ_{max} (Mg m^{-3})	-	* (*)	* (ns)	* (ns)	* (ns)	* (ns)	* (ns)	* (ns)
WC_{crit} (%)	-	ns (ns)	* (ns)	ns (ns)	++ (*)	* (*)	* (ns)	+++ (ns)
TOC (g kg^{-1})	ns (ns)	ns (ns)	ns (ns)	ns (*)	ns (ns)	+++ (ns)	+++ (ns)	ns (ns)

(1) P: Irrigated pasture; NVP: natural vegetation close to P; MB: Irrigated corn and beans in succession; NVMB: natural vegetation close to MB; $B2_R$: row of irrigated banana crop after two years of planting; $B2_I$: inter-row space of irrigated banana crop after two years of planting; NVB2: natural vegetation close to B2; $B15_R$: row of irrigated banana crop after 15 years of planting; $B15_I$: inter-row space of irrigated banana crop after 15 years of planting; NVB15: natural vegetation close to B15. (2) Clay: <2 µm; Silt: 2-50 µm; TS: total sand 50-2,000 µm; Cc: compression index (adimensional); σ_p: preconsolidation pressure; e_0: void index (adimensional); ρ: soil bulk density; DC: degree of compactness; Sr: degree of water saturation; Mv: volumetric water content; Ms: water content; ρ_{max}: maximum bulk density; WC_{crit}: critical water content; TOC: total organic carbon. ns: not significant, *: significant at 5 %, + significant at 10 %, ++ significant at 15 %, +++ significant at 20 % by bilateral t-test of the means and F-test of variances, -: not estimated.

where the clay content at a layer of 0.00-0.10 m for MB was significantly different ($p<0.05$) from NVMB, which is due to the natural differences of these soils since they belong to different soil classes (Table 1).

To assess the possible influence of texture on the variables tested, the Pearson correlation between clay content and the compression index (*Cc*) and between clay content and preconsolidation pressure (σ_p) were calculated. The correlation coefficients (r) indicated a weak correlation of clay content with *Cc* ($r = 0.23$, $p>0.05$) and a moderate correlation with σ_p ($r = -0.49$, $p<0.05$), demonstrating that comparison of the variables associated with the compressive behaviour of the soil was not strongly influenced by the clay content, which may be due to the mean values for clay content of the evaluated soils. Compressive behaviour of the soil shows little influence from clay content up to 30 % (Imhoff et al., 2004).

In general, for the variables tested, the coefficient of variation was low, less than 10 %, with the exception of TOC, σ_p, and *Cc*, which had coefficients of variation of 35.8, 22.2, and 23.5 % respectively.

Degree of compactness

The use of degree of compactness (*DC*) to characterise the status of the soil structure makes possible the comparison of different types of soils, since the effects of texture and organic matter are removed, as noted by Silva et al. (1997). In this study, the *DC* was used only to assess the impact of the different agricultural uses and management systems on the soil structure.

It was seen that the different agricultural uses being evaluated showed *DC* values statistically similar to those of the reference areas ($p<0.05$) (Table 3), but with a tendency ($p<0.15$) for MB to have a greater effect on *DC* at the second layers (Table 2). The mean values for *DC* in areas under agricultural use were numerically higher at 0.00-0.10 m and lower at 0.20-0.30 m, except for MB, which had a higher *DC* at 0.20-0.30 m (Tables 2 and 3).

Although machine traffic is not frequent, it is probably the main cause of the higher *DC* between rows in areas under banana ($B2_I$ and $B15_I$) since a single pass of machinery when the soil is wetter and more susceptible to compaction is enough to increase soil resistance and bulk density (Braunack and Johnston, 2014). Mota et al. (2015) also related higher values of bulk density in soils cultivated with banana in the same region. In soils cultivated with orchards, the controlled traffic between crop rows results in increased compaction, which was evidenced by the increase in penetration resistance and preconsolidation pressure (σ_p), and the reduction in soil macroporosity in the inter-row position (van Dijck and van Asch, 2002; Lima et al., 2004; Becerra et al., 2010).

The values for *DC* at a layers of 0.00-0.10 m are above the optimal range for plant development, as observed by other authors. Carter (1990) observed values for *DC* between 80 and 87 % for obtaining maximum yield in cereal crops, while Lipiec et al. (1991) reported values for *DC* between 88 and 91 % for obtaining maximum yield in barley crops. In Brazil, maximum soybean production has been obtained with a *DC* in the 80 to 86 % range (Beulter and Centurion, 2004; Suzuki et al., 2007).

One of the main problems with an increase in *DC* is reduction in available water (Dias Junior and Estanislau, 1999). Other studies have demonstrated through evaluation of the least limiting water range (LLWR) that values for *DC* over 90 % are restrictive to plant development (Silva et al., 1994; Betioli Júnior et al., 2012). Taking these restrictive values as a reference, it was seen that MB displayed limiting conditions at both layers (0.00-0.10 and 0.20-0.30 m), while $B2_R$, $B2_I$, $B15_R$, and $B15_I$ only displayed limiting conditions at a layer of 0.00-0.10 m. The *DC* in the crop rows of $B2_R$ and $B15_R$ had lower values than in the other positions (P, MB, $B2_I$, and $B15_I$). The reduction in available water in soils with a higher *DC* is consistent with the results of Pereira et al. (2012) in a study conducted on the same site as the present study (P, MB, B15, and NVB15). According to these authors, the soils under P and MB showed greater reductions in available water compared to treatment B15.

The adoption of a no-till or minimum tillage system, associated with crop rotation in the area under corn/beans is suggested as a strategy for improving the physical quality of the soil (Guedes Filho et al., 2013; Moraes et al., 2016). A sustainable alternative for the permanent pasture area is an integrated crop-livestock system with rotation of annual crops; however, it is essential to manage grazing height (Petean et al., 2010; Moreira et al., 2014).

Maximum bulk density and critical water content

Maximum bulk densities (ρ_{max}) in the agricultural areas differed from areas under natural vegetation (NV) ($p<0.05$) (Tables 2 and 3), with higher values at a layer of 0.00-0.10

m in $B15_R$, where ρ_{max} was statistically similar to NVB15. With the exception of P, it was found that cropping the soil resulted in a reduction in ρ_{max} (Table 2).

For the soils under evaluation, increasing *TOC* was associated with a reduction in ρ_{max} ($\rho_{max} = 1.78 - 0.003\ TOC$, $R^2 = 0.38$, $p < 0.00$) and an increase in critical water content (WC_{crit}) ($WC_{crit} = 0.15+0.002\ TOC$, $R^2 = 0.65$, $p< 0.00$). Considering only the layer of 0.00-0.10 m, the reduction ratio for ρ_{max} was higher with *TOC* ($\rho_{max} = 1.81\text{-}0.003TOC$, $R^2 = 0.55$, $p < 0.02$) than with *LOM* ($\rho_{max} = 1.82+0.004LOM$, $R^2 = 0.40$, $p < 0.05$). The greater impact of TOC in reducing ρ_{max} can be attributed to the fact that the *LOM* is linked to the organic matter composed of plant materials at an early stage of decomposition. As TOC includes fractions with a higher degree of humification that can provide organic cementing materials when connected to the primary soil particles, it favours the formation of more stable aggregates (Li et al., 2015) and makes the soil more resistant to compaction. The relationship between TOC and ρ_{max} has been identified by other authors (Díaz-Zorita and Grosso, 2000; Blanco-Canqui et al., 2009; Viana et al., 2011). Others studies have shown that the degree of humification (Zhang et al., 1997) and the levels of oxidisable organic matter (Zhao et al., 2008) contribute more to reduction of ρ_{max} than TOC does.

The WC_{crit} in the soils under evaluation ranged from 0.13 to 0.32 kg kg^{-1} and from 0.17 to 0.21 kg kg^{-1} at layers of 0.00-0.10 and 0.20-0.30 m, respectively. At the first layer, close values for WC_{crit} and water content at field capacity were seen, expressed by the gravimetric water content (*Ms*) of samples equilibrated at a matric potential of -10 kPa. However, at the layer of 0.20-0.30 m, the WC_{crit} was generally lower than the *Ms* (Figure 1). WC_{crit} values higher than field capacity increase the range of moisture in soil where machine traffic and/or trampling by animals can take place, with a lower risk of compaction (Figueiredo et al., 2000).

At the layer of 0.00-0.10 m in P, the trend toward an increase in TOC ($p<0.20$) (Tables 2 and 3) may be associated with values of WC_{crit} higher than the water content at field capacity. Perennial grasses favour a higher input of soil organic matter compared to annual crops due to intense root production and mortality in grasses and the release

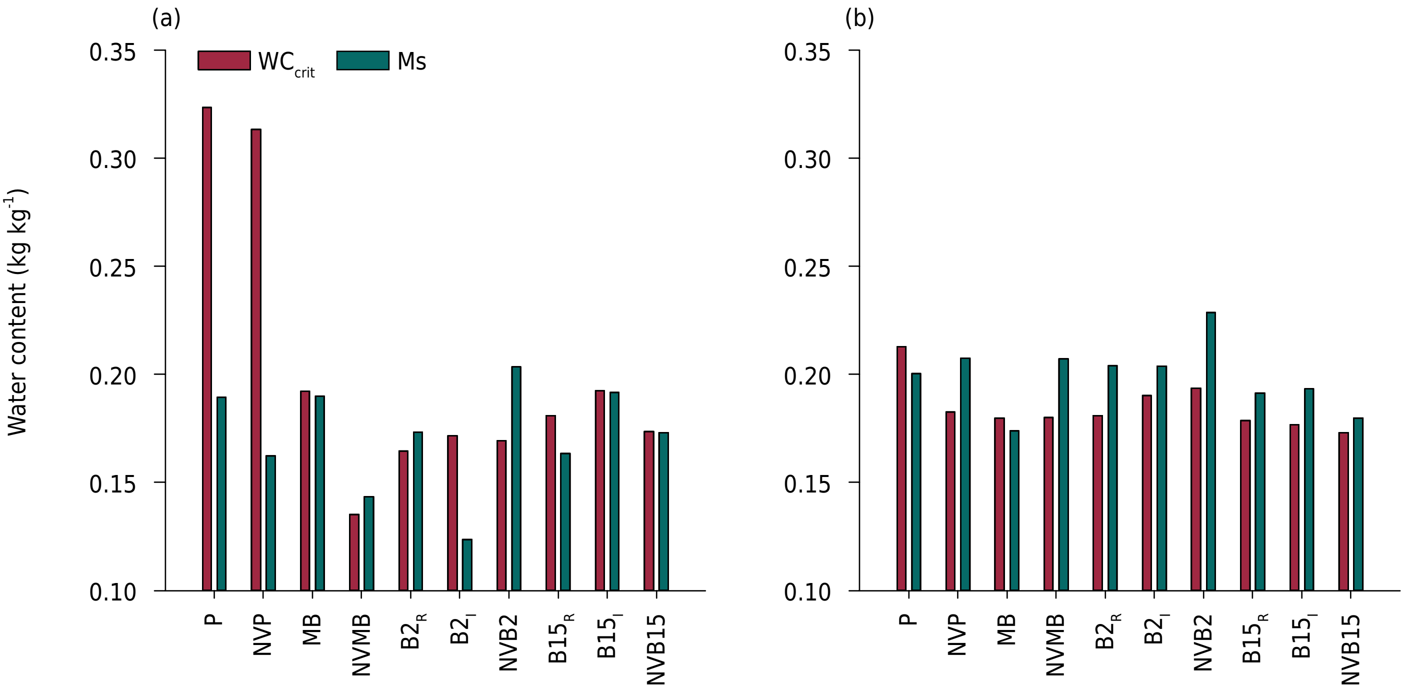

Figure 1. Mean critical water content (WC_{crit}) and water content at field capacity (*Ms*) at layers of 0.00-0.10 m (a) and 0.20-0.30 m (b) for irrigated soils under pasture (P), corn and beans in succession (MB), banana (B2 and B15), and natural vegetation (NVMB, NVB2, and NVB15) in the Jaguaribe/Apodi Irrigated Area. Subscribed letters represent the crop row (R) and inter-row (I) spaces, respectively. Errors bars indicate standard error of the mean (n=4).

of organic exudates (Silva and Mielniczuk, 1997; Kodešová et al., 2011). The irrigation and fertilisation practices adopted in P favoured an increase in TOC levels at the layer of 0.00-0.10 m. Several authors have observed an increase in C stocks in well-managed pastures in relation to soil under natural vegetation (Fearnside and Imbrozio Barbosa, 1998; Aguiar et al., 2006; Maia et al., 2009).

When high pressures are applied to the soil surface, they are transmitted to the subsurface layers (Keller et al., 2004) and may result in persistent compaction of the deeper layers if associated with conditions of high soil water content (Håkansson and Reeder, 1994). Values for WC_{crit} were different between the layers of 0.00-0.10 and 0.20-0.30 m, and for an increase in soil compaction to be avoided, it is suggested that a smaller value for WC_{crit} be adopted when planning mechanised activities on the soil.

Preconsolidation pressure and compression index

Values for preconsolidation pressure (σ_p) ranged from 71 to 136 kPa and from 64 to 219 kPa, respectively, at the layers of 0.00-0.10 and 0.20-0.30 m, values classified as medium to very high for the first layer and medium to extremely high for the second, as per Horn and Fleige (2003). These values for σ_p are close to those found in other studies for soils under different agricultural systems, such as no-tillage (55 to 196 kPa, Suzuki et al., 2008), sugarcane (22 to 305 kPa, Imhoff et al., 2004), orange orchards (170 kPa in the crop rows and 305 kPa for the inter-row spaces and canopy projection, Lima et al., 2004). Values were influenced by the equilibration matric potential of the soils, ranging from -10 to -100 kPa, including the matric potential adopted in this study.

No significant differences were found for σ_p between the agricultural uses tested and the NV ($p<0.05$) (Table 3). Fidalski et al. (2015) also found no difference between treatments, because σ_p was highly variable. The average values for σ_p for P were 7 % lower than for NVP at a layer of 0.00-0.10 m, and 29 % lower at a layer of 0.20-0.30 m. The reduction in σ_p seen in P is associated with the type of soil tillage at the time the crop was planted and with root activity. Grasses have a high capacity for repairing soil structure (Silva and Mielniczuk, 1997; Kodešová et al., 2011) because they are constantly renewing their root system (Acharya et al., 2012), favouring the formation of biopores and the accumulation of C and promoting better physical quality of the soil than annual crops (Blainski et al., 2008).

Despite the values for σ_p being classified as high and very high in P at layers of 0.00-0.10 and 0.20-0.30 m (Horn and Fleige, 2003), they are lower than the pressure exerted on the ground by cattle, where values range from 350 to 400 kPa (Proffitt et al., 1993; Nie et al., 2001). Therefore, controlling the intensity of grazing and monitoring soil moisture in operations involving traffic of agricultural machinery and implements in P are important strategies for avoiding an increase in soil compaction (Silva et al., 2003; Flores et al., 2007).

Classification of σ_p as medium for the layer of 0.00 to 0.10 m in MB (Horn and Fleige, 2003) does not indicate better structural conditions, but can be explained by the destruction of soil aggregates from conventional management practices which include chiselling, ploughing, and harrowing. This reduces soil resistance to compaction in the upper layers (Silva et al., 2002a; Figueiredo et al., 2011) and increases the depth reached by stresses applied to the soil by machine traffic, making it more susceptible to compaction at deeper layers (Arvidsson, 2001; Alakukku et al., 2003); this explains the higher values for σ_p and ρ at the layer of 0.20-0.30 m.

The degree of water saturation (*Sr*), approximately 40 % higher in MB at a layer of 0.00-0.10 m relative to NVMB ($p<0.10$) (Table 3), reduces the load-bearing capacity and resistance to soil compaction in MB (Braunack and Johnston, 2014). The formation of a film of water between the soil aggregates facilitates the displacement and rearrangement of solid particles in the soil matrix (Hillel, 1980), contributing to soil compaction. Similarly, at the layer of 0.20-0.30 m, the greater value of *Sr* may be associated with σ_p being numerically lower

(Table 2), since an increase in water content leads to plastic deformation from the application of lower pressures. Increases in *Sr* from 46-60 to 61-75 % reduced the σ_p of the surface layer of an Oxisol under conventional tillage 2.4 times, as noted by Silva et al. (2002b).

The high ρ in $B2_R$ at the layer of 0.00-0.10 m resulted in little variation in the void ratio, making it impossible to estimate σ_p or the compression index (*Cc*). This happened because the values of parameter *m* in the Gompertz equation (Gregory et al., 2006) were higher than the maximum load (1200 kPa) applied in the uniaxial compaction test. Such a condition is not recommended; it limits the estimate of *Cc* since there is insufficient data to define a range of values with linear behaviour, which leads to overestimation of the preconsolidation pressure (Gregory et al., 2006; Keller et al., 2011). However, the average values for σ_p at 0.20-0.30 m in $B2_R$ and $B2_I$ were close to those of $B15_R$ and $B15_I$, respectively (Table 2), which indicates that the maximum pressure exerted on the soil takes place in the first years of land use for the situation under study. This results in the need for further investigation into whether this condition is reached in the initial planting phase of the crop or during the first years of harvesting and/or of cultivation due to agricultural machine traffic. The values for σ_p observed for this condition are within the contact pressure range of 30 to 150 kPa exerted by agricultural tractors (Proffitt et al., 1993).

The σ_p values depends on the manner of soil sampling, the method of compression testing, the time of loading, and the type of mathematical analysis, which makes it very difficult to estimate σ_p in the laboratory (Défossez et al., 2014). But these authors also highlighted that advances in mechanical measurements require the acquisition of more data from various soils and establishment of soil databases for mechanical properties such as those that exist for hydraulic properties. Our results play an important role in presenting compressive behaviour data for these calcareous soils and information on load-bearing capacity since they can be used in a data base for the σ_p of Brazilian soils.

The compression index (*Cc*) at the layer of 0.00-0.10 m in the soil under agricultural use displayed lower values than in the areas of natural vegetation, except for P, where an increase in *Cc* was seen ($p<0.05$) (Table 2). At the layer of 0.20-0.30 m, only P, $B2_R$, and $B15_I$ displayed reduced values for *Cc* ($p<0.05$) (Tables 2 and 3). Although σ_p did not show differences for agricultural use, the results for *Cc* suggest that the use of soil

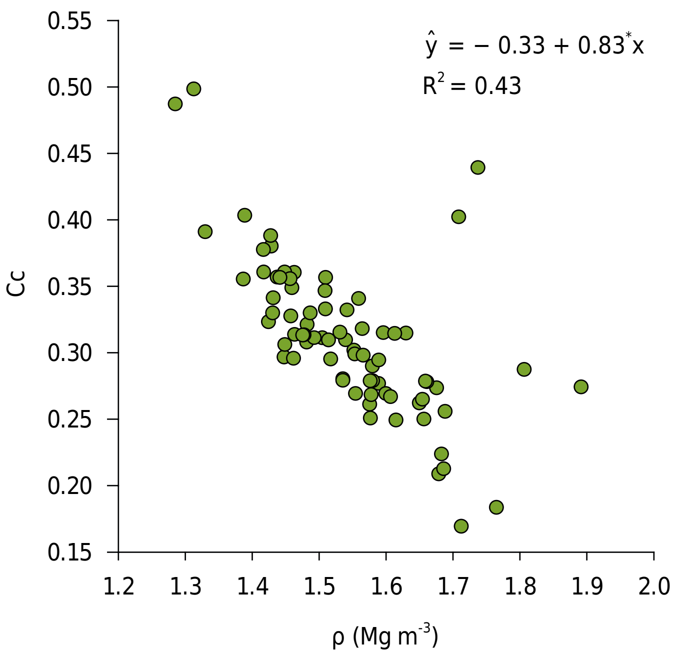

Figure 2. Relationship between soil compaction index (*Cc*) and bulk density (ρ) at layers of 0.00-0.10 and 0.20-0.30 m for soils under irrigated crops and natural vegetation in the Jaguaribe/Apodi Irrigated Perimeter, Limoeiro do Norte, CE, Brazil (n = 76). *: significant $p<0.05$.

with irrigated crops reduces its susceptibility to compaction, due to soil management practices favouring an increase in soil bulk density.

At depths of 0.00-0.10 and 0.20-0.30 m, decreased susceptibility of the soil to compaction is related to increased soil bulk density (Figure 2) due to intensification of traffic for agricultural crops (Blainski et al., 2008). This decreases the pore space and increases the frictional force between soil particles, making it difficult for these particles to move and rearrange into denser soil (Keller et al., 2011).

Further studies should be undertaken in the field to assess the effects of tyre inflation and different wheel configurations on stress propagation in calcareous soils from the Apodi Plateau. Stress propagation in the field is one important step for predicting the impact from agriculture vehicle traffic.

CONCLUSIONS

The hypothesis tested in this study was not confirmed, as the use of land with irrigated annual crops showed low susceptibility to compaction and high load-bearing capacity.

The use of perennial crops, such as banana and pasture, results in better soil conditions for crop growth than annual crops. For the banana crop it is still necessary to investigate whether compaction takes place at the time of planting and establishing the crop, or during crop management operations; however, controlling soil moisture is a key factor in mechanised operations.

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