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Is cassava yield affected by inverting tillage, chiseling or additional compaction of no-till sandy-loam soil?

José Miguel Reichert[(1)*], Eracilda Fontanela[(2)], Gabriel Oladele Awe[(3)] and Johnson Toyin Fasinmirin[(4)]

[(1)] Universidade Federal de Santa Maria, Departamento de Solos, Santa Maria, Rio Grande do Sul, Brasil.
[(2)] Universidade do Pampa, Departamento de Engenharia Agrícola, Alegrete, Rio Grande do Sul, Brasil.
[(3)] Soil Resources and Environmental Management Department, Faculty of Agricultural Sciences, Ekiti State University, Ado Ekiti, Nigeria.
[(4)] Agricultural Engineering Department, Federal University of Technology, Akure, Nigeria.

*** Corresponding author:**
E-mail: reichert@ufsm.br

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ABSTRACT: Defining a suitable soil tillage option that provides adequate soil physical conditions for optimum cassava (*Manihot esculenta* Crantz) productivity has not been adequately researched in southern Brazil. This study aimed to evaluate, in an *Argissolo Vermelho-Amarelo Distrófico* (Acrisol or Hapludalf), three tillage methods - conventional (inverting) tillage, chiseling, and long-term no-tillage (without and with, additional soil compaction), as affecting soil hydro-physical properties and cassava yield, in southern Brazil. Undisturbed and disturbed soil samples were collected from row and interrow positions, from the soil surface down to 0.40 m depth to determine soil bulk density, degree of compaction, porosity, water retention, plant available water, air and water permeability, mechanical properties (compressibility and elasticity), and chemical properties. The yield of cassava storage roots was obtained at crop physiological maturity. Conventional (inverting) and chisel tillage of soil previously under long-term no-tillage increased soil macroporosity - a composition or capacity physical property – of the surface soil, but did not improve the functioning/intensity properties air and water permeability. Soil reconsolidation over a short-time significantly affects soil structural condition, and thus soil tillage is not needed to improve soil structure. Additional compaction on the no-till soil causes detrimental consequences on composition/capacity and functioning/intensity physical properties. Nonetheless, neither improvement of soil structure by tillage nor further compaction affects cassava storage root yield in the sandy loam soil. Therefore, no-tillage is the best management system, in which soil loosening is done only during furrowing for cassava-stem planting.

Keywords: soil tillage methods, soil management, soil structure and functioning, sandy soil, soil reconsolidation.

INTRODUCTION

Diversification of farming for crops and food production is an urgent endeavor, outspreading towards roots and tubers, among other crops. For instance, cassava (*Manihot esculenta* Crantz) is one of the crops grown globally that can fulfill the daily energy demands of the populace, especially the inhabitants in the Sub-Sahara Africa, Asia, Latin America, and the Carribean (Parmar et al., 2017). The largest cassava producers are Nigeria, Thailand, Indonesia, and Brazil (Oriola and Raji, 2013). Brazil is the third major world producer, but production has reduced over the years, as the 21,083 MT produced in 2016 decreased to 18,501 MT in 2017, and declined further 17,644 MT in 2018 (FAO, 2019). Nevertheless, the northern part of the country accounts for the major producing area (FAO, 2018) while, in southern Brazil, the Rio Grande do Sul State accounts for about 1.30 million tons of cassava produced in the country (Instituto Brasileiro de Geografia e Estatística, 2012).

Cassava (*Manihot esculenta*), also known as *mandioca*, manioc, and yuca, is a woody, semi-perennial plant belonging to the family Euphorbiaceae (Hillocks et al., 2002). This crop requires an average of 10-12 months, at times up to 24 months, before farmers can harvest the roots. Cassava plant grows under cultivation to a height of about 2.4 m. Cassava grows only toward the end of the branches and, as the plant grows, the main stem forks usually into three branches, which then divide similarly. The storage roots emerge from the stem just below the soil surface, while feeder roots grow vertically from the stem and from the storage roots, penetrating deep into the soil, reaching soil depths ranging between 0.50 and 1.00 m. This cassava plant’s capacity enables it to obtain nourishment and water from deeper soil depth, which explains its ability to survive drought and grow on inferior soils (FAO, 1977).

The crop is grown as sole crop, intercrop with other early maturing staple food such as corn, beans, yam, or interplant with tree crops such as rubber, coconut, and cashew nut (Aye and Howeler, 2012). As a drought-resistant plant, cassava adapts well to the most varied conditions of climate and soil (Burrel, 2003; Yu and Tao, 2009), where sandy and medium-textured soils are ideal for growing cassava because they allow for ease of root growth, good drainage, and easy harvesting (Silva et al., 2008). Furthermore, cassava grows well in any soil or marginal lands with or without fertilizers and limited water (Yu and Tao, 2009; Reichert et al., 2015), where other crops would have difficulties to grow and develop properly. Cassava storage roots have high starch production capacity (Kosugi et al., 2009; Yu and Tao, 2009), producing around 40 % more carbohydrates than rice and 25 % more than corn (Tonukari, 2004). Furthermore, cassava constitutes livestock feed (Kordylas, 2002), energy (bio-ethanol) source (Kosugi et al., 2009), and one of the most consumed food in many regions. In many African countries, cassava is a major staple food (Bayata, 2019) and has contributed immensely to food security in this region (Fischer et al., 2014).

Because of the demand to conserve soil and water, and mitigate against soil erosion, no-tillage method has become an advocated tillage method globally. However, soil compaction has been a problem due to machine traffic and natural reconsolidation. Soil chiseling is a tillage method used to reduce surface soil compaction in no-tillage systems by reducing soil bulk density and enhancing pore space (Cavalieri et al., 2006; Klein and Camara, 2007; Fasinmirin and Reichert, 2011; Awe et al., 2020; Reichert et al., 2020a; França et al., 2021; Reichert et al., 2021a; Rosa et al., 2021). Conventional tillage, the traditional tillage method used for cassava (Santos et al., 2020; Thomaz and Fidalski, 2020), is another option for decreasing soil compaction, but the excessive disturbance from soil inverting and mixing by plowing and disking causes undesirable effects such as soil disaggregation, with further exposion to rainfall impact (Lima et al., 2015), especially in sandy soils that are highly prone to erosion (Cantalice et al., 2005; Silva et al., 2020; Thomaz and Fidalski, 2020). In Brazil and elsewhere, the different tillage methods have been evaluated for soil compaction by quantifying the limiting soil bulk density and the performance of several crops (Suzuki et al., 2007; Reinert et al., 2008; Reichert et al., 2009a; Secco et al., 2009; Suzuki et al., 2013; Mentges et al., 2016; Moraes et al., 2019; Reichert et al., 2016a, 2017, 2018; Ambus et al., 2018; Andognini et al., 2020; Reichert et al., 2021a,b).

Despite the adaptability of cassava to poor and marginal soils, compaction affects growth and crop yield (Howeler et al., 1993). Several studies assessed the impacts of tillage practices and degree of compaction on cassava performance (Ohiri and Ezumah, 1990; Oliveira et al., 2001; Aiyelari et al., 2002; Otsubo et al., 2012; Lamidi, 2016; Figueiredo et al., 2017). No-tillage and minimum tillage promoted higher cassava storage root yield than conventional tillage by 40 and 23 %, respectively (Ohiri and Ezumah, 1990); Oliveira et al. (2001) and Lamidi (2016) reported the highest cassava yield from conventional tillage; Aiyelari et al. (2002) recorded the highest yield from minimum tillage; and no significant difference in cassava storage root yield was observed between conventional tillage and no-tillage by Otsubo et al. (2012). Moreover, Figueiredo et al. (2017) observed the highest dry matter content in no-tillage, while cassava storage root yield did not differ between the minimum and conventional tillage methods. These results indicate none of the tillage methods was universally superior for cassava production. The inconsistence results may be due to contrasting soil granulometry, climatic conditions, crop variety, soil management practices, and other soil-plant-atmosphere interactions.

Research on soil tillage for cassava is still very limited in Santa Maria, southern Brazil (Fasinmirin and Reichert, 2011). Information from such studies could help to develop sustainable tillage strategies and policy-making for cassava production. We tested the hypothesis that pre-planting loosening of sandy-loam soil in no-tillage system produces favorable soil physical conditions for optimum cassava yield. Therefore, this research aimed to define the best soil tillage method for cassava by investigating the impacts on soil hydro-physical properties and cassava yield in a subtropical sandy loam soil in southern Brazil.

MATERIALS AND METHODS

Location and climate

The experiment was conducted in the Experimental Station of the Soils Department, Federal University of Santa Maria, Santa Maria, southern Brazil (latitude 29° 42′ South, longitude 53° 48′ West, and 90 m a.s.l.). According to Köppen classification system (Moreno, 1961), the climate of the region is “Cfa”, i.e., a humid subtropical climate, with the summer period having a mean temperature not exceeding 22 °C, while the winter period has daily temperatures ranging between -3 and 18 °C. Rainfall is well distributed throughout the year, with no single month without rain and a total annual rainfall ranging between 1300 and 1800 mm. The soil was classified as *Argissolo Vermelho-Amarelo Distrófico* (Santos et al., 2018), which corresponds to an Acrisol (IUSS Working Group WRB, 2015) and Hapludalf (Soil Survey Staff, 1999), located on an undulating relief and with sandy loam texture. Composite soil samples were collected from the 0.00-0.20 m surface layer at four representative points to determine soil physical and chemical properties, and the results are shown in tables 1 and 2, respectively. Prior to the experiment, the field had been under no-tillage and planted to corn, soybean, and cassava. The land was also allowed to fallow for two years, with weeds and ryegrass.

Experimental design and treatments

The experiment was established on October 5, 2010. The experimental design was a randomized complete block design (RCBD) in three replications. Treatments comprised

Table 1. Sand, silt, and clay content in the soil, in five different layers

Soil layer	Sand		Silt	Clay
	Coarse	Fine		
m	g kg^{-1}			
0.00–0.05	233	436	233	98
0.05–0.10	218	446	237	99
0.10–0.20	212	442	244	102
0.20–0.40	186	439	271	104

Table 2. Soil chemical properties at five locations in the study area before treatments allocation

Soil layer	pH(H_2O)	P	K	MO	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	K^+	CECe	CECp	Sum of bases	Saturation	
													Al	Bases
m		mg dm^{-3}		%	cmol$_c$ dm^{-3}								%	
0.00-0.05	5.10	19.9	52.0	1.3	1.8	0.5	0.4	3.5	0.14	2.84	5.94	2.44	14.1	41.0
0.05-0.10	5.00	22.8	68.0	1.3	1.3	0.4	0.6	3.5	0.18	2.48	5.38	1.88	24.2	34.9
0.10-0.20	4.90	20.8	68.0	1.4	1.1	0.3	0.8	3.9	0.18	2.38	5.48	1.58	33.7	28.8
0.20-0.40	4.80	23.8	68.0	1.3	1.0	0.3	0.8	3.9	0.18	2.28	5.38	1.48	35.1	27.47

MO: organic matter; CECe: effective cation exchange capacity; CECp: potential (pH 7) cation exchange capacity.

four soil tillage methods, namely long-term no-tillage (NT), conventional tillage (CT), chisel plow (Chi), and compacted no-tillage (NTc). The NT and Chi treatments were done on the soil previously under long-term NT. Conventional tillage was established with one disc plowing operation and two disc-harrowings, causing significant soil inversion (Figure 1a). Chiseling was performed to the 0.30 m soil depth using chisel plough equipped with three chisels, spaced at 0.80 m apart (Figure 1b). Compaction of the no-tillage treatment plot was performed by two overlapping, parallel wheelings of a pay loader machine with a total mass of 8 Mg (Figure 1c), when the soil water content was 0.16 kg kg^{-1}, around field capacity of this sandy loam soil (Vaz et al., 2005; Reichert et al., 2009b; 2020b). Opening of furrows was done on no-tillage method for planting (Figure 1d). A Massey Ferguson (MF 275 model) tractor was used for applying the treatments.

A non-selective systemic herbicide was applied to the site and the immediate environment before applying the treatments. The area was divided into 12 plots; each block was designated for each replicate, with 5 m spacing between plots to allow tractor maneuvering during tillage operations. Each plot was 10 m long and 3.2 m wide.

Cassava (yellow cassava, vitamin A fortified variety) stem cuttings, about 0.15 m long, were planted at approximately 0.20 m depth and inclined at about 45° to the horizontal in five rows. The cassava stems were planted at 1.0 m apart, while interrow spacing was 0.80 m, giving a plant population of 12,500 stands. At planting, furrows about 0.25 m deep were opened, and a base fertilizer, NPK comprising 44 kg ha^{-1} of urea, 100 kg ha^{-1} of single superphosphate, and 80 kg ha^{-1} of potash, was incorporated according to the recommendations of CQFS-RS/SC (2004). Agronomic practices of combined manual weeding and herbicide sprayings (diuron at the application rate of 3 L ha^{-1}) were carried out to control weeds. Pesticides and insecticides were also applied whenever necessary.

Soil sampling

Soil sampling was conducted two times. The first sampling was conducted one month after planting cassava in the row and interrow positions to characterize the initial soil conditions. The second sampling was conducted at 12 months, shortly before harvesting, though

Figure 1. Soil tillage for cassava planting: (a) conventional tillage (plowing and harrowing), (b) chisel plowing, (c) compacting no-till soil, and (d) opening of furrows for cassava planting.

only from the row position due to technical issues. Structured, undisturbed soils were sampled from the center of 0.00-0.05, 0.05-0.10, 0.10-0.20, 0.20-0.40, and 0.40-0.60 m soil layers, using core samplers of 0.05 m diameter and 0.04 m height, to evaluate soil hydro-physical properties and soil penetration resistance in the laboratory. To evaluate the soil strength parameters pre-compression stress (σp) and compression coefficient (Cc), another set of undisturbed soil samples was obtained only from the crop rows, at both sampling campaigns, from soil layers 0.00-0.10, 0.10-0.20, and 0.20-0.40 m, using core samplers of 0.057 m diameter and 0.03 m height.

Soil composition or capacity properties

Soil water, porosity, bulk density, and degree of compaction

The undisturbed soil samples were used to evaluate soil water retention. The samples were saturated in plastic containers by capillary action for 48 h, and then equilibrated to -1, -6, and -10 kPa matric potential on a tension table (Reinert and Reichert, 2006; Gubiani et al., 2009) and to -33, -70, and -100 kPa on pressure plates (Klute, 1986). Water retention at lower matric potentials of -500, -1000, and -1500 kPa was determined using the Dewpoint PotentiaMeter (WP4, Decagon Incorporation, USA), following the methodology by Klein et al. (2006) and modified by Gubiani et al. (2013), using air-dried and homogenized soil samples after passing through a 2-mm sieve. All measurements were expressed on a volumetric basis using the gravimetric soil water content and the respective bulk density.

The van Genuchten (1980) model was then fitted to the observed water retention data, using the RETC software to obtain the water retention curve (SWRC) and quantify soil water retention properties (van Genuchten et al., 1991):

$$\theta(\psi) = \theta_r + \frac{(\theta_s - \theta_r)}{[1 + (\alpha\psi)^n]^m} \qquad \text{Eq. 1}$$

in which θ(y) is the soil volumetric water content ($m^3\ m^{-3}$) at matric potential y (kPa); θ_s is the soil volumetric water content ($m^3\ m^{-3}$) at saturation (0 kPa); θ_r is the residual soil volumetric water content ($m^3\ m^{-3}$); α (0< α <1 in m^{-1}) is a fitting parameter associated with inverse of the air entry tension; and n (n >1) is a parameter related to pore-size distribution, and m=1–1/n.

From the SWRC, the soil volumetric water content at field capacity (FC) was obtained at -10 kPa matric potential (Reichert et al., 2020), while the soil volumetric water content at permanent wilting point (PWP) was obtained at -1500 kPa matric potential. Soil available water (AW) was computed as the difference between FC and PWP.

Total porosity (Pt) was considered as the volumetric water content at soil saturation (0 kPa), with the premise that soil pores are fully occupied with water. Soil microporosity (Mi) was obtained at the volume occupied by water at -6 kPa matric potential. Soil macroporosity (Ma) was determined as the difference between Pt and Mi. After removing the soil samples from pressure plates at -100 kPa matric potential, they were dried in an oven set at 105 °C for 48 h to determine the bulk density (Bd) following the methodology of Blake and Hartge (1986). Soil air-pore space or air porosity is the difference between Pt and volumetric water content measured in each soil layer.

Pore size distribution

Following the assumption that soil pores are cylindrical, the water pressure head was related to the equivalent pore diameter, D (μm), as:

$$D = \frac{4\sigma \cos\gamma}{\rho w\ g\ |\psi|} \qquad \text{Eq. 2}$$

in which σ is the surface tension, given as 72.75 × 10^3 N m^{-1}; γ is the contact angle of water curvature in soil pores, considered as zero (0); ρ*w* is the density of water, given as 1.0 × 10^3 kg m^{-3}; g is the acceleration due to gravity, 9.81 m s^{-2}; and y is the water tension, m; simplifying to $D = \frac{2980}{|\psi|}$ (Kutılek and Nielsen, 1994).

Soil water content variation in the field

Soil water content sensors were installed in the soil layers of 0.00-0.05, 0.05-0.10, 0.10-0.20, and 0.20-0.40 m to monitor temporal variations in soil water status. Soil water was monitored automatically by connecting the sensors to TDR multiplexers (TDR 1000, Campbell Equipment Incorporation, USA) and datalogger (TDR 100, Campbell Equipment Incorporation, USA). Soil water content was recorded following the calibration done by Kaiser et al. (2010).

Soil degree of compaction

The soil degree of compaction (DC) one month after planting of cassava and at crop maturity was obtained using the relation:

$$DC = \frac{Bd}{Bdref} \times 100 \qquad \text{Eq. 3}$$

in which Bd is the field bulk density, Mg m^{-3}; and Bdref is the reference bulk density given as Bdref = 0.00053 (Clay + Silt) + 1.84321 (Reichert et al., 2009a).

Soil functioning or intensity properties

Pre-compression stress, compression coefficient, and elasticity

To determine the soil pre-compression stress (σp) and compression coefficient (Cc), the soil samples were capillary-saturated and then equilibrated to -10 kPa matric potential

(FC) in the tension table. Subsequently, the samples were subjected to successive static loads of 12.5, 25, 50, 100, 200, 400, 800, and 1600 kPa in a consolidometer for five minutes (the time during which more than 90 % of the compaction have occurred) (Silva et al., 2000; Arvidsson and Keller, 2004). After the mechanical test, the samples were oven-dried at 105 °C for 48 h.

The relationship between void index (ε = dp ds^{-1}) and applied loads (σ) was described following the van Genuchten model (1980), by exchanging the soil water retention parameters for soil deformation parameters as expressed below in equation 4:

$$\varepsilon = \varepsilon_o + (\varepsilon_o - \varepsilon_f)/[1 + (\alpha\sigma)^n]^{1+1/n} \qquad \text{Eq. 4}$$

in which ε_o (m^3 m^{-3}) is the void ratio without load application; ε_f (m^3 m^{-3}) is the final void rate after the test; and n is an empirical parameter. To fit equation 4 and obtain the σp and Cc, the data of static loads, displacement, bulk density, particle density, and core sampler dimension were subjected to the Soil Compression Curve (SCC) Excel® Add-in developed by Gubiani et al. (2017).

Soil elasticity analysis was performed by loading the soil (equilibrated to -10 kPa) in two stages using the uniaxial compression oedometer. First, loading was applied up to the 400 kPa, and, subsequently, the sample was unloaded, after which all loads were re-applied and then stepwise increased to a maximum load of 1600 kPa. In both loading and unloading, deformation readings were taken after 5 min of loading (or unloading). Soil elasticity is taken as the decompression coefficient (Dc), obtained from the slope of the unloading/loading line, while the recovery index (Ri) was estimated using equation 5 (Braida et al., 2008):

$$Ri\ (\%) = (De_d/De_c)\times 100 \qquad \text{Eq. 5}$$

in which Ri is the recovery index (%); De_d is the variation in the void index during unloading; and De_c is the variation of void index during loading.

Soil air permeability and saturated hydraulic conductivity

The set of structured soil samples used for soil water retention determination was also employed to evaluate air permeability, using a constant-head permeability apparatus at the different water tensions following the methodology of Peth (2004). For the calculation of air conductivity (K_l, cm s^1), equation 6 was used:

$$K_l = \rho_l g \frac{0.001\Delta Vl}{60\Delta t 100\Delta pA} \qquad \text{Eq. 6}$$

in which ρ is the density of air (kg m^{-3}); g (gravity) is 9.81 (m s^{-2}); ΔV is the volume of air (m^3) passing through the soil sample during time interval Δt (s); l is the soil sample length (m); Δp is the applied air pressure (kg m s^{-2}); and A is the area of the soil sample (m^2).

Air permeability Ka (mm^2) was calculated from air conductivity (K_l) according to Upadhyaya et al. (1994), as follows:

$$K_a = K_l \frac{\eta}{\rho_l g} \qquad \text{Eq. 7}$$

in which Ka is the air permeability (mm^2); K_l is the air conductivity (cm s^{-1}); η is the air viscosity (g s^{-1} cm^{-1}); ρ_l is the air density at the time of measurement (kg m^{-3}), and g is the acceleration of gravity (9.81 m s^{-2}).

After the determination of water retention and air permeability at -100 kPa water tension, the soil samples were re-saturated for 48 h and then subjected to saturated soil hydraulic conductivity test. Water flow through the saturated soil samples was measured in constant-head permeameter until steady-state flow was reached (Klute and Dirksen, 1986).

Cassava storage root yield

For the evaluation of cassava yield, three representative cassava stands were randomly selected per experimental plot, totaling nine replicates per treatment. The cassava storage roots were cut off from the main stem, and the weight of the storage roots was measured using an electronic, sensitive weighing scale, and yield was converted to Mg ha^{-1}.

Statistical analysis

Soil data were first tested for normal distribution using the Shapiro-Wilk test. Soil saturated hydraulic conductivity and soil air permeability showed non-normal distribution and were thus log-transformed for analysis of variance (ANOVA). Results obtained from the first soil sampling for soil Bd, Ma, Mi, Pt, and PR were subjected to 2-way ANOVA and, when F-value was significant, means were compared using the Least Significant Difference (LSD) test at 5 % probability level. Soil tillage was considered as the main factor, while sample collection position was the subfactor. For the statistical analysis of the σp and Cc from the first sampling, as well as all the variables measured during the second sampling, the data were subjected to one-way ANOVA and, when F-value was significant, the LSD test was used to separate means at 5 % probability level, with treatments as the main factor. Pearson correlation analysis was also performed on the physical properties measured. All the statistical analyses were done in SAS (SAS Institute, 1999).

RESULTS

Soil condition at one month after cassava planting

Soil composition or capacity properties

In the initial phase of crop growth, soil Bd (Table 3) differed ($p<0.05$) due to soil tillage though only in the 0.05-0.10 m layer. For all soil tillage methods, the lowest Bd was observed in the soil surface layer (0.00-0.05 m). No differences in soil bulk density were observed in 0.00-0.05 and 0.20-0.40 m layers. Possibly, this occurred because of the presence of organic material in the surface layer of NT soil, and conceivably the presence of “plow-pan” in the deepest layer (0.20-0.40 m) of CT soil, a common characteristic of conventional tillage. Soil macroporosity (Table 3) differed ($p<0.05$) between sampling positions (row and interrow) in the soil layers down to 0.20 m depth and was also affected by the soil tillage method but only in the 0.05-0.10 m soil layer. The lowest macroporosity values were obtained in NTc in all soil layers and between cassava rows, where the highest values of Bd were observed. Furthermore, macroporosity decreased with increasing soil bulk density. Similar to macroporosity, total porosity (Table 3) was higher in cassava rows than in interrows, but only in the 0.00-0.05 m soil layer. Microporosity (Table 3) values were higher in the cassava inter-rows than in rows in the soil layers 0.05-0.10 and 0.10-0.20 m.

Soil functioning or intensity properties

Soil penetration resistance (PR) did not differ in the crop interrows (Figure 2), with the average values of PR exceeding 2 MPa. In the cassava planting row (Figure 2b), there was significant difference ($p<0.05$) between soil tillage methods only in the 0.15 m depth, where NT had the highest value of Pr (4.21 MPa).

Soil precompression stress (σp) did not differ ($p<0.05$) due to soil tillage (Table 4), but there was a numerical trend of increasing σp with soil depth, where the ratio of the first (0.00-0.10 m) to the second layer (0.10-0.20 m) was on average 0.81, and the first to the third layer (0.20-0.40 m) was 0.64. Soil compression coefficient (Cc) also was influenced ($p<0.05$) by soil tillage only in the 0.10-0.20 m layer (Table 4), where NTc had the lowest and CT the highest Cc. There was a numerical trend of decreasing Cc with soil depth,

Table 3. Soil bulk density, macroporosity, microporosity, and total porosity, in four soil layers and tillage methods, in interrow and row one month after planting of the cassava crop

Position	Bulk density					Macroporosity					Microporosity					Total Porosity				
	Mg m^{-3}					m^3 m^{-3}														
	Chi	CT	NT	NT$_C$	Mean	Chi	CT	NT	NT$_C$	Mean	Chi	CT	NT	NT$_C$	Mean	Chi	CT	NT	NT$_C$	Mean
0.00-0.05 m																				
Interrow	1.45	1.42	1.46	1.55	1.47A	0.20	0.23	0.18	0.12	0.18B	0.27	0.26	0.26	0.30	0.27A	0.47	0.49	0.43	0.42	0.45B
Row	1.37	1.35	1.26	1.33	1.33B	0.23	0.25	0.26	0.23	0.25A	0.25	0.26	0.23	0.27	0.26A	0.48	0.51	0.49	0.51	0.50A
Mean	1.41a	1.39a	1.36a	1.44a		0.22a	0.24a	0.22a	0.18a		0.26a	0.26a	0.24a	0.29a		0.47a	0.50a	0.46a	0.46a	
0.05-0.10 m																				
Interrow	1.64	1.50	1.55	1.61	1.58A	0.11	0.17	0.13	0.10	0.13B	0.28	0.27	0.28	0.29	0.28A	0.39	0.44	0.41	0.39	0.41A
Row	1.50	1.34	1.46	1.61	1.48A	0.18	0.24	0.20	0.13	0.19A	0.26	0.25	0.24	0.27	0.25B	0.44	0.49	0.44	0.40	0.44A
Mean	1.57a	1.42b	1.51ab	1.61a		0.15ab	0.20a	0.16ab	0.12b		0.27a	0.26a	0.26a	0.28a		0.41ab	0.46a	0.43ab	0.39b	
0.10-0.20 m																				
Interrow	1.78	1.64	1.68	1.72	1.71A	0.09	0.11	0.10	0.08	0.10B	0.27	0.27	0.25	0.28	0.27A	0.36	0.39	0.35	0.36	0.36A
Row	1.58	1.47	1.63	1.69	1.59B	0.16	0.19	0.13	0.11	0.14A	0.26	0.26	0.24	0.26	0.25B	0.42	0.45	0.37	0.37	0.40A
Mean	1.68a	1.56a	1.66a	1.70a		0.13a	0.15a	0.12a	0.09a		0.26a	0.27a	0.25a	0.27a		0.39a	0.42a	0.36a	0.36a	
0.20-0.40 m																				
Interrow	1.72	1.77	1.72	1.77	1.74A	0.09	0.09	0.11	0.09	0.10A	0.26	0.27	0.27	0.26	0.27A	0.36	0.36	0.38	0.35	0.36A
Row	1.74	1.76	1.66	1.73	1.72A	0.10	0.10	0.10	0.10	0.10A	0.27	0.27	0.26	0.26	0.26A	0.37	0.37	0.37	0.36	0.37A
Mean	1.73a	1.76a	1.69a	1.75a		0.10a	0.10a	0.11a	0.10a		0.27a	0.27a	0.27a	0.26a		0.36a	0.37a	0.37a	0.36a	

Means followed by the same capital letters in a given column or same small letters in a given row are not different using Least Significant Difference (LSD) at 5 % probability level. Chi: chisel; CT: conventional tillage; NT: no-till; NTc: compacted no-tillage.

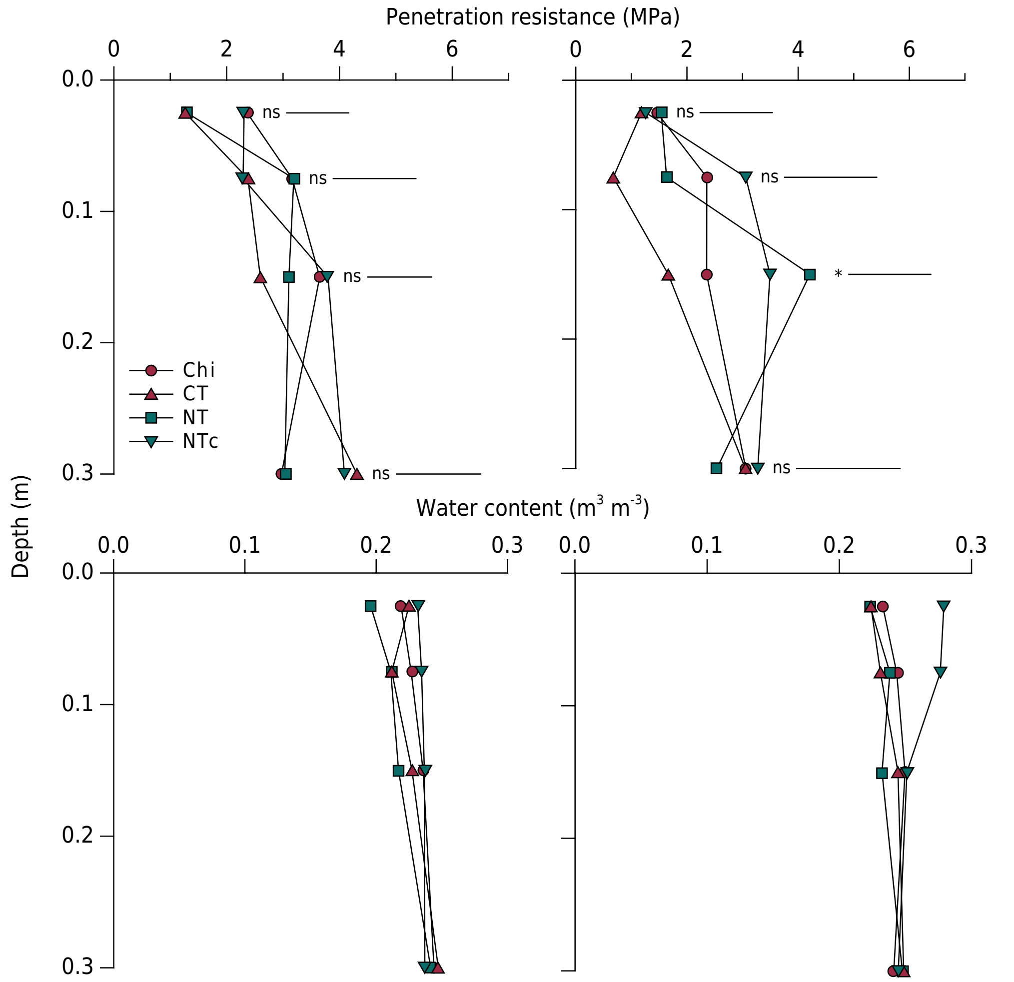

Figure 2. Soil penetration resistance and volumetric water content in inter-row (left) and within row (right) of cassava crop, under chisel tillage (Chi), conventional tillage (CT), no-tillage (NT), and compacted no-tillage (NT$_C$), one month after cassava planting. *: significant (DMS test, 5 % probability level); ns: not significant.

Table 4. Soil preconsolidation stress and compressibility coefficient in three soil layers and four tillage methods one month after planting of the cassava crop

Layer	Treatment					CV
	Chi	CT	NT	NTc	Mean	
m						%
	Preconsolidation stress (kPa)					
0.00-0.10	107.38a	85.06a	104.12a	120.94a	104.37	48.45
0.10-0.20	162.70a	95.65a	101.93a	151.12a	127.85	7.16
0.20-0.40	197.80a	156.14a	133.58a	167.84a	162.87	48.94
	Compressibility coefficient					
0.00-0.10	0.21a	0.21a	0.17a	0.15a	0.19	19.50
0.10-0.20	0.14ab	0.23a	0.15ab	0.11b	0.16	21.52
0.20-0.40	0.13a	0.11a	0.14a	0.11a	0.12	9.57

Means followed by the same letters in a given row are not different using Least Significant Difference (LSD) at 5 % probability level. Chi: chisel; CT: conventional tillage; NT: no-till; NTc: compacted no-tillage; CV: coefficient de variation.

Table 5. Soil bulk density, macro and microporosity, and total porosity in three soil layers and four tillage methods at physiological maturity of the cassava crop

Layer	Treatment				Mean	CV
	Chi	CT	NT	NTc		
m	Bulk density (Mg m^{-3})					%
0.00-0.10	1.56a	1.56a	1.58a	1.59a	1.57	3.17
0.10-0.20	1.63a	1.53a	1.56a	1.58a	1.57	4.14
0.20-0.40	1.59a	1.58a	1.59a	1.62a	1.60	4.90
	Macroporosity (m^3 m^{-3})					
0.00-0.10	0.17ab	0.20a	0.14b	0.18ab	0.17	13.71
0.10-0.20	0.15a	0.14a	0.13a	0.12a	0.14	21.90
0.20-0.40	0.12a	0.11a	0.12a	0.12a	0.11	25.37
	Microporosity (m^3 m^{-3})					
0.00-0.10	0.29ab	0.27b	0.30a	0.28ab	0.28	5.29
0.10-0.20	0.27a	0.28a	0.29a	0.27a	0.28	8.66
0.20-0.40	0.29a	0.29a	0.27a	0.28a	0.28	8.19
	Total porosity (m^3 m^{-3})					
0.00-0.10	0.46a	0.46a	0.44a	0.46a	0.46	3.74
0.10-0.20	0.42a	0.42a	0.42a	0.39a	0.41	9.74
0.20-0.40	0.41a	0.40a	0.39a	0.40a	0.40	7.31

Means followed by the same letters in a given row are not different using Least Significant Difference (LSD) at 5 % probability level. Chi: chisel; CT: conventional tillage; NT: no-till; NTc: compacted no-tillage; CV: coefficient de variation.

where the ratio of the first (0.00-0.01 m) to the second layer (0.01-0.02 m) was on average 1.19, and the first to the third layer (0.02-0.04 m) was 1.58.

Soil condition at cassava maturity

Soil composition or capacity properties

At cassava physiological maturity, soil Bd and total porosity (Tp) did not differ ($p<0.05$) for the soil tillage methods and in all the soil layers (Table 5). Nonetheless, both soil macroporosity (Ma) and microporosity (Mi) presented significant differences ($p<0.05$)

only in the 0.00-0.10 m surface soil layer (Table 5). The highest Ma was found in CT, while the highest Mi was observed in NT, which was about 3, 7, and 10 % greater than the values observed in Chi, NTc, and CT, respectively.

Pore size distribution was not influenced by soil tillage (Figure 3). Comparing the pore classes, pore volume was highest in the soil class with pore diameter <3 µm for all soil layers and tillage systems; however, the water retained in these pores is held tightly to the soil particle and unavailable to plants. The pore size class 50-300 µm gave the highest volume in the surface layer (0.00-0.10 m) for all treatments.

Air-filled pore space (aeration porosity) of all treatments in all layers remained, in general, above 10 m^3 m^{-3} (Figure 4), and was considered adequate for crop growth and development. In all soil layers, Chi and CT treatments presented higher aeration porosity, while NT and NTc showed lower values. Maximum bulk density (Bdmax) and soil degree of compaction (DC), also known as relative soil bulk density, were not affected by tillage (Table 6), both one month after planting and at crop maturity.

In the surface layers, there were only some days with a difference in water content among soil tillage methods (Figure 5). The uppermost layers had soil water content below the field capacity (FC) most days during the growing cycle, with very few days during which water content was smaller than the water content permanent wilting point (PWP). In the subsurface layers, soil water was smaller than FC for most days, but never reached the PWP value. In the 0.20-0.40 m deepest layer, soil water content was less variable.

Throughout the cassava crop cycle, soil available water for plant growth was not influenced by soil tillage (Figure 6). In general, the treatments showed similarity in water availability to the plants. As already mentioned, there were few days and only in the uppermost soil layer (0.00-0.05 m) where water content was below the PWP, thus severely limiting cassava crop growth and development. There were significant correlations between the soil composition/capacity properties (Table 7), namely Bd with Pt and Ma and Ksat, and Pt with Ma and Mi.

Soil functioning or intensity properties

The soil surface layer showed the highest saturated hydraulic conductivity (Ksat), with a significant effect of soil tillage and a very high coefficient of variability (Table 8). Soil Ksat correlated ($p<0.05$) with bulk density, macroporosity, and total porosity (Table 7). No difference was observed in soil air permeability (Ka) at -6, -10, and -33 kPa matric potentials

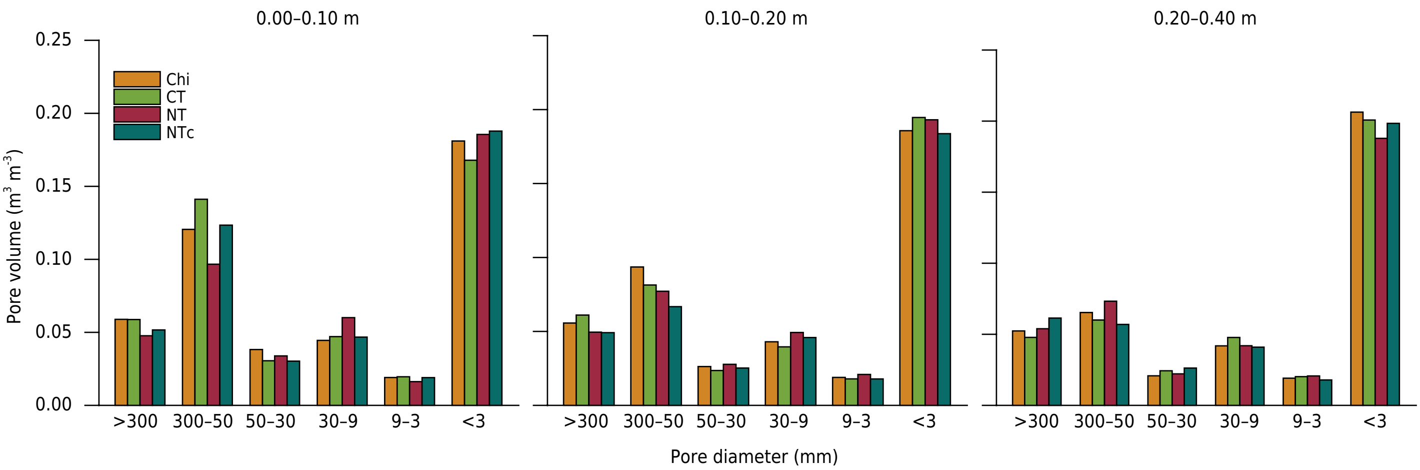

Figure 3. Pore size distribution (PSD) for chisel (Chi), conventional tillage (CT), no-tillage (NT), and compacted no-tillage (NT_C), in three soil layers.

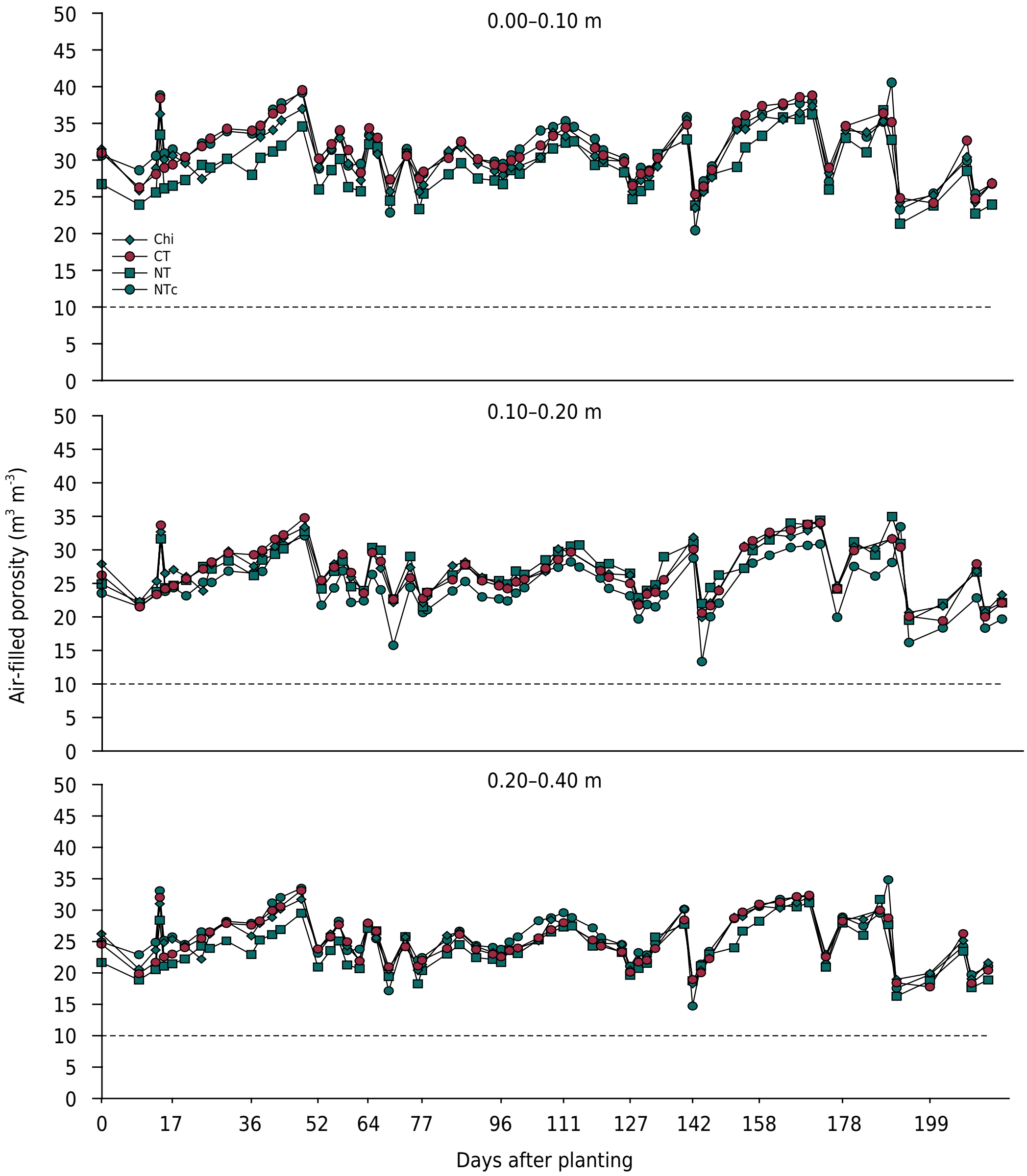

Figure 4. Air-filled pore space for chisel plow (Chi), conventional tillage (CT), no-tillage (NT), and compacted no-tillage (NT_C), in three soil layers, during cassava growth.

Table 6. Maximum bulk density for 1600 kPa in uniaxial compression and degree of compaction in three soil layer and four tillage methods at physiological maturity of cassava crop

Layers	Treatments				Mean	CV
	Chi	CT	NT	NT_C		
m						%
			Maximum bulk density (Mg m^{-3})			
0.00-0.10	1.84a	1.87a	1.88a	1.86a	1.86	3.28
0.10-0.20	1.92a	1.90a	1.92a	1.95a	1.92	4.69
0.20-0.40	1.77a	1.98a	1.96a	2.01a	1.93	13.99
			Degree of compaction (%)			
0.00-0.10	78.22a	79.36a	80.42a	84.07a	80.59	3.14
0.10-0.20	84.12a	81.20a	88.09a	86.50a	84.99	2.22
0.20-0.40	86.93a	84.41a	88.88a	88.88a	87.23	3.08

Means followed by the same letters in a given row are not different using Least Significant Difference (LSD) at 5 % probability level. Chi: chisel; CT: conventional tillage; NT: no-till; NTc: compacted no-tillage; CV: coefficient de variation.

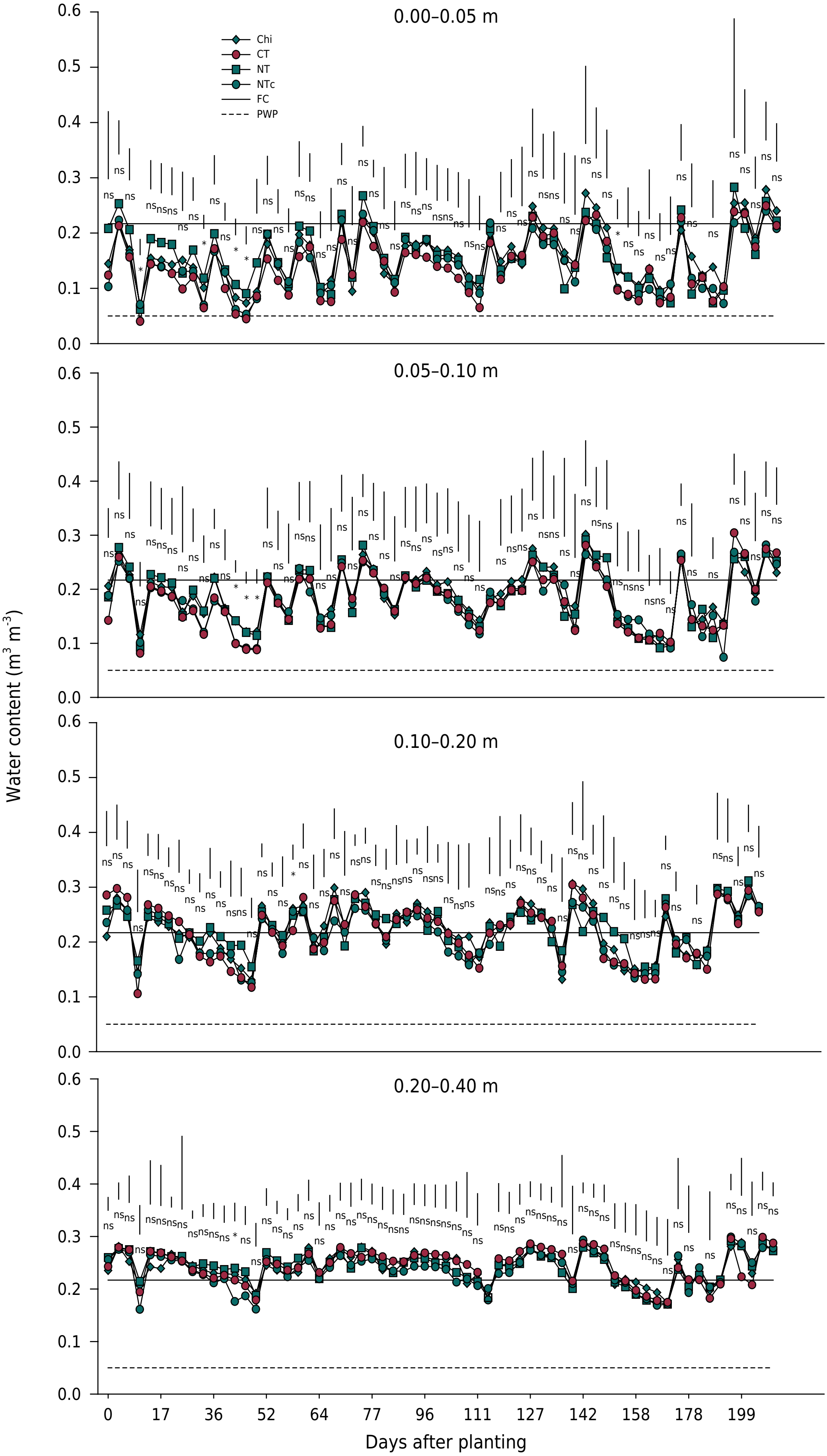

Figure 5. Soil water content during the cassava cycle for chisel plough (Chi), conventional tillage (CT), no-tillage (NT), and compacted no-tillage (NT_C), in four soil layers, during cassava growth. *: significant (DMS test, 5 % probability level); ns: not significant.

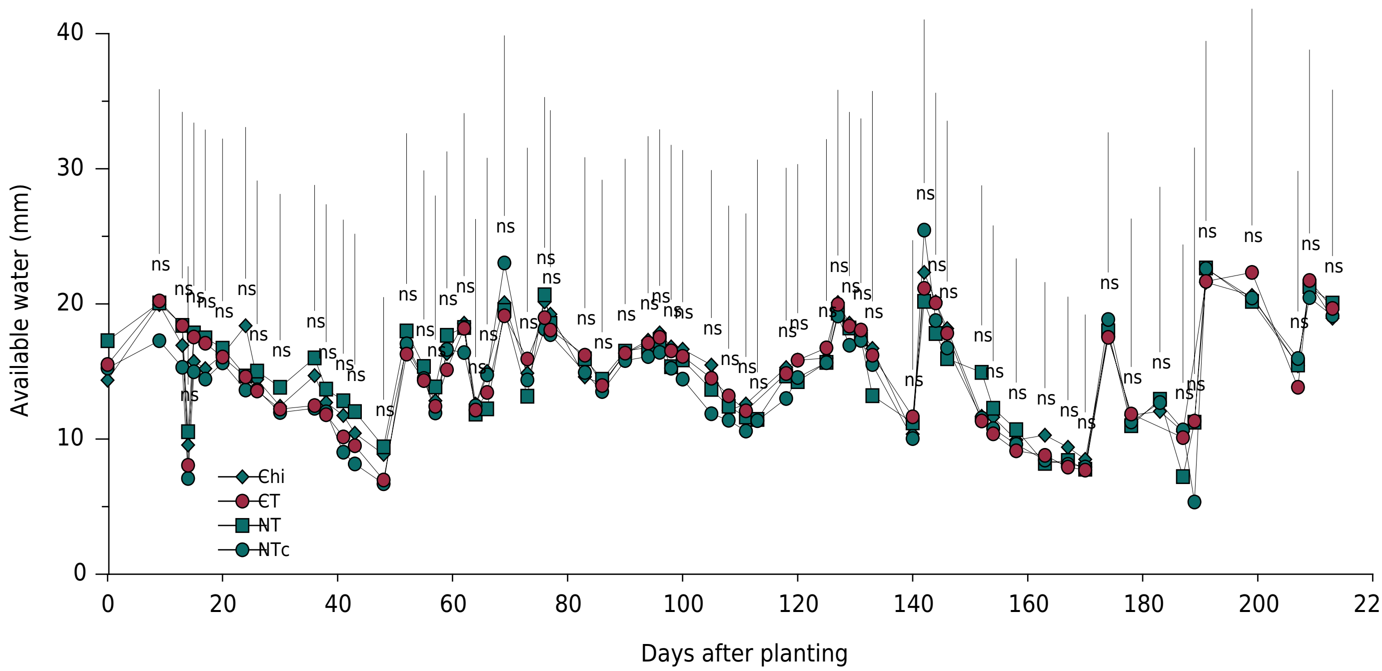

Figure 6. Available water in the 0.00-0.40 m layer, for chisel plough (Chi), conventional tillage (CT), no-tillage (NT), and compacted no-tillage (NT_C), in three soil layers, during cassava growth. ns: not significant (DMS test, 5 % probability level).

Table 7. Pearson correlation between soil physical properties: soil bulk density, macro and microporosity, total porosity, and saturated hydraulic conductivity

	Bd	Mac	Mic	PT	Ksat
Bd	1	-0.82**	0.13ns	-0.82**	-0.75**
Mac	-	1	-0.03ns	0.83**	0.67**
Mic	-	-	1	0.54**	-0.15ns
PT	-	-	-	1	0.65**
Ksat	-	-	-	-	1

** significant at 0.0001; ns: not significant. Bd: soil density; Mac: macroporosity; Mic: microporosity; PT: total porosity; Ksat: saturated hydraulic conductivity.

Table 8. Saturated soil hydraulic conductivity (mm h^{-1}) in three soil layers and four tillage methods at physiological maturity of the cassava crop

Layer	Treatment				Mean	C
	Chi	CT	NT	NT_C		
m	mm h^{-1}					%
0.00-0.10	66.07ab	100.81a	23.33b	103.74a	73.70	46.84
0.10-0.20	52.00b	117.19a	43.51b	8.75c	55.70	95.77
0.20-0.40	7.01a	10.22a	6.09a	14.21a	9.45	97.43

Means followed by the same letters in a given row are not different using Least Significant Difference (LSD) at 5 % probability level. Chi: chisel; CT: conventional tillage; NT: no-till; NTc: compacted no-tillage; CV: coefficient de variation.

(Figure 7). On average, the uppermost soil layer had greater Ka than in the deepest soil layer, and a larger increase as the soil dries (lower matric potential), especially for CT.

Soil precompression stress (σp), compression coefficient (Cc), and elasticity parameters (recovery index Rc, and decompression coefficient Dc) were not influenced by soil tillage (Table 9). In relative terms, the surface layer had smaller σp and greater Cc

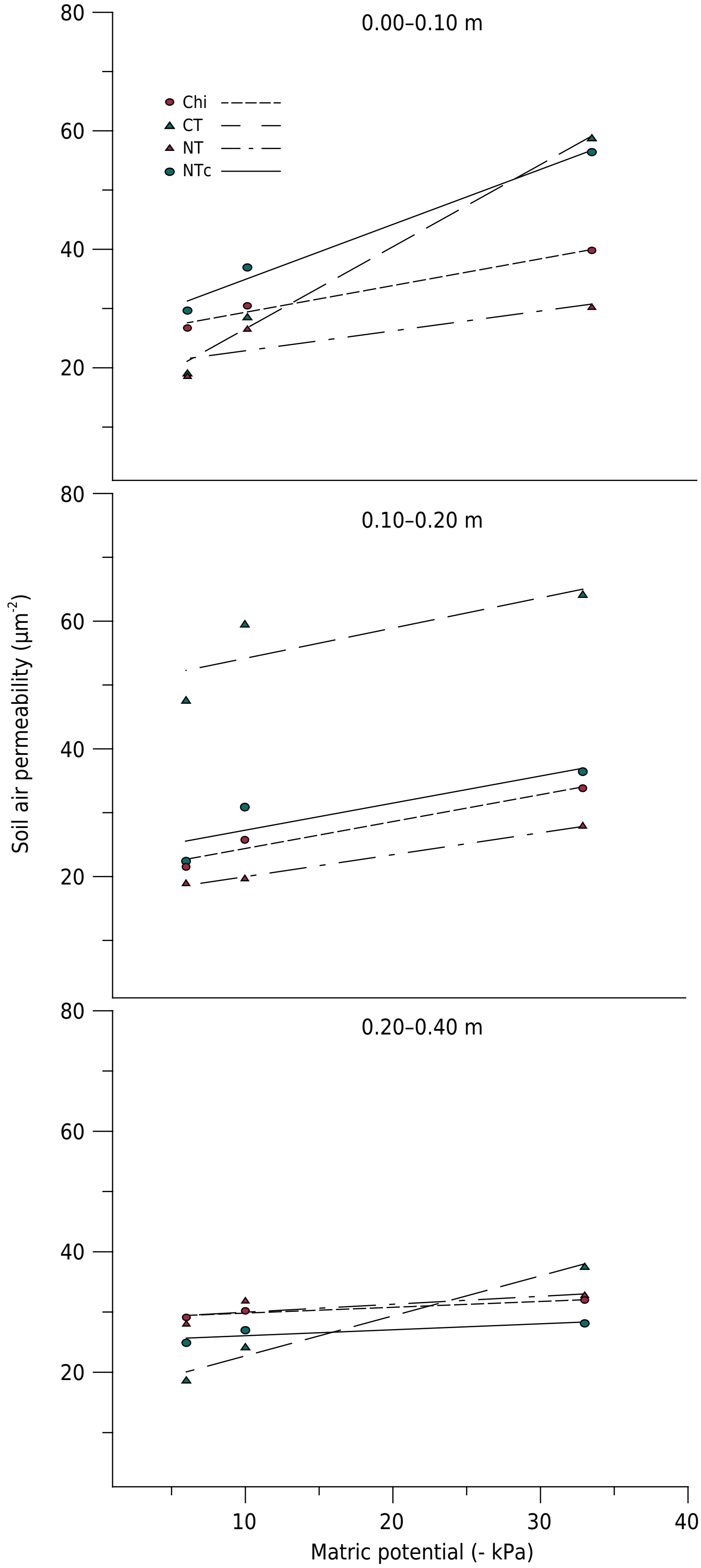

Figure 7. Soil air permeability (Ka, μm^2) at matric potentials (0, -6, -10, and -33 kPa) for chisel plough (Chi), conventional tillage (CT), no-tillage (NT), and compacted no-tillage (NT_C), in three soil layers at physiological maturity of the cassava crop.

Table 9. Soil preconsolidation stress, compressibility coefficient, recovery index, and decompression coefficient in three soil layers and four soil tillage methods at physiological maturity of cassava crop

Layers	Treatment				Mean	CV
	Chi	CT	NT	NTc		
m						%
	Preconsolidation stress, σp (kPa)					
0.00-0.10	81.59a	85.49a	100.51a	94.13a	90.72	45.16
0.10-0.20	95.31a	80.20a	98.03a	100.38a	93.74	30.79
0.20-0.40	195.13a	103.47a	128.89a	124.81a	138.34	48.82
	Compressibility coefficient (Cc)					
0.00-0.10	0.25a	0.22a	0.23a	0.17a	0.22	87.87
0.10-0.20	0.18a	0.20a	0.12a	0.14a	0.16	56.08
0.20-0.40	0.20a	0.16a	0.11a	0.12a	0.15	46.61
	Recovery index (Ri) (%)					
0.00-0.10	10.87a	4.47a	5.19a	6.11a	6.79	117.86
0.10-0.20	5.97a	4.52a	9.95a	7.67a	7.01	39.59
0.20-0.40	7.94a	5.28a	7.80a	11.36a	8.10	50.72
	Decompression coefficient (Dc)					
0.00-0.10	0.06a	0.05a	0.05a	0.04a	0.05	342.44
0.10-0.20	0.04a	0.05a	0.04a	0.04a	0.04	40.35
0.20-0.40	0.05a	0.04a	0.03a	0.03a	0.04	43.86

Means followed by the same letters in a given row are not different using Least Significant Difference (LSD) at 5 % probability level. Chi: chisel; CT: conventional tillage; NT: no-till; NTc: compacted no-tillage; CV: coefficient de variation.

than deeper soil layers. The decompression coefficient was almost at par for all soil tillage methods and soil depths. The average values of σp at physiological maturity were smaller than those obtained one month of planting cassava, while the reverse was observed for Cc.

Cassava storage roots yield

The yield of cassava storage roots ranged from 19.8 7 t ha^{-1} (NTc) to 32.7 t ha^{-1} (NT), a numerical difference of 39 %, while the overall average yield was 25.3 t ha^{-1} (Figure 8). Nonetheless, cassava storage root yield was not significantly ($p<0.05$) affected by soil tillage.

DISCUSSION

Soil composition or capacity properties

The lowest soil density (Bd) recorded in the surface layer and the cassava crop rows results from soil rupturing for cassava planting. Low Bd in the surface layer of NT can be linked to organic material in the surface layer of this treatment, while high Bd in the 0.20-0.40 m subsurface layer of CT can be attributed to the presence of “plow pan”. Higher soil Bd observed in subsurface layers in all the soil tillage methods compared to surface layer could occur due to natural densification and traffic effect of farm machinery used for tillage operations and no-till pan in NT soil (Reichert et al., 2009a). The high Bd in all treatments at cassava physiological maturity was expected, and is attributed to soil reconsolidation after tillage (Reichert et al., 2016a, 2017).

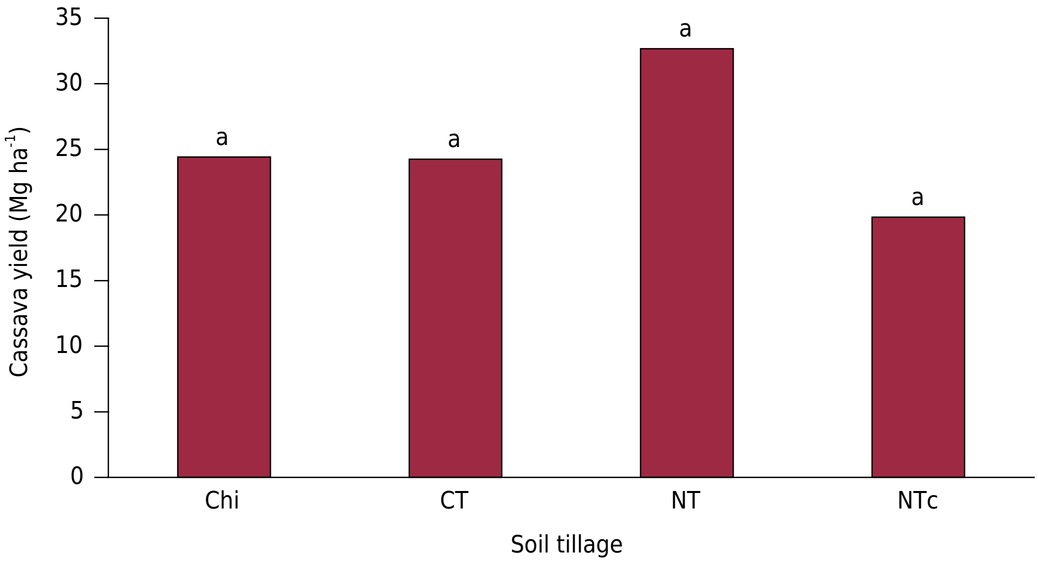

Figure 8. Yield of cassava storage roots, for chisel plough (Chi), conventional tillage (CT), no-tillage (NT), and compacted no-tillage (NT_C). Means followed by same letter do not differ (DMS test, 5 % probability level).

The high degree of compaction (DC) in CT and NTc at crop maturity with respect to one month after planting showed a direct relationship with soil Bd as these treatments presented higher Bd. The increase in DC may result in difficulty for the soil matrix to recover after any applied load. Thus, if the soil is subjected to moderate or severe compaction due to prolonged vehicular traffic or natural consolidation, it is not likely the soil shows elastic behavior if the compaction persists (McBride and Watson, 1990).

In programs designed for assessing the degradation or improvement of soil structure, the degree of soil compaction is an important concept for evaluating different tillage methods (Reichert et al., 2009a, 2021a; Suzuki et al., 2013, 2015). Low DC may impede water retention and reduce soil-seed and soil-root contacts, while a high DC is an indication of low soil pore space, thus reducing soil aeration and increasing soil penetration resistance, resulting in restricted root growth and crop performance (Modolo et al., 2008). In our study, the DC values obtained in the surface soil layers of all the treatments were within the optimum range (77-87 %) for most crops (Suzuki et al., 2007), while those of the subsurface layers are above 90 % upper limit suggested at one month after planting (Reinert et al., 2008), but the DC values were smaller than the upper limit at crop harvest, indicating that the soil is considered as non-restrictive to root growth during the growing cycle.

At harvest, soil macroporosity (Ma) was greater than the minimum value of 0.10 $m^3 m^{-3}$ for adequate root growth (Vomocil and Flocker, 1966). The highest Ma in the surface layer of CT obtained in this study agrees with the findings of Silva et al. (2008), who found CT, when compared to NT in sandy soil cropped to cassava, had smaller density and higher total soil porosity, especially Ma. The increased Mi due to tillage could be attributed to particle rearrangement and distortion of the pore system as large pores are reduced to micropores, indicating that water storage could not be a problem for crop performance. However, gaseous exchange and solute movement may be a factor of concern when considering soil physical quality status since soils with high Mi exhibit low permeability compared to soils with a low volume of micropores.

The marked changes in soil water content occurred in the surface layers, the layer more affected by rainfall and water losses due to evapotranspiration. The amount of available water is associated with the amount and temporal distribution of rainwater, its distribution in the soil profile, losses by evaporation or drainage, and absorption by plants. In general, the different soil tillage options followed the same pattern of available water, i.e., the treatments showed similarity in the water content available to the plants. Similar behavior was found by Kaiser (2010), when comparing water retained in the soil under the corn crop under different levels of compaction. It is noted that during the few days in which the water content was below the permanent wilting point, the availability of water to the cassava crop was not affected. The highest pore volume in the surface layer of all treatments is possibly related to the decrease in soil bulk density, and increase in macroporosity and total porosity. The different pore volumes for the 50-300 μm pore diameter class may be attributed to changes in soil structure caused by the different soil tillage options.

Soil functioning or intensity properties

Soil penetration resistance (RP) is an important indicator used to classify the degree of soil compaction, a process highly influencing soil structure and its intended functions (Celik et al., 2010). In our study, the high penetration resistance recorded in NT followed by NTc, in the 0.15 m surface depth in the cassava inter-row, suggests the presence of no-till pan and additional compaction. On the other hand, the low penetration resistance obtained in CT in the same soil layer can be attributed to the short-term loosening effect of tillage, such as observed by Abreu et al. (2004) when compared to CT and Chi in similar soil.

The 0.20-0.40 m soil layer of Chi and NT and 0.10-0.20 m layer of NTc presented low values of Ksat below the critical values of Ksat of 13.8 and 10.6 mm h^{-1}, suggested by Reichert et al. (2007) and Kaiser (2010), respectively, for the same sandy loam Hapludalf. The low Ksat could inhibit water flow, creating pores filled with much water and anaerobic condition in the root zone, which can greatly impede crop growth and development. Conversely, the essentially high Ksat in the 0.10-0.20 m subsurface layer of CT may cause preferential flow (Dörner and Horn, 2006). Additional compaction did not reduce Ksat in the soil surface layer, possibly due to the contribution of organic material and partial mobilization of this layer at the time of cassava planting. The significant correlation between Ksat versus Bd, Ma, and Pt indicates water movement in the soil matrix is highly affected by these properties. Low Bd and large pores (Ma) are responsible for adequate water flow in the soil. The high variability observed with Ksat may be due to bio pores or cracks in certain soil samples.

Similar to Ksat, soil air pemeability (Ka) is a soil property very sensitive to compaction as it is highly controlled by the large pores (soil macroporosity), which in turn is influenced by soil bulk density (Ambus et al., 2018; Holthusen et al., 2018a). Thus, the high Ka in CT tillage in the 0.10-0.20 m soil layer may be explained by the increased Ma observed, while the lower Ka in Chi and NT treatments may be attributed to an observed higher increase in bulk density. Chen et al. (2014) reported that Ka decreased in the 0.00-0.12 m surface layer due to soil compaction and associated the decrease to the modification of pore structure. The effect of matric potential (y) on soil Ka was also observed more clearly, because as y increases (in module) soil Ka gradually augments, particularly in the surface layer. This behavior could be so because the soil pores previously occupied by water may have been emptied, allowing air to flow.

The surface layer of all the tillage methods had the lowest precompression stress (σp) during both sampling campaigns, which indicates a smaller load-bearing capacity than deeper soil layers. Ambus et al. (2018) also reported the highest σp in the surface layer, as this behavior could result from the positive effects of surface residues such as the addition of organic matter in the surface layer, improving soil structure, and thus offering resistance to external stresses by acting as a shock absorber (Braida et al., 2006; Reichert et al., 2016a, b, c; Reichert et al., 2018; Holthusen et al., 2018b). Conversely, the highest values of Cc in the surface layer in all the tillage treatments are an indication of greater susceptibility to compaction in this layer.

The decrease in σp and increase in Cc at crop physiological maturity followed strictly the reduction in Bd observed, and this agrees with the results of Reichert et al. (2018), who reported increasing Bd increases σp but decreases Cc. Reichert et al. (2018) also stated that both σp and Cc are highly associated, processes that affect the σp also affect Cc, but the response is the opposite. The absence of tillage effect on recovery index (Ri) indicates that irrespective of soil tillage, the soil shows resilience to external stresses. It is interesting to note that additional imposed loading did not trigger compaction, thus the soil remains in a quasi steady-state condition.

Cassava storage roots

The absence of tillage effects contradics previous results where tilled soil yielded more cassava storage roots than no-tillage soil (Oliveira et al., 2001; Devide et al., 2009; Byju et al., 2010; Lamidi, 2016; Oshunsanya et al., 2018) or where cassava storage root yields were equal for both no-tillage and conventional-tilled plots (Aiyelari et al., 2002).

Although CT had the better soil physical conditions, especially in the surface layer where the tubers concentrate, the more consolidated soil under NT did not restrict cassava yield, showing that the soil physical conditions were not enough to affect cassava yield. Conversely, the low yield of cassava storage roots recorded in NTc (in relative terms) could be due to impedance to root growth caused by high Bd and RP observed in this treatment. Cassava storage roots need to explore the soil first, and subsequently grow in diameter (Onwueme, 1978); however, the impedance created by the compacted soil may limit tuber formation and expansion, thus allowing the stem to accumulate more dry-matter at the expense of the roots (Figueiredo et al., 2017). Moreover, low soil Ka has a direct effect on crop growth, mainly due to lack of adequate aeration (Stepniewski et al., 1994), especially in compacted soils. Although the DC values for this system were within the optimum range, these values were below the upper limit as already discussed, with the assumption that the impedance created by the system would not affect crop yield due to water availability for plant growth by rainfall during the cassava growing cycle; however, this was not the case in this study.

Furthermore, the high yield of cassava storage roots from NT in our study indicates that there should be no need for the disturbance of this soil, as the short-time improvement in soil structure due to tillage did not necessarily increased cassava storage root yield. Therefore, employing NT as a tillage method for cassava production in this region will, in the long run, reduce overhead cost, promote soil and water conservation and carbon sequestration, and ensure a more sustainable environment.

CONCLUSIONS

For cassava production in soil with sandy loam texture, conventional (inverting) and chisel tillage of soil previously under long-term no-tillage improves soil quality in terms of macroporosity - a composition/capacity physical property - in surface soil but does not augment the functioning/intensity properties air and water permeability. Soil reconsolidation over short-time significantly affects soil structural condition, and soil tillage is not needed to improve soil structure. Additional compaction on no-till soil causes detrimental consequences on composition/capacity and functioning/intensity physical properties. Nonetheless, neither soil structure improvement by tillage nor further compaction affects cassava storage root yield in the sandy loam soil. Therefore, no-tillage is the best management system, in which soil loosening is done only during furrowing for cassava-stem planting.

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AUTHOR CONTRIBUTIONS

Conceptualization: Eracilda Fontanela (equal), Johnson Toyin Fasinmirin (equal), and José Miguel Reichert (equal).

Methodology: Eracilda Fontanela (equal), Gabriel Oladele Awe (equal), and Johnson Toyin Fasinmirin (equal).

Formal analysis: Gabriel Oladele Awe (equal).

Investigation: Eracilda Fontanela (equal), Gabriel Oladele Awe (equal), and Johnson Toyin Fasinmirin (equal).

Funding acquisition: José Miguel Reichert (lead).

Data curation: Eracilda Fontanela (equal), Gabriel Oladele Awe (equal), and José Miguel Reichert (equal).

Writing - original draft: Eracilda Fontanela (equal), Gabriel Oladele Awe (equal), Johnson Toyin Fasinmirin (equal), and José Miguel Reichert (equal).

Writing - review and editing: Eracilda Fontanela (equal), Gabriel Oladele Awe (equal), Johnson Toyin Fasinmirin (equal), and José Miguel Reichert (equal).

Supervision: José Miguel Reichert (lead).

Project administration: José Miguel Reichert (lead).

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