CASSAVA YIELD AND SOIL PHYSICAL PROPERTIES UNDER DIFFERENT TILLAGE SYSTEMS IN PARANÁ, SOUTHERN BRAZIL

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Abstract: Soil physical properties and climate conditions affect the growth of root and tuber crops, then studies about soil physical indexes, that can indicate more adequate management systems, are important. This study sought to verify if the least limiting water range (LLWR) could indicate the best tillage system for cassava crop (*Manihot esculenta*, Crantz), presenting correlationship with the yield, independently of crop season. The study aimed to evaluate the soil physical properties under three tillage systems cultivated with cassava crop, in a Rhodic Ferralsol in Northwestern Paraná State in Southern Brazil; and to analyse their effects on characteristics of cassava plant growth and yield over two crop seasons, under La Niña influence. The treatments included conventional tillage (CT), reduced tillage (RT) and no-tillage (NT). The results indicated that the plant growth and yield characteristics were both affected by the tillage systems. It was observed significant correlations between characteristics of plant growth and yield and the soil bulk density (Bd), the available water content (AWC) and the LLWR during the driest season. The LLWR in the CT was greater than in the other treatments during the driest season but was statistically equal to the RT in the least dry season. The increase in the LLWR led to an increase in yield. The better precipitation distribution during the least dry season provided more similarities between the CT and RT regarding the cassava yield. Under driest season, the influence of soil physical properties had effect more pronounced on yield, or, under adequate moisture conditions, the yield is less affected by soil physical condition.
Keywords: soil compaction, edible roots, climatic conditions.

1. Introduction

Cassava (*Manihot esculenta*, Crantz) is a crop that is cultivated in tropical and subtropical areas and can tolerate low soil fertility and drought conditions (Ramella et al., 2020; Wellens et al., 2022; Adjei et al., 2023). In addition, cassava is increasingly being targeted by governments in Africa as a strategic crop to reduce cereal imports, and in Asia, twinned with mandatory blending requirements with gasoline, is also aiding the cassava industry through the establishment of ethanol distilleries that use cassava as a feedstock (OECD-FAO, 2015). Cao et al. (2022) emphasize that the properties of cassava make it a highly attractive crop for biofuels in China, surpassing crops such as maize (*Zea mays* L.) and sugarcane (*Saccharum officinarum* L.) in terms of economic benefit.

The average worldwide yield of cassava in 2022 was approximately 10 Mg ha^{-1}. However, among the ten largest countries of cassava production, large yield variations of 6 Mg ha^{-1} in Nigeria to 27 Mg ha^{-1} in Indonesia occur (FAOSTAT, 2024). These different yields result from the different crop management practices that are used to cultivate cassava in different countries. Specifically, the soil tillage system, the soil fertility conditions, and the climate differ between countries in addition to the use of different cassava cultivars. Reichert et al (2021) reported that cassava is grown under many different soil management practices. However, like most root crops, cassava is sensitive to soil physical properties, such as soil mechanical impedance or a lack of soil oxygen, which may affect the induction of storage roots or result in the decay of already established roots (Reichert et al., 2021; Gobbi et al., 2022).

The impact of different tillage systems on cassava yield depends primarily on the soil type, site management history, and weather conditions during soil preparation (Gobbi et al., 2022). Machinery, traffic and tillage operations loosen, granulate, crush or even compact soil particles and alter the soil physical properties that influence plant growth, including the available water content and the soil atmosphere (Ramella et al., 2020). These physical properties and others, such as soil resistance to root penetration and aeration, are generally modified by tillage systems. Therefore, it is very important to analyse the effects of these properties on cassava yield in a given tillage system, such as conventional or no-tillage systems.

In Brazil, soil tillage for cassava has traditionally been performed using conventional tillage, with one ploughing and two harrowing passes across the soil (Reichert et al., 2021; Gobbi et al., 2022), which expose the soil to water erosion and increase the soil degradation prior to successive crop growth. However, these authors verified that conventional tillage for cassava production reduces the soil bulk density and increases the total porosity (mainly the macroporosity), which establishes better soil physical conditions for cassava plant growth and yields relative to no-tillage systems. This conventional tillage effect results from the loosening of the soil. In agreement with Gobbi et all. (2022), conventional tillage can provide better cassava performance in Brazil, while no-tillage systems have been shown to reduce plant growth. However, Otsubo et al. (2008) observed that the reduced tillage

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associated with cover crops had improvements in cassava yield compared to conventional tillage. In contrast, soil erosion is prevalent in conventional tillage systems, despite the fact that cassava is generally well-adapted to growth on eroded slopes and despite the drastically reduced yields that are caused by soil erosion (Reichert et al., 2021). In addition, soil losses that are caused by water erosion are very harmful to the environment. Thus, conservation tillage systems have become a priority for sustainable cassava production systems.

Soil physical properties used as quality indexes are important tools that are used to determine what tillage systems might be the best in terms of soil physical quality. Indeed, according to Letey (1985), factors that directly and indirectly affect plant growth can be changed by tillage due to its relationship with soil structure. Bulk density, texture, aggregation, aggregate stability, and pore size distribution are widely measured, but their effects on water, aeration, temperature, and mechanical resistance also affect crop production indirectly. Tillage generally reduces the soil bulk density and mechanical resistance, increases the soil penetrability and permeability (Letey, 1985), and improves the available soil moisture content and the soil hydraulic conductivity (Reichert et al., 2021; Gobbi et al., 2022). However, the analysis of only one property, such as bulk density, might not provide sufficient information about the effects of tillage. Thus, soil physical quality indexes that use more than one soil property are more suitable for identifying the impacts of soil tillage systems on the factors that limit the crop.

The least limiting water range (LLWR) has been shown to be an adequate indicator of soil physical quality (Benjamin et al., 2003; Silva et al., 2014, Safadoust et al., 2014; Zangiabadi et al., 2020) because it integrates most of the physical factors that limit plant growth into a single parameter. The physical properties that compose the LLWR include the available water capacity (AWC), soil resistance to penetration, and air-filled porosity, which minimally limits root growth. Indeed, the LLWR may be more robust than the AWC in terms of indicating the physical limitations of root growth (Cavalieri et al., 2006; Zangiabadi et al., 2020), mainly under drier conditions, such as strong La Ninã in Paraná State. In addition, the relationships between the LLWR and crop growth and yield characteristics have been performed for cereals and grains (Benjamin et al., 2003; Wilson et al., 2013; Gubiane et al., 2013), but rarely for roots and tubers.

We hypothesise that soil tillage systems influence the soil physical properties and that the LLWR is the best index for cassava yield, under driest weather conditions. The objective of this study was to evaluate the soil physical properties in a Rhodic Ferralsol under different tillage systems and to determine the influences of the soil physical properties on cassava growth and yield over two seasons under La Niña effect.

2. Material and Methods

2.1. Experimental site

This study was conducted during two cassava growing seasons, under a strong La Niña (1999/2000), considered the driest season, and a weak La Niña (2000/2001), considered the least dry season, at the experimental farm belonging to Pinduca Indústria Alimentícia LTDA in the municipality of Araruna (25º55'S, 52º30'W), northwest of Paraná state in Southern Brazil. The climate is classified as Cfb (mesothermic, wet subtropical, without a dry season and with a warm summer), with mean annual precipitation and temperature of 1,620 mm and 21.5ºC, respectively. Figure 1 shows the monthly precipitation and maximum and minimum temperature data for 1999 to 2001.

The soil is classified as a Rhodic Ferralsol (FAO, 1988), deep and well-drained. The textural composition of topsoil was 310, 10, and 680 g kg^{-1} of clay, silt, and sand, respectively. The area was previously cultivated for coffee plants (*Coffea arabica*) prior to becoming a pasture (*graminea* species). Three years before supporting the growth of cassava (*Manihot esculenta* Crantz), annual crops were introduced to the area under no-tillage. The experiment began with a cover crop of black oats (*Avena strigosa* Schreb.) + fodder radish (*Raphanus sativus* L. *var. oleiferus* Metzg.) that were seeded directly using a drill in April 1999 and again in May 2000 before starting the cassava crop. A roller crimper was used to manage the black oats and fodder radish at nearly 100% bloom. The planting of cassava crops began in October of each year evaluated.

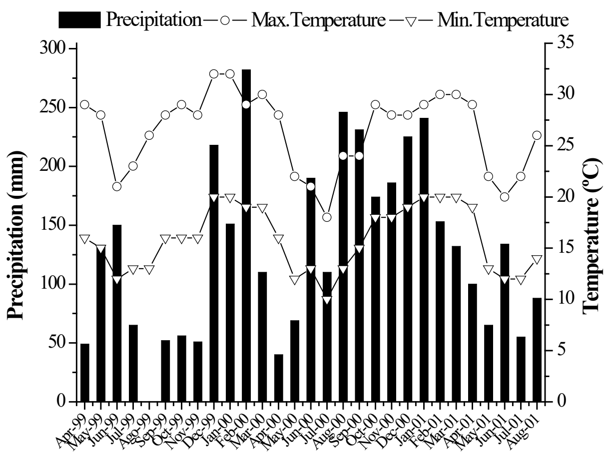

Figure 1 – Data of pluvial precipitation, maximum e minimum temperature during study.

3. Treatments, experimental design and soil sampling

The experiment was originally designed in a randomised complete block (eight replications) with three tillage treatments. Each of the eight replications were arranged to be located at approximately the same landscape position to help reduce the variability within the block. The tillage treatments included no-tillage (NT) with a cassava planter with motorised traction (Model PC 20, Plant Centre); reduced or minimum tillage with chisel ploughing (Ikeda, Model DP-220 M) with evener roller, at a depth of 0.25-0.30 m (RT); and conventional tillage with ploughing using a moldboard plough at a depth of 0.25-0.30 m with harrow disking (Baldan (CT)). For these operations, a Valmet 1280 tractor was used. This procedure was always adopted after rolling the oats + fodder radish and before planting the cassava. Each replication covered a total area of 75 m^2 (5 × 15 m), and a usable area of 30 m^2 (2 × 15 m) was employed for the soil and crop measurements.

Soil sampling was conducted in July over two years under La Niña effect. Undisturbed soil samples were collected from each experimental unit at the centre of the 0.00-0.15 m and 0.15-0.30 m depth layers using cores with an inner diameter of 5 cm and a height of 5 cm. For the first sampling (driest season), 288 samples were collected with six cores per layer per experimental unit for a total of 96 samples per treatment and 48 samples per treatment layer. For the second sampling in least dry season, only 144 samples were collected due to the observation that one-half of samples would be sufficient for the study. Next, the samples were collected using three cores per layer for each experimental unit for a total of 48 samples per treatment and 24 samples per layer in each treatment. Then, the core samples were wrapped in plastic film and maintained at 5°C until processing.

4. Soil bulk density (Bd), least limiting water range (LLWR) and available water capacity (AWC)

The undisturbed soil samples were saturated with water for 48 h and equilibrated step-by-step at eight different matric potentials, -2, -6 and -10 kPa using a tension table and -30, -50, -100, -400 and -1,500 kPa using pressure plates (Klute, 1986), to determine the soil water retention curve (SWRC) as described by Silva et al. (1994). After reaching equilibrium at the above potentials, the soil resistance to penetration (SR) was determined for each core according to Tormena et al. (1999). Next, the samples were oven dried at 105ºC until a constant weight was achieved to determine the soil water content (θ) and soil bulk density (Bd) in accordance with the methods of Gardner (1986) and Blake and Hartge (1986), respectively.

The SWRC was fit to the equation proposed by van Genuchten (1980):

$$\theta = \theta_r + \{(\theta_s - \theta_r)/[(1+\alpha\psi)^n]^{1-1/n}\} \tag{1}$$

where θ is the volumetric water content (m^3 m^{-3}), ψ is the matric potential (kPa), θ_r is the residual water content (m^3 m^{-3}), and α is a constant. In addition, θ_s is the soil water content at saturation or the total porosity (m^3 m^{-3}) and was obtained by using $\theta_s = (1\text{-}Bd/2.65)$ while assuming a particle density of 2.65 Mg m^{-3}. The effects of soil bulk density were incorporated into the model using the parameter *n*, according to Tormena et al. (1999) as follows:

$$n = n_0 + n_1 Bd + n_2 Bd^2 \tag{2}$$

Here, n_0, n_1, and n_2 are constants in the model that corresponds to 12.92, -13.37, and 3.87, respectively, for the first crop season and 12.16, -11.66, and 3.10, respectively, for the second crop season.

The data for the SR (MPa) were regressed against ρ (Mg m^{-3}) and θ (m^3 m^{-3}) using the following model described by Busscher (1990) and employed by Silva et al. (1994):

$$SR = c\theta^d Bd^e \tag{3}$$

where *c*, *d* and *e* are the model constants that were fit by tillage system and crop season. Equation 3 was linearized and rearranged to calculate the soil water content at the critical SR value according to Eq. (4).

$$\theta = \left[\frac{SR}{(\exp c)(Bd^e)}\right]^{\frac{1}{d}} \tag{4}$$

The estimates of θ for an air-filled porosity (θ_{afp}) of 0.10 m^3 m^{-3} (Grable and Siemer, 1968) were calculated using Eq. 5.

$$\theta_{afp} = \theta_s - 0.10 \tag{5}$$

The LLWR was determined according to Silva et al. (1994). The soil water content at field capacity Ψ=-10 kPa (θ_{fc}) and the wilting point Ψ = -1,500 kPa (θ_{wp}) were both estimated using the water retention curve equation (Equation 1). An estimate of θ established a critical SR value for root growth of 2.5 MPa (θ_{sr}) according to Eqs. 3 and 4, and a critical air-filled porosity of 10% (θ_{afp}) was obtained using Eq. 5. Then, the LLWR ($m^3 m^{-3}$) at each Bd is the difference between the upper and lower critical limits. The upper limit is the drier θ of either θ_{fc} or θ_{afp}, whereas the lower limit is the wetter θ of either θ_{wp} or θ_{sr}.

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Table 1 – Mean values of soil bulk density (Bd), available water content (AWC), least limiting water range (LLWR), soil penetration resistance (SR) and soil water content (WC) for conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) at two crop seasons.

Soil variables	CT	RT	NT	Mean
Driest crop season				
Bd (Mg m^{-3})	1.51 c	1.56 b	1.63 a	1.57 B
AWC (m^3 m^{-3})	0.082 a	0.083 a	0.084 a	0.083 B
LLWR (m^3 m^{-3})	0.064 a	0.046 b	0.023 c	0.044 A
SR* (MPa)	1.77 b	2.31 b	3.25 a	2.44 B
WC*(m^3 m^{-3})	0.241 a	0.245 a	0.243 a	0.243 A
Least dry crop season				
Bd (Mg m^{-3})	1.57 b	1.61 b	1.67 a	1.62 A
AWC (m^3 m^{-3})	0.101 a	0.100 a	0.096 a	0.099 A
LLWR (m^3 m^{-3})	0.047 a	0.039 a	0.010 b	0.032 B
SR* (MPa)	2.70 b	2.67 b	3.27 a	3.03 A
WC*(m^3 m^{-3})	0.252 a	0.259 a	0.257 a	0.256 A

*is the average of all data at different water potentials. Different normal letters, at line, indicate statistically significant differences among treatments and capital letters, at Mean column, indicate statistically significant differences between crop seasons, by Tukey's test ($P < 0.05$).

The critical soil bulk density (Bdc) is considered as the Bd at which the LLWR = 0. When the Bd is higher than the Bdc, the soil physical conditions are severely restrictive and negatively affect plant development independent of the soil water content.

The AWC (m^{3}m^{-3}) was calculated as the difference between the soil water contents at field capacity (θ_{fc}) and wilting point (θ_{wp}).

$$AWC = \theta_{fc} - \theta_{wp} \tag{6}$$

5. Determining the cassava plant growth characteristics

All determinations were performed inside the useable experimental area by using the random measurements of twenty plants. The final plant population was obtained by counting all plants in units of thousands of plants per hectare. Plant height was considered equivalent to the distance (m) between the soil surface and the tip of the terminal shoot of each plant. The measurements were performed 90 days after planting (90 DAP) and at harvest (270 DAP). The first branching height measurement was made between the soil surface and the base of the first branch emitted by each plant. The stem diameter was recorded as the mean value (cm) obtained at a height of 0.05 m from the soil surface. The shoot yield was determined by weighing the shoots that were harvested (kg ha^{-1}) 0.10 m from the soil surface for all plants inside the useable area of each replication. The root number was obtained by counting the roots of each plant. The root length and diameter (cm) were measured using 20 roots from each replication. The root yield (kg ha^{-1}) was obtained by weighing the roots of all plants that were harvested in each replication.

Dry mass and starch content values were measured in g kg^{-1} for a 3 kg sample of roots according to the method reported by Grosmann and Freitas (1950). The dry mass and starch yield (kg ha^{-1}) were calculated using the root yield and the percentage of dry mass and starch.

6. Statistical analyses

The treatments were analysed using an analysis of variance, and the means were compared using Tukey's test ($p<0.05$). The soil water retention and the soils resistance to penetration curves were fit using the SAS/STAT software package (SAS, 2000). The soil water retention parameters and the soil resistance to penetration curves were considered statistically significant when the confidence interval did not include the zero value (Glantz and Slinker, 1990). Pearson's correlation was used to study the correlations among the Bd, LLWR, AWC and the characteristics of the cassava plants in each crop season.

7. Results

The climate conditions (Figure 1) (mainly precipitation – La Niña effect) during each crop season potentially influenced the treatment effects directly regarding the characteristics of cassava growth and yield. During the study period, the total precipitation was lower during the first crop season than during the second (1,724 and 2,351 mm, respectively), with monthly average values of 108 mm and 147 mm, respectively. According to Oceanic Niño Index (https://ggweather.com/enso/oni.png) there was a strong La Niña between 1999 and 2000.

Table 1 shows the mean values of Bd, AWC, LLWR, SR and WC for the treatments when considering the two sampling depths. The soil tillage systems affected the soil physical properties, presenting significantly differences for Bd, LLWR and SR in both crop seasons. NT system had the worst soil physical conditions compared to the others. In addition, the last column presents an average of the treatments for each property that was obtained during each crop season. The final average shows that the Bd, AWC and SR values during the first crop season (driest season) were significantly lower than the values recorded during the second crop season (least dry season). However, the opposite trend was observed for the LLWR, and no differences were found for the WC.

The critical soil bulk densities (Bdc) were 1.69 and 1.66 Mg m^{-3} for the driest, and leat dry seasons, respectively, and did not differ among the treatments for either season. The mean Bd values were below the mean Bdc values, except in the NT during the least dry crop season, which surpassed the Bdc values (Table 1). For cassava yield, the crop seasons had effect on dry mass content of the roots in which was higher during the first crop season relative to the second crop season, with mean values of 365 and 345 g kg^{-1}, respectively. However, for mean values of the other yield variables, such as the root yields and dry mass yields of the roots, there is no difference between the two crop seasons - 27,577 and 28,328 kg ha^{-1} and 10,051 and 9,793 kg ha^{-1}, respectively, for the driest and least dry crop seasons.

Significant correlations were verified for each variable (Table 2). However, most of these correlations occurred for the driest crop season. Overall, twelve characteristics of cassava growth and yield and three soil variables were studied. Of these characteristics, nine were correlated with Bd and ten were correlated with AWC and LLWR in 1999/2000. For the second crop season (least dry), the number of these significant correlations decreased to seven for the Bd and LLWR and to one for the AWC. The LLWR was the most significant variable in the performed evaluations for the first crop season. The correlations for AWC and LLWR with Bd were also significant, but the LLWR showed a higher Pearson's correlation coefficient than the AWC for the least dry crop season.

Some of the significant correlations that were obtained were plotted as a function of LLWR (Figures 2 and 3). The plant population, plant height, root yield and dry mass yield of the roots increased as the LLWR increased, except for the plant population during the least dry season, for which no correlation could be established. This increase was more pronounced during the crop season with lower precipitation, which was verified by the higher slope of the equations in Figures 2A and 3A and surpassed more than three times the slope value for the root yield and dry mass root yields during the driest season. Moreover, the yield variables that were correlated to the LLWR were lower for NT, intermediate for RT and the highest for CT. This behaviour was not as pronounced for the second crop season, in which the amount of precipitation was higher.

Table 2 – Values of Pearson's correlation among soil physical properties and cassava growth and yield characteristics at two crop seasons.

							Driest Crop season							
	AWC	LLWR	PP	PH(1)	PH (2)	FBH(3)	SDi	SYield	RN	RL	RDi	RYield	DMC	DMYield
Bd	-0.914	-0.970	-0.683	-0.787	-0.504	-0.586	-0.334	-0.475	-0.655	0.169	-0.242	-0.759	-0.776	-0.784
Probability	*<.0001*	*<.0001*	*0.000*	*<.0001*	*0.012*	*0.003*	*0.110*	*0.019*	*0.001*	*0.429*	*0.255*	*<.0001*	*<.0001*	*<.0001*
AWC		0.945	0.679	0.820	0.595	0.663	0.465	0.544	0.704	-0.086	0.216	0.754	0.781	0.779
Probability		*<.0001*	*0.000*	*<.0001*	*0.002*	*0.000*	*0.022*	*0.006*	*0.000*	*0.689*	*0.311*	*<.0001*	*<.0001*	*<.0001*
LLWR			0.759	0.865	0.620	0.694	0.444	0.599	0.730	-0.164	0.274	0.818	0.731	0.835
Probability			*<.0001*	*<.0001*	*0.001*	*0.000*	*0.030*	*0.002*	*<.0001*	*0.443*	*0.195*	*<.0001*	*<.0001*	*<.0001*
							Less dry Crop season							
	AWC	LLWR	PP	PH(1)	PH (2)	FBH(3)	SDi	SYield	RN	RL	RDi	RYield	DMC	DMYield
Bd	-0.557	-0.957	0.216	-0.553	-0.122	-0.581	-0.043	-0.429	-0.457	0.276	0.446	-0.551	-0.115	-0.514
Probability	*0.005*	*<.0001*	*0.310*	*0.005*	*0.571*	*0.003*	*0.840*	*0.036*	*0.025*	*0.191*	*0.029*	*0.005*	*0.593*	*0.010*
AWC		0.613	0.141	0.285	0.111	0.235	0.069	0.291	0.146	-0.298	-0.295	0.373	0.021	0.338
Probability		*0.001*	*0.510*	*0.177*	*0.607*	*0.270*	*0.748*	*0.168*	*0.497*	*0.157*	*0.162*	*0.073*	*0.922*	*0.106*
LLWR			-0.173	0.570	0.225	0.591	0.092	0.420	0.427	-0.242	-0.489	0.505	0.122	0.473
Probability			*0.419*	*0.004*	*0.290*	*0.002*	*0.668*	*0.041*	*0.038*	*0.255*	*0.015*	*0.012*	*0.570*	*0.020*

Bd= soil bulk density; AWC= available water capacity; LLWR= least limiting water range; PP= plant population; PH(1)= Plant height with 3 months;PH(2)= Plant height with 9 months; FBH(3)= stem diameter with 9 months; SDi= stem diameter; SYield= shoot yield; RN= root number per plant; RL= root length; RDi= root diameter; RYield= root yield; DMC= dry mass content of roots; DMYield= dry mass yield of roots.

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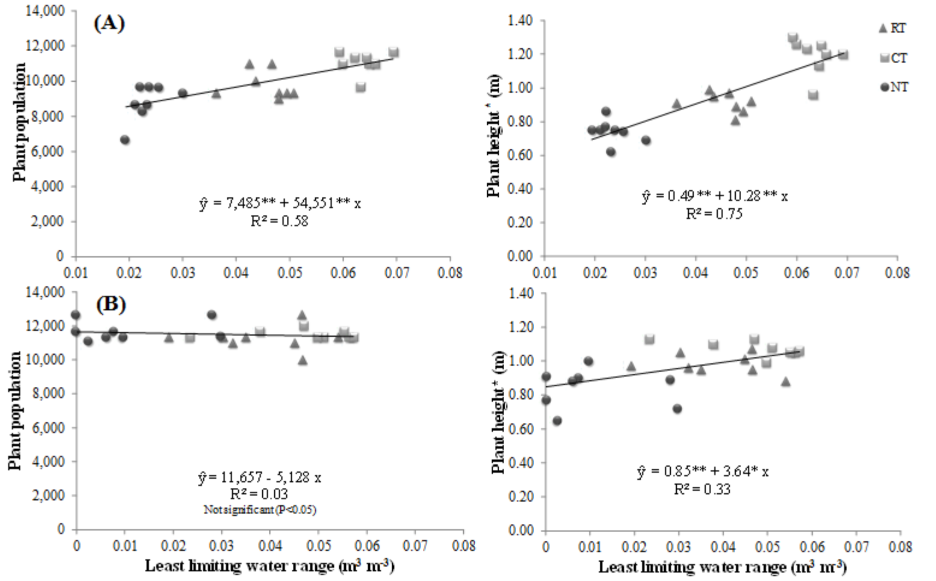

Figure 2 – Plant population (PP) and plant height*(PH) (90 DAP) in function of least limiting water range (LLWR). RT= conventional tillage; CT= conventional tillage and NT= no-tillage. (A) Driest season and (B) Least dry season.

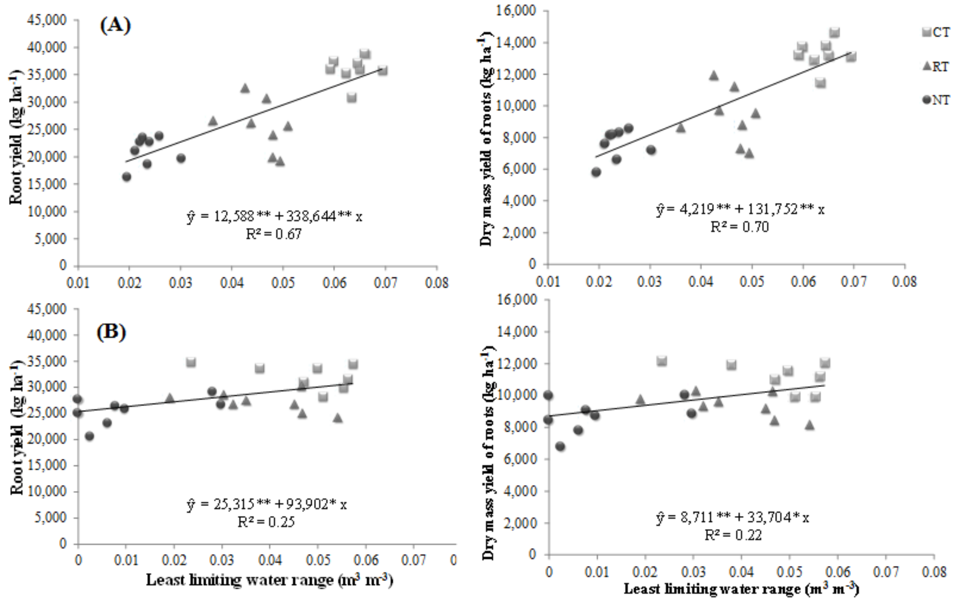

Figure 3 – Root yield (RY) and dry mass yield of roots (DMYR) in function of least limiting water range (LLWR). RT= conventional tillage; CT= conventional tillage and NT= no-tillage. (A) Driest season and (B) Least dry season.

8. Discussion

Soil loosening induced by tillage produced better soil physical conditions for the cassava crop in terms of growth and yield than the other systems. In addition, the soil physical properties, such as Bd, were significantly different among the soil tillage systems and crop seasons (Table 1), which determined the changes in the LLWR. The increases in the Bd and SR during the second crop season reduced the LLWR was, probably, due to the increase of soil compaction susceptibility in wetter crop seasons. In fact, the LLWR is even lower than the AWC in the range of Bd. This result occurred because it was necessary to maintain higher soil water contents to keep the soil resistance at non-limiting levels. In addition, this result implies that the lower air filled pores restrict the soil water availability, as reported by Cavalieri et al. (2006) in the same experiment.

In general, the NT had a lower cassava yield than the CT, most likely due to the effects of the absence of tillage on the soil physical properties, which results in higher mechanical resistance to root growth. as also observed by Reichert et al. (2021) in a dystrophic Red-Yellow Alfisol in Southern Brazil. The same was not observed by TerAvest et al. (2015) that did not improve the cassava yield with the tillage studied in two research sites in Malawy, Africa, with annual rainfall averaged of 1,450 mm and 834 mm, respectively. On the other hand, Adekiya et al. (2011) observed differences in the soil physical properties due to different tillage systems among the crop seasons with different distributions of rainfall for cocoyam yield. First, the authors verified that CT produced a significant increase in Bd from approximately 1.26 Mg m^{-3} during drier seasons to 1.75 Mg m^{-3} during wetter seasons. These authors attributed this finding to the breakdown in soil structure due to slaking and raindrop impacts and to repetitive tillage. Second, the authors of these processes indicated that the soil quality was degraded and caused a rapid collapse in the soil structure, especially under tropical conditions. Cocoyam showed a higher cormel yield under manual clearing or NT compared with CT during wetter seasons. During drier seasons, the opposite results were observed (Adekiya et al., 2011). Similar results were reported by Ramella et al., 2020 in a Red Ferralsol in Paraná, according to the authors, this result was due to the higher water content of the soil and the plant residues that remained on the surface, which caused an increase in C, N, P, K and organic Mg. This finding was correlated with the soil water content and the plant residues that were left on the surface, which caused an increase in organic C, N, P, K and Mg. This effect was more pronounced under no-tillage systems than under any other tillage system. Results from Agbede (2010) showed higher values for sweet potato yield variables, such as vine length, vine girth and leaf area under CT, although these variables were not significantly different from those observed under NT. However, the storage tuber yield was significantly higher under CT. These results corroborate those observed in the present study for cassava crops.

The Bd values in the NT were similar to those found by Asadu et al. (2002) in soils that were fallow for approximately 8 years prior to running cassava trials. In contrast, values of approximately 1.40 and 1.21 Mg m^{-3} were found for NT and CT, respectively, in a sandy loam with a similar texture that was studied by Agbede (2008) and < 1.50 Mg m^{-3} for NT and CT in soils with 12% clay by TerAvest et al. (2015). Reichert et al. (2021) observed higher Bd values in NT, which resulted in losses in cassava productivity in a Red-Yellow Alfisol in Southern Brazil, however, according to the authors, furrowing the soil for cassava planting promotes a reduction in Bd sufficient to not compromise the development of the roots. In contrast, Maduakor (1993) observed that soil compaction had little effect on the root yield of cassava in a loamy sand soil under different levels of soil compaction (1.4, 1.6 and 1.8 Mg m^{-3} of Bd), most likely because the plants were not water stressed under the experimental conditions. Our results showed that higher Bd values have greater impacts on crop productivity in seasons under drier conditions.

Soil physical properties, such as Bd, macroporosity and total porosity, normally affect the soil AWC, which in turn affects the nutrient availability and accessibility (Asadu et al., 2002). In addition, high soil bulk densities can mechanically restrict root growth, which could adversely affect nutrient and water uptake. Our results did not show differences in AWC for both crop seasons. This can suggest that only AWC is not enough to indicate the reduction of yield for cassava. Another point is that tillage systems cannot influence the development and establishment of the various tissues that form tuberous cassava before 180 days after planting (DAP) (Figueiredo et al., 2015), then the importance to analyse the yield after this time. Cavalieri et al. (2006) showed that the increasing Bd increased the AWC under the same soil and experimental site. Nevertheless, the increment of Bd implies an increasing soil resistance, which nullifies the effects of AWC.

The soil resistance (SR) depends on the Bd and the soil water content, but their effects are different. Thus, when the Bd is increased, the SR also increases, and when the water content increases, the SR decreases. In this way, the SR can be compensated for or maintained by increasing the water content. However, most of the time, this increase is not sufficient for avoiding an increase in the SR due to Bd.

The absence of tillage (NT) resulted in greater soil compaction, which caused higher Bd values and lower LLWR values. Compaction reduces porosity, which results in less porous space available for water storage and gas flux for plants. In addition, compaction increases the soil resistance, which decreases the LLWR (Silva et al., 1994; Reinert et al., 2002; Olibone et al., 2010). Then, the LLWR can be used to evaluate improvement or degradation of soil physical properties (Benjamin and Karlen, 2014). The decrease in the LLWR as the tillage is reduced under RT and NT mainly resulted from the effects of SR. In fact, the SR sets the lower limit of the LLWR instead of the permanent wilting point, as shown by Cavalieri et al. (2006), and after by Chen et al. (2014) evaluating sandy loam and loamy sand soils. The critical air-filled pores affected the LLWR, specifically during the second crop season, setting the upper limit of LLWR at water contents less than field capacity and within a small range of Bd. Thus, this effect was greatly reduced relative to the SR effect. Similarly, Kadžienė et al. (2011) found that the LLWR mainly depended on the field capacity and penetration resistance for reduced tillage, harrowing and ploughing treatments and that poor aeration did not appear to be a significant problem under reduced tillage in a Danish sandy loam.

The correlations between the soil physical properties and the plant and yield variables were similar for both crop seasons: significant and negative correlations between the soil bulk density (Bd) and plant growth and yield and a positive correlation between plant growth and yield and the available water capacity (AWC) and least limiting water range (LLWR) (Table 2). A negative correlation between Bd and root yield (yam and sweet potato) was also observed by (Agbede, 2006, 2010). Stronger correlations between yield and LLWR suggest that the LLWR is more sensitive than the AWC, especially under drier weather conditions for cassava crop. This better link with LLWR is expected because it incorporates the effects of soil resistance and aeration in addition to matric potential, which is the only physical limitation that affects the AWC. However, Gubiane et al. (2013) did not find good correlations between LLWR and growth and grain yield variables of corn.

In the driest season, the LLWR showed a greater Pearson's coefficient (r) among the soil physical properties and was correlated with ten plant growth and yield variables. The same number of significant correlations was found for the AWC, but their coefficient values were lower than the correlations for LLWR. In fact, the improved rainfall distribution during the least dry season (Fig. 1) potentially kept the water content within the limits of the LLWR, producing fewer significant correlations compared with the driest season. Moreover, as a variable, the AWC was only significant for one plant variable (root yield). This result indicates that the soil physical properties that incorporate the mechanical impedance to roots growth, such as Bd and LLWR, are capable of better

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explaining the productivity of cassava crop. Thus, during drier crop seasons, the probability that mechanical impedance to roots limits the productivity is greater than that during wetter crop seasons. High bulk density (Agbede, 2006, 2010; Adekiya et al., 2011) caused by soil tillage systems increases the growth and root development restrictions. In addition, the associated with poor aeration (Vine and Ahmad, 1987) and mechanical impedance (Cavalieri et al., 2006) reduce plant growth, which is indicated by the better correlations between the cassava plant variables and LLWR.

At two crop seasons the LLWR showed the same or more significant correlations with plant growth and yield variables than other soil physical properties, indicating strong relationships between plant growth and yield variables and LLWR. Benjamin et al. (2003) found that the correlations between LLWR and different crops, wheat and corn, were different, these correlations were stronger for wheat than corn, in which appears to be less sensitive to soil condition than wheat. Moreover, during the least dry season, one plant growth and yield variable (root diameter) presented an inverse correlation with LLWR, which indicated that the increase in LLWR resulted in thinner roots with a higher root number per plant. Thus, an inverse correlation between LLWR and Bd was also observed, with the latter presenting a positive correlation with root diameter. This finding suggests that the roots were thicker under the higher Bd and lower LLWR. Therefore, the soil tillage systems that decreased the Bd caused an increase in the LLWR and improved the crop yield. In addition, the root yield and the dry mass root yield increased, most likely due to the greater number of roots per plant.

Regarding the soil physical properties that were measured, the LLWR was the best indicator of the effects of the soil physical conditions on cassava growth and yield. The resistance of the soil to penetration (as one of the LLWR critical limits) improves the accuracy of relationships between the LLWR and the growth and yield variables of cassava. According to Vine and Ahmad (1987), the penetration resistance largely determined the cassava yield, even when the AWC and aeration were sufficient. The authors emphasise that the effects of soils resistance to penetration, the aeration and the available water content on the storage-root number, size and yield are principally due to the effects of these conditions on the crop's overall growth, which is supported by the fact that the LLWR captures all of these physical properties.

Figs. 2 and 3 show the results regarding cassava growth and yield as a function of LLWR in each soil tillage system. The behaviour of the selected variables was similar between the two crop seasons, except for that of the plant population, which was not significant in least dry season. The loosening caused by tillage (as mentioned earlier) resulted in a higher LLWR, which positively affected the plant population, plant height (90 DAP), root yield and dry mass yield of the roots.

In fact, the effects of the rainfall distribution during the two crop seasons resulted in few divergences from the LLWR within the soil tillage systems. Interestingly, during the driest season, the LLWR values for each soil tillage system appeared grouped, presenting low values for NT, intermediate values for RT and high values for CT. This behaviour was not clearly observed during the wetter crop season (least dry season) in which the LLWR values were similar among the CT, RT and NT treatments. It is important to highlight the increase in soil water during the second crop season that most likely caused soil compaction and affected the soil structures of all soil tillage systems, which resulted in physical characteristics that were more similar than those of the first crop season. These observations suggest that water plays an important role in determining the limitations that are imposed by soil physical properties that are derived from soil tillage systems and that the LLWR is appropriate for evaluating these effects on cassava growth and yield characteristics.

Drier soil water conditions provided clear evidence regarding the effects of the soil physical properties on cassava plant growth and yield and presented higher values for the determination coefficients (R^2) of the equations (Figures 2 and 3). The higher observed slope indicates that under drier conditions, the soil tillage system greatly affects cassava plant growth and yield due to the effects of the tillage on the soil physical properties and as evidenced by an increase in the Bd and a reduction in the LLWR. Vine and Ahmad (1987) verified that cassava grows best during wet seasons in fine sandy loam soils that are tilled. Drier season conditions produced no further increases in the storage root fresh weight but potentially resulted in increased root dry matter.

Losses in cassava production in the least dry season in the NT with CT treatments were also found. However, the magnitudes of these losses were lower. For root yield, the NT treatment was lower than the CT treatment by 20%, and was more than 40% in the driest season. Furthermore, Howeler et al. (1993) stated that minimal or reduced tillage, though resulting in erosion control, quicker land preparation and less subsoil compaction, has inconclusive effects on tuber yield. For example, in one season, the yield may be reduced in RT, and in the next season, it may equal CT.

Our findings indicate that even under climate conditions that are favourable to plant growth and yield, soil tillage systems may affect the cassava crop productivity. In addition, the LLWR is efficient for detecting poor soil physical conditions due to soil tillage systems. Thus, it is very important that similar studies be conducted for different soils, climates, crops and land uses. To highlight the soil tillage systems in spite of the soil erosion probability, the CT resulted in better growth and yield characteristics than the RT and NT tillage systems in northwest Paraná in southern Brazil, even during moderate La Niña, with a better rain distribution. However, RT is used more often in this region because of the soil erosion hazard.

9. Conclusions

Soil tillage systems significantly affected the cassava plant growth and yield, which supported the hypothesis of this study.

The effects of tillage systems were the most marked in the driest season (Stronger La Niña).

The LLWR was the physical indicator that best indicated the differences among the soil tillage systems during the two crop seasons for cassava crop, pointing to CT as having the best cassava growth and yield characteristics.

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