PAB
Pesquisa Agropecuária Brasileira

ISSN 1678-3921

Journal homepage: www.embrapa.br/pab

For manuscript submission and journal contents, access: www.scielo.br/pab

Crop Science/ Original Article

Cassava yield in conventional and no-tillage cultivation in integrated crop-livestock systems

Abstract – The objective of this work was to evaluate cassava (*Manihot esculenta*) crop yield, as well as soil density and carbon content, under no-tillage and conventional cultivation, in rotation with palisade grass (*Urochloa brizantha*) subjected to grazing. Treatments consisted of cassava cultivated as follows: in conventional tillage after 2 (CC-2P) and 4 (CC-4P) years of pasture; in no-tillage after 2 (NTC-2P) and 4 (NTC-4P) years of pasture; and with perennial pasture (PP) of palisade grass. The CC-2P treatment showed higher cassava yield in the 2016/2017 crop year (63.29 Mg ha^{-1}) than NTC-2P (47.85 Mg ha^{-1}). However, in the 2018/2019 crop year, no significant yield differences were observed between CC-4P (60.95 Mg ha^{-1}) and NTC-4P (60.68 Mg ha^{-1}). Between 2012 and 2019, soil carbon content (0–10 cm) decreased in the CC-2P treatment. In 2019, carbon stock was higher for NTC-4P compared with CC-4P and CC-2P, increasing from 16.41 to 21.46 Mg ha^{-1} between 2012 and 2019. Cassava yield varies depending on crop year, whereas soil carbon content decreases after CC-2P, but increases after NTC-4P.

Index terms: *Manihot esculenta*, *Urochloa brizantha*, carbon, crop-livestock integration, soil quality, straw.

Produtividade de mandioca em cultivo convencional e plantio direto em sistemas de integração lavoura-pecuária

Resumo – O objetivo deste trabalho foi avaliar a produtividade de mandioca (*Manihot esculenta*), bem como a densidade e o teor de carbono do solo, sob cultivo em plantio direto e convencional, em rotação com capim-marandu (*Urochloa brizantha*) submetido a pastejo. Os tratamentos consistiram de mandioca cultivada como a seguir: em plantio convencional após dois (CC-2P) e quatro (CC-4P) anos de pastagem; em plantio direto após dois (NTC-2P) e quatro (NTC-4P) anos de pastagem; e com pastagem perene (PP) de capim-marandu. O tratamento CC-2P apresentou maior produtividade de mandioca no ano-safra de 2016/2017 (63,29 Mg ha^{-1}) do que o NTC-2P (47,85 Mg ha^{-1}). No ano-safra de 2018/2019, não foram observadas diferenças significativas quanto à produtividade entre CC-4P (60,95 Mg ha^{-1}) e NTC-4P (60,68 Mg ha^{-1}). Entre 2012 e 2019, o teor de carbono no solo (0–10 cm) diminuiu no tratamento CC-2P. Em 2019, o estoque de carbono foi maior para o NTC-4P, em comparação aos de CC-4P e CC-2P, tendo aumentado de 16,41 Mg ha^{-1} a 21,46 Mg ha^{-1}. A produtividade da mandioca varia conforme o ano-safra, enquanto o teor de carbono no solo diminui após o tratamento CC-2P, mas aumenta após o NTC-4P.

Termos para indexação: *Manihot esculenta*, *Urochloa brizantha*, carbono, integração lavoura-pecuária, qualidade do solo, palhada.

Kátia Fernanda Gobbi[(1 ✉)],
Mário Takahashi[(1)],
Mateus Carvalho Basílio de Azevedo[(1)],
Jonez Fidalski[(1)] and
Simony Marta Bernardo Lugão[(1)]

[(1)] Instituto de Desenvolvimento Rural do Paraná – Iapar-Emater, Estação de Pesquisa de Paranavaí, CEP 87701-970 Paranavaí, PR, Brazil.
E-mail: kfgobbi@idr.pr.gov.br, takaha@idr.pr.gov.br, azevedo@idr.pr.gov.br, fidalski@idr.pr.gov.br, lugao@idr.pr.gov.br

✉ Corresponding author

Received
September 03, 2021

Accepted
May 20, 2022

How to cite
GOBBI, K.F.; TAKAHASHI, M.; AZEVEDO, M.C.B. de; FIDALSKI, J.; LUGÃO, S.M.B. Cassava yield in conventional and no-tillage cultivation in integrated crop-livestock systems. **Pesquisa Agropecuária Brasileira**, v.57, e02677, 2022. DOI: https://doi.org/10.1590/S1678-3921.pab2022.v57.02677.

Introduction

The northwestern region of Paraná, Brazil, the leading producer of beef cattle in the state, also stands out as one of the largest cassava producers in Brazil. The cities of Paranavaí and Umuarama, in this region, produced 2,249,800 metric tonnes of cassava alongside 93,300 ha, in the 2020/2021 crop year (Paraná, 2020). In this region, cassava crops usually occupy degraded pastures unable to meet sustainable and profitable livestock production levels.

The cultivation of cassava is usually done under conventional tillage, characterized by the mechanical manipulation of the soil with plowing and harrowing. This practice can be detrimental, since it results in the increase of soil losses by erosion, especially slowing the complete development of cassava canopy cover, and causing soil disturbance during harvesting (Figueiredo et al., 2017). In addition, no-tillage is a system rarely adopted by cassava producers.

Integrated crop-livestock systems (ICLS) are potentially sustainable alternatives for cassava and livestock production, including no-tillage cassava on pasture straws. The benefits of ICLS on grass straw is related to the improvement of soil attributes in degraded areas, such as soil organic matter content, better water infiltration/storage rates, and carbon sequestration (Salton et al., 2014; Cecagno et al., 2018), in comparison with a monoculture (Salton et al., 2011). Furthermore, sandy soils, such as those found in this region, greatly benefit from constant coverage due to decreases of erosion processes.

Despite the beneficial effects of no-tillage, yield variability is observed in different types of soil, and this contributes to the non-adoption of the conservative management for cassava (Fasinmirin & Reichert, 2011).

There are few studies on the effect of tillage on the productivity of cassava tuberous roots, and the results obtained are divergent. Pequeno et al. (2007) and Figueiredo et al. (2014) have shown that no-tillage resulted in the decrease cassava yield; however, Otsubo et al. (2012) showed that no-tillage can provide higher production, although in some cases there are no differences between conventional and no-tillage cassava yield (Otsubo et al., 2008). It is also important to report that no literature was found on cassava cultivation in crop-livestock systems in rotation with well-managed pasture areas under grazing and with adequate fertilization.

The objective of this work was to evaluate cassava crop yield, as well as soil bulk density and carbon content, under no-tillage and conventional cultivation, in rotation with palisade grass subjected to grazing.

Materials and Methods

The experiment was carried out at the Estação Experimental de Paranavaí (23.092°S; 52.444°W) of the Instituto de Desenvolvimento Rural do Paraná – Iapar-Emater (IDR-Paraná), in the state of Paraná, Brazil. The soil is classified as a Latossolo Vermelho distrófico típico, according to the Brazilian Soil Classification System (Santos et al., 2018), that corresponds to a Ustox Acrustox Oxisol (Soil Survey Staff, 2015), containing 100 g kg^{-1} clay, 20 g kg^{-1} silt, and 880 g kg^{-1} sand, at a 0–20 cm soil depth. According to the Köppen-Geiger's classification, the regional climate is Cfa, subtropical (mesothermal) with hot summers, infrequent frosts, and a tendency to concentrate rainfall in the summer months.

An integrated crop-livestock system with the cultivar *Manihot esculenta* IPR B-36 and palisade grass *Urochloa brizantha* 'Marandu' (Syn. *Brachiaria brizantha* 'Marandu') was used.

The experiment was carried out in a randomized complete block design, with five treatments and four replicates, totaling 20 plots with an average area of 800 m^2. Treatments were as follows: cassava subjected to conventional tillage (CC-2P), with soil preparation using a harrow, moldboard plow, and leveling harrow, followed by 2 years of pasture; cassava subjected to no-tillage on palisade grass straw (NTC-2P), followed by 2 years of pasture; cassava in conventional tillage followed by 4 years of pasture (CC-4P); cassava in no-tillage followed by 4 years of pasture (NTC-4P); and perennial palisade grass pasture (PP).

After liming, soil was prepared with harrow, moldboard plow, and leveling harrow. Fertilization was undertaken with a no-till seeder with 17 cm row-spacing, and pure viable seed of palisade grass at 4 kg ha^{-1} was sown at 3 cm soil depth, on February 22, 2012. As no grazing was performed on palisade grass before the cassava planting, the pasture was desiccated, using glyphosate (on July 3, 2012), and provided straw coverage with 4,518 kg ha^{-1} dry mass (DM).

The first cassava croppings under no-tillage and conventional systems were planted between August 2012 and December 2013 on the recently established palisade grass straw. No effect from the 2- and 4-year treatments is expected in this case.

Palisade grass was replanted on January 31, 2014. Top-dressing was performed on March 18, 2014, with 33 kg ha^{-1} N and 90 kg ha^{-1} K_2O. Grazing started on April 22, 2014, using two livestock groups: one for CC-2P and NTC-2P, and other for CC-4P and NTC-4P.

Rotational grazing was used in the areas with palisade grass – cassava integration, by the put-and-take technique to adjust animals for the available forage (Table 1).

Each paddock was separated by electrical fences and had four testers and a variable number of regulatory animals according to forage availability. The animals were crossbred bulls (Purunã × Nellore, and Purunã × Red Angus). Stocking rate was calculated by dividing the animal load (kg ha^{-1} per day) by 450 kg body mass (1 AU). The animal weight was obtained by summing the average weight and multiplying it by the number of grazing days. The result was divided by the number of days of paddock occupation and multiplied by the paddock area.

In both crop years, the animals remained in the same area until March, after five rotations of summer grazing and, then, were the animals were removed from the system, to allow of the accumulation of palisade grass dry matter for straw formation. The amount of palisade grass DM was estimated immediately before desiccation, to implement the rotation with cassava by weighing four samples per square meter per plot. The samples were dried at 65°C, for 72 hours, in a stove.

The planting in the 2016/2017 crop year occurred on July 20, 2016, at 0.9 m between rows, and 0.6 m between plants in the row, in a total of 18,519 ha^{-1} plants; pruning was performed on July 12, 2017, and harvest on January 23, 2018.

The observed climate conditions were within the regional historical average for 2016, but rainfall was 21% greater (320 mm) in 2017 (Figure 1).

Table 1. Crop rotation schedule of cassava (*Manihot esculenta*) and palisade grass (*Urochloa brizantha* 'Marandu') pasture in the experimental plots of the integrated crop-livestock systems.

System[(1)]	2011/2012 crop year		2012/2013 crop year		2013/2014 crop year	
	Summer	Winter	Summer	Winter	Summer	Winter
PP	Pasture	Pasture	Pasture	Pasture	Pasture	Pasture
CC-2P	Pasture	Cassava	Cassava	Cassava	Cassava	Pasture
NTC-2P	Pasture	Cassava	Cassava	Cassava	Cassava	Pasture
CC-4P	Pasture	Cassava	Cassava	Cassava	Cassava	Pasture
NTC-4P	Pasture	Cassava	Cassava	Cassava	Cassava	Pasture
	2014/2015 crop year		2015/2016 crop year		2016/2017 crop year	
	Summer	Winter	Summer	Winter	Summer	Winter
PP	Pasture	Pasture	Pasture	Pasture	Pasture	Pasture
CC-2P	Pasture	Pasture	Pasture	Cassava	Cassava	Cassava
NTC-2P	Pasture	Pasture	Pasture	Cassava	Cassava	Cassava
CC-4P	Pasture	Pasture	Pasture	Pasture	Pasture	Pasture
NTC-4P	Pasture	Pasture	Pasture	Pasture	Pasture	Pasture
	2017/2018 crop year		2018/2019 crop year		2019/2020 crop year	
	Summer	Winter	Summer	Winter	Summer	Winter
PP	Pasture	Pasture	Pasture	Pasture	Pasture	Pasture
CC-2P	Cassava	Pasture	Pasture	Pasture	Pasture	Cassava
NTC-2P	Cassava	Pasture	Pasture	Pasture	Pasture	Cassava
CC-4P	Pasture	Cassava	Cassava	Cassava	Cassava	Pasture
NTC-4P	Pasture	Cassava	Cassava	Cassava	Cassava	Pasture

[(1)]PP, perennial palisade grass pasture; CC-2P, cassava subjected to conventional tillage, with soil preparation using a harrow, moldboard plow, and leveling harrow, followed by 2 years of pasture; NTC-2P, cassava subjected to no-tillage on palisade grass straw, followed by 2 years of pasture; CC-4P, cassava in conventional tillage followed by 4 years of pasture; and NTC-4P, cassava in no-tillage followed by 4 years of pasture.

DOI: 10.1590/S1678-3921.pab2022.v57.02677

Basal dressing was performed on December 7, 2016, with 140 kg ha^{-1} single superphosphate (18% P_2O_5), and topdressing, with 190 kg ha^{-1} potassium chloride (60% K_2O) and 120 kg ha^{-1} urea (45% N).

Cassava was planted on August 7, 2018, for the 2018/2019 crop year, at the same spacing and population (18,519 ha^{-1} plants) of the 2016/2017 crop year. Pruning was performed on July 9, 2019, and the roots were harvested on December 9, 2019. Observed rainfall averages were 6.5% (2018) and 23% (2019), which is below the regional historical average (Figure 1).

Basal dressing was performed with 120 kg ha^{-1} of single superphosphate (18% P_2O_5); and top-dressing, with 180 kg ha^{-1} of potassium chloride (60% K_2O) and 150 kg ha^{-1} ammonium sulfate (20% N), on October 2, 2018. The cassava sample area was 54 m^2 in each plot (6 × 10 m long rows). A fluffer tool was used to loosen the roots and facilitate the operation.

The cassava harvest evaluation considered the final stand of plants per hectare, number of tuberous roots per plant (total number of roots divided by the total number of plants in the plot), fresh and dry root yields (oven at 65°C, until constant weight). The dry root yields were obtained through the correction of fresh root yields by the DM percent.

Soil bulk density was evaluated through one undeformed sample per experimental plot from the beginning of the experiment period, before carrying out the treatments (October 2012) and before harvesting the last cassava crop year (October 2019), using metal cylinders (5 cm height per 5 cm diameter) at 0–10 and 10–20 cm soil depth. The samples were dried in an

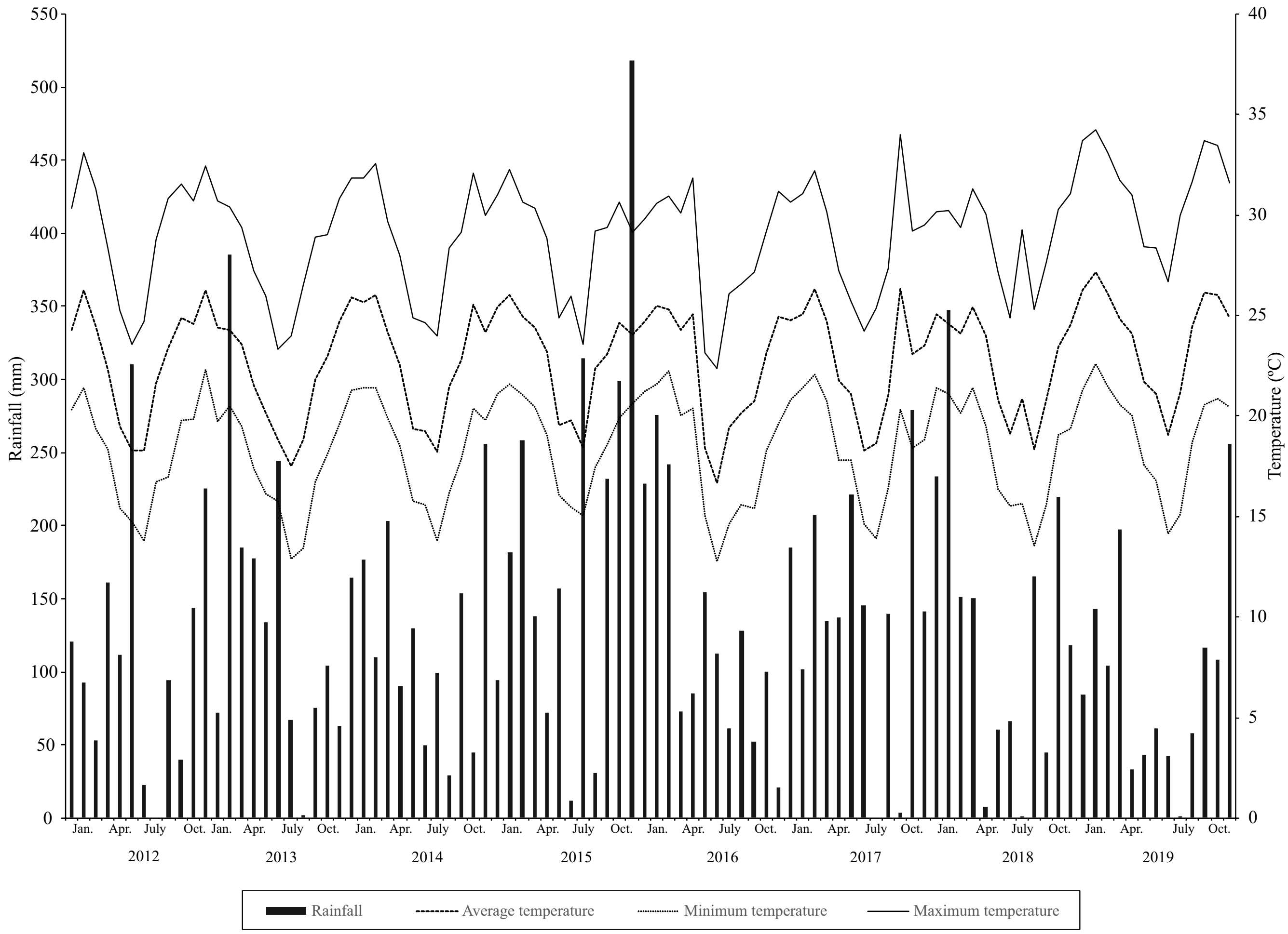

Figure 1. Rainfall, maximum, and minimum temperatures during the experimental period. Source: weather station in the Instituto de Desenvolvimento Rural do Paraná, in the municipality of Paranavaí, in the state of Paraná, Brazil.

oven at 105°C, for 48 hours, to obtain the soil bulk density (Teixeira et al., 2017).

Deformed soil samples were collected in October 2018 and October 2019, to determine the soil C content through the method of Walkley and Black (Teixeira et al., 2017). The apparent density and thickness of the studied soil layer were used to calculate the carbon content per area unit (Fernande & Fernandes, 2013). Soil C stocks were calculated through the C content and the apparent density at 0–10 and 10–20 cm soil depths, according to the following equation: C stock = ($SOC_i \times BD_i \times t$) /10), where SOC_i, BD_i, and “t” represent respectively: the soil organic C content (g kg^{-1}), soil bulk density (g cm^{-3}), layer thickness (cm), and i^{th} soil layer thickness (cm).

The cassava production results were subjected to the analysis of variance, using the F-test at 5% probability. Soil bulk density, C content, and soil C stock were evaluated by comparing treatments, using plots subdivided through the time, with treatments into the plots, and years into subplots. Significant interactions were unfolded, and means were compared by the Tukey’s test, at 10% probability. The analysis was performed using the SAS v. 9.4 software (SAS Institute Inc., Cary NC, USA).

Results and Discussion

The average stocking rate per year on the palisade grass pasture, until the cassava 2016/2017 crop year (CC-2P and NTC-2P), was 9.3 animals ha^{-1} (6.9 AU ha^{-1}), and the average forage DM production reached 7,970 kg DM ha^{-1} before desiccation. In the 2016/2017 crop year, when cassava was cultivated after 2 years of pasture, the average stand of palisade grass showed 99.65% of plants, and there were no significant differences between the conventional and no-tillage systems.

The conventional system showed significant differences for the number of roots per plant, and for fresh and dry root yields, in comparison with the no-tillage system, in the 2016/2017 crop year (Table 2). Similar results were reported for 'Mombasa' grass (*Panicum maximum* 'Mombasa'), with higher values in conventional and minimum tillage compared with no-tillage (Takahashi & Fidalski, 2019). Our results differ from those obtained by Gobbi et al. (2019), who did not observe differences among conventional and no-tillage systems preceded by different amounts of palisade grass. Figueiredo et al. (2014) did not observe different dry root yields and root numbers in cassava under conventional and no-tillage on black oat straw. In the rotation with 2 years of pasture, correlations were observed between fresh root yields (r = 0.91**), dry root yields (r = 0.92**), and the number of roots per plant, that is, this production component maintained the lowest productivity under no-tillage.

In the 4 years of pasture, before the cassava 2018/2019 crop year (CC-4P and NTC-4P), the stocking rate of 9.6 animals per hectare (6.5 AU ha^{-1}) was obtained, with forage accumulation reaching 2,093 kg ha^{-1} DM before the planting of cassava. This crop year did not show differences between conventional and no-tillage systems, after 4 years of pasture for its stand, as well as for the number of roots per plant and for the wet, fresh, and dry yields of cassava roots. The average stand had 94,57% of plants evidencing again the adequate planting by the planter in both planting systems. The root DM was higher in no-tillage than that of the conventional system (Table 3). The similarity of results between the conventional and no-tillage systems for the number of roots per plant and the yield of fresh

Table 2. Final stand of plants, number of roots per plant (NRP), root dry matter (RDM), and fresh (FRY) and dry root yields (DRY) of cassava (*Manihot esculenta*) cultivated in conventional and no-tillage systems in the 2016/2017 crop year, after 2 years of pasture[(1)].

Treatment		Final stand	Roots			
Pasture	Cassava system	(plants ha^{-1})	NRP	RDM (%)	FRY (Mg ha^{-1})	DRY (Mg ha^{-1})
2 years	Conventional	18,422.25a	5.02a	37.27a	63.29a	23.59a
2 years	No-tillage	18,470.50a	3.41b	36.62a	47.85b	17.58b
Mean		18,446.37	4.21	36.94	55.57	20.58
CV (%)		6.29	8.05	1.61	7.25	7.89

[(1)]Means followed by equal letters in the columns, do not differ by the F-test, at 5% probability.

and dry roots differ from those obtained by Devide et al. (2017) and Pequeno et al. (2007) who evaluated cassava crops preceded by different forage plants and obtained higher results in the conventional tillage system than those of the no-tillage system. There were also no differences for the productivity of fresh root yields in conventional tillage, in comparison to no-tillage, according to Reichert et al. (2021).

Results differed among the treatments under 2 years of pasture, and the conventional system overcame the no-tillage cultivation for the number of roots per plant, and for fresh and dry root yields (Table 2). The 2018/2019 crop year was under dry weather with rainfall lower than the regional average, which is the opposite of the 2016/2017 crop year. Not only may these conditions have influenced the lower production of palisade grass DM, but they may have also affected the cassava productivity under both the conventional and no-tillage systems. The different results showed by the two croppings may be intimately related to the preceding culture and type of straw. Some authors, for instance, prepared and cultivated cassava, with different results in their studies, as follows: Reichert et al. (2021), after corn and soybean; Takahashi & Fidalski (2019), after 'Mombasa' grass; Gobbi et al. (2019), after palisade grass; and Devide et al. (2017), after sorghum, crotalaria, *Brachiaria ruziziensis*, and *Brachiaria decumbens*.

There was no interaction between year and treatments for soil bulk density of both evaluated layers, and a significant effect was observed only for the year (Table 4). Soil bulk density at 0–10 and 10–20 cm soil depths did not differ among treatments, when comparing the beginning (2012) and the end of the experimental period (2019). Soil preparation for conventional tillage did not affect soil bulk density in comparison with no-tillage with cassava, and the perennial pasture was statistically equal to integrated systems with cassava. On average, the evolution of bulk density in treatments over time showed significantly different results between 2012 and 2019. The lower density in 2012 can be attributed to the soil preparation

Table 3. Final stand of plants, number of roots per plant (NRP), root dry matter (RDM), and fresh (FRY) and dry root yields (DRY) of cassava (*Manihot esculenta*) cultivated in conventional and no-tillage systems in the 2018/2019 crop year, after 2 years of pasture[(1)].

Treatment		Final stand	Roots			
Pasture	Cassava system	(plants ha^{-1})	NRP	RDM (%)	FRY (Mg ha^{-1})	DRY (Mg ha^{-1})
4 years	Conventional	17,171.75a	6.63a	32.71b	60.95a	19.93a
4 years	No-tillage	17,719.00a	6.03a	33.75a	60.68a	20.46a
Mean		17,445.37	6.33	33.23	60.81	20.19
CV (%)		3.62	14.70	1.55	4.42	5.46

[(1)]Means followed by equal letters in the columns, do not differ by the F-test, at 5% probability.

Table 4. Soil bulk density – at 0-10 and 10-20 cm soil depths – under perennial pasture and conventional and no-tillage cassava (*Manihot esculenta*) systems in the 2012 and 2019 crop year, after 2 and 4 years of pasture[(1)].

Treatment		Soil bulk density (Mg m^{-3})		Mean	Soil bulk density (Mg m^{-3})		Mean
Pasture	Cassava system	2012	2019		2012	2019	
		0–10 cm layer			10–20 cm layer		
Perennial	-	1.50	1.61	1.55a	1.57	1.66	1.61a
2 years	Conventional	1.48	1.71	1.59a	1.54	1.66	1.60a
2 years	No-tillage	1.48	1.61	1.55a	1.64	1.69	1.67a
4 years	Conventional	1.52	1.56	1.54a	1.56	1.65	1.60a
4 years	No-tillage	1.43	1.60	1.51a	1.68	1.68	1.68a
Mean		1.48B	1.62A		1.60B	1.67A	

[(1)]Means of layers followed by equal letters – uppercases in the rows and lowercases in the columns – do not differ by Tukey's test, at 10% probability.

for the correction and treatments carried out. At the end of the experimental period, the soil bulk density showed no impeditive values for the farming activities in perennial pastures and integrated systems with cassava.

Soil bulk density between rows of cassava grown in no-tillage, conventional, and minimal preparations also showed no significant differences in a study performed by Takahashi & Fidalski (2019). The average density values at 0–10 and 10–20 cm soil depths were 1.58 and 1.72 Mg m^{-3}. When evaluating cassava productivity under different preparation methods on sandy loam soil, in Santa Maria, in the state of Rio grande do Sul, Brazil, Reichert et al. (2021) did not observe differences for soil densities among conventional and no-tillage systems at 0–5, 5–10, and 10–20 cm soil depths, and average yield values were 1.37, 1.46, and 1.61 Mg m^{-3}, respectively.

As to soil C content, an interaction was found between year and treatments at 0–10 cm soil depths (Table 5). There was a significant reduction of soil C content in that layer for cassava in the conventional system after 2 years of pasture, between 2012 and 2019, showing that a 2-year rotation with pasture was not sufficient to maintain carbon in the soil. Furthermore, soil tillage probably contributed to C loss through mineralization and erosion. The most positive effect of no-tillage is the maintenance of soil C content, as observed in a perennial pasture and no-tillage cassava treatments after 2 years of pasture and in conventional tillage after 4 years of pasture, according to Bayer et al. (2006).

The treatment with no-tillage cassava was the only one to show a significant increase of C content in that same layer after 4 years of pasture, therefore, it is a more sustainable option for those soils. The higher C content may be attributed to the synergism between integrated systems with a greater well-managed rotation period, associated with a quicker C increase caused by pasture desiccation to produce straw, which does not occur in perennial pastures.

The intensive management of tropical forage pastures like palisade grass, with the application of correctives and fertilizers, provides increased DM production in the aerial parts and roots, positively contributing to the C dynamics and nutrient cycles in integrated systems. This correct pasture management favors good economic and environmental results, since a more productive pasture can potentially mitigate greenhouse gas emissions, increasing the C sequestration capacity of the soil (Segnini et al., 2019; Sakamoto et al., 2020). However, in 2019, seven years after implementing the treatments, a significant difference could be observed among treatments with no-tillage cassava compared to conventional tillage, which showed a higher C content at 0–10 cm soil depths, due to a lower organic matter mineralization rate than the conventional tillage. The perennial pasture did not differ from other treatments for the C content (Table 5).

There was no variation for the soil C content, at the 10–20 cm soil depths, among years and treatments with an average of 6.44 g kg^{-1} (Table 5). The C dynamics decreased as depth increased, that is, showing an entirely dependence on root mass and decomposition. Another factor observed was the lower C content at 10–20 cm in comparison with the 0–10 cm soil depths, due to the quick decline of root mass along with the depth (Costa et al., 2012).

Table 5. Total carbon content in soil under perennial pasture and conventional and no-tillage cassava (*Manihot esculenta*) systems in the 2012 and 2019 crop year, after 2 and 4 years of pasture[(1)].

Treatment		Total soil carbon content (g kg^{-1})		Mean	Total soil carbon content (g kg^{-1})		Mean
Pasture	Cassava system	2012	2019		2012	2019	
		0–10 cm layer			10–20 cm layer		
Perennial	-	11.46Aa	11.77Aabc	11.62	6.47	6.16	6.32a
2 years	Conventional	11.44Aa	9.63Bc	10.54	6.87	6.85	6.86a
2 years	No-tillage	12.26Aa	12.15Aab	12.20	6.86	6.13	6.50a
4 years	Conventional	10.62Aa	10.93Abc	10.78	6.05	6.75	6.40a
4 years	No-tillage	11.50Ba	13.47Aa	12.49	6.10	6.17	6.14a
Mean		11.45	11.59		6.47A	6.41A	

[(1)]Means of layers followed by equal letters – uppercases in the rows and lowercases in the columns – do not differ by Tukey's test, at 10% probability.

Pastures accumulate large amounts of organic C in the soil, due to their high underground allocation, root renewals, and rhizodeposition, in addition to the incorporation of surface plant residues and feces/urine. The gross primary production of pastures represents the leading entry of C into the soil, estimated as 31.3 Pg C per year (31.3 10^{-9} Mg C per year) for tropical pastures (Lorenz & Lal, 2018).

The average C content at 10–20 cm soil depth did differ neither among treatments nor at the beginning and the end of the experimental period, with an average of 8.96 g kg^{-1} in 2012 and 9.0 g kg^{-1} in 2019. As per Sousa & Lobato (2004), the C content of 0.87% (8.7 g kg^{-1}) at 0–20 cm soil depths of sandy soil (<15% of clay) is classified as high. Thus, according to the averages, only treatments with conventional cassava after 4 years of pasture showed and adequate C content (8.59 g kg^{-1}) at 10–20 cm soil depths, while the other treatments showed a high C content.

Significant interaction was detected among years and treatments in soil C stock only at 0–10 cm soil depths (Table 6). Only the treatment for cassava under no-tillage had its C stock significantly increased after 4 years of pasture, when the beginning and end of the experimental period were compared.

The C stock did not differ among treatments in 2012, but the no-tillage system after 4 years of pasture showed a higher stock 7 years later that the conventional tillage systems, not differing from the perennial pasture and no-tillage system after 2 years of pasture (Table 6).

Pastures show different rates of annual C accumulation in the soil for up to 1 m depth, depending on the soil class, texture, use, management, and stabilization period, varying from 0.1 to 1.7 Mg ha^{-1} per year (Sá et al., 2015; Lorenz & Lal, 2018). Carbon stocks between 18 and 26 Mg ha^{-1} are considered adequate (Sousa & Lobato, 2004) for sandy soils with the average density of 1.5 g dm^{-3} at 10–20 cm soil depths. Carbon stocks above 26 Mg ha^{-1} are considered high.

At 0-20 cm soil depths, C stock showed no differences among treatments; however, at this layer, C stock was higher (29.54 Mg ha^{-1}) in 2019 than that (27.57 Mg ha^{-1}) in 2012. In the present study, the average C stock at 0–20 cm soil depths was already considered high at the beginning of the period (2012), and it was maintained at the end (2019), with an average increase of 1.97 Mg ha^{-1} in 7 years, and an annual C accumulation rate of 0.28 Mg ha^{-1} in the soil. Tropical pastures have a great potential to accumulate C in the soil, contributing to the mitigation of greenhouse gas emissions, especially when adequate grazing, fertilization, and crop-livestock integration (CLI) practices are employed (Almeida, 2020).

In a long-term CLI experiment, well-managed pasture systems reached the highest levels of C stock at 0–20 cm soil depths, followed by systems integrated with no-tillage soybean after 2 years of pasture (*B. decumbens* Stapf) (Salton et al., 2014). The pasture contributed to a greater biomass accumulation in the aerial part and roots. The authors also observed that the continuous conventional tillage system resulted in the lowest C stocks.

The results obtained in the present study confirm the importance of well-managed pastures in integrated cassava production systems – especially when the pasture remains in the system for longer periods (4 years) – as well as the use of no-tillage, which

Table 6. Carbon stocks in soil under perennial pasture and conventional and no-tillage cassava (*Manihot esculenta*) systems in the 2012 and 2019 crop years, after 2 and 4 years of pasture(1).

Treatment		Soil carbon stocks (Mg ha^{-1})		Mean	Soil carbon stocks (Mg ha^{-1})		Mean
Pasture	Cassava system	2012	2019		2012	2019	
		0–10 cm layer			10–20 cm layer		
Perennial	-	17.09Aa	18.94Aab	18.01	10.18	10.19	10.19a
2 crop years	Conventional	16.88Aa	16.43Ab	16.65	10.71	11.39	11.05a
2 crop years	No-tillage	18.23Aa	19.57Aab	18.90	11.26	10.37	10.82a
4 crop years	Conventional	16.16Aa	17.10Ab	16.63	9.41	11.12	10.27a
4 crop years	No-tillage	16.41Ba	21.46Aa	18.94	10.25	10.33	10.29a
Mean		16.95	18.70		10.36A	10.68A	

(1)Means of layers followed by equal letters – uppercases in the rows and lowercases in the columns – do not differ by Tukey's test, at 10% probability.

contributes to the increase of soil C stocks and to the maintenance of the soil physical quality.

Conclusions

1. Cassava (*Manihot esculenta*) yield varies according to the crop year, and it is higher in conventional tillage system.
2. Soil bulk density increases with time in both conventional and no-tillage systems.
3. Cassava grown in conventional tillage system, after two years of pasture cultivation, leads to the decrease of soil carbon content.
4. Cassava in no-tillage system, after four years of pasture cultivation, leads to the increase of soil carbon content and to a higher final carbon stock, in comparison to conventional tillage.

Acknowledgments

To Financiadora de Estudos e Projetos (Finep), for financial support.

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