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Green manure, a sustainable strategy to improve soil quality: a case study in an oxisol from northern Brazil

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Abstract

Cassava (*Manihot esculenta* Crantz) is an easy to manage crop with good tolerance to drought and low-fertility soils. Although chemical fertilization is known to improve cassava yield, little is known about the potential of legume green manures to enhance soil chemical properties and consequently increase crop production. Here we analyze how different legume green manures affect cassava root growth and soil quality in an oxisol from northern Brazil. In this field study, we evaluated the effect of four green manure treatments (no fertilization, Crotalaria, jack bean, and cowpea) on soil exchangeable cation contents, pH H_2O, pH KCl, ΔpH, exchangeable aluminum, sum of bases (SB), cation-exchange capacity (CEC), soil organic carbon (SOC), plant diameter, plant height, and root yield. Cowpea treatment was the most effective in increasing exchangeable cations, CEC, SB, and root yield, whereas jack bean treatment increased acid cations and SOC. A hierarchy of exchangeable cations was observed, $Ca^{2+}>Mg^{2+}>K^{+}$, a result likely associated with nutrient absorption by cassava plants. Plant diameter had a positive linear correlation with root yield. Overall, our results indicate that green fertilization positively influences SOC, minimizing the depletion of exchangeable cations and thereby preventing yield losses. Cowpea treatment, however, acted more broadly on the variables studied.

Keywords: Soil fertility, Green fertilization*, Manihot esculenta*, Soil Organic Matter, Acidic soil.

Introduction

Native to the Amazon basin, cassava (Manihot esculenta Crantz) is a major staple crop worldwide (Howeler et al., 2013). It is cultivated in Latin America, Africa, and Asia (Sarma and Kunchai, 1991; Howeler, 2014; Malik et al., 2020), in both tropical and subtropical countries. Cassava is mostly produced by small farmers and commonly re-ferred to as "food of the poor" and "bread of the tropics" (Oghenejoboh et al., 2021). It is one of the main root crops grown in adverse soil and climate conditions, representing a source of income and sub-sistence for more than 800 million people in developing countries (Burns et al., 2010). The roots are the main source of energy reserves, and the aerial part can be used as animal feed (Howeler et a., 2013).

In Brazil, this staple crop is a source of subsistence and income, having great soci-ocultural importance, as family farming is responsible for 87% of the national production (Fao, 2016). With 18.49 million tonnes produced on 1.19 million hectares of planted land in 2019, Brazil ranked fourth in worldwide cassava production (Fao, 2020). However, crop yield is usually limited by cultivation on marginal, acidic, low-fertility soils (Byju and Suja, 2020). Small changes in management practices could increase crop yield and soil quality (El-sharkawy, 1993). Although some studies have reported on the importance of chemical fertilization for increasing crop yield (Chua et al., 2020; Wasonga et al., 2020; Adiele et al., 2021), little is known about the fertilizing potential of green manure.

Even if field application of synthetic fertilizers can enhance crop yield, small farmers generally do not have access to these expensive inputs (Pimentel et al., 2021). Thus, green manures may serve as a source of fertility, increasing soil organic matter (Agbede, 2018), and promoting root development (Pypers et al., 2012). Amendment of soil with organic waste is even more important from a food security and soil health perspective, as cassava utilizes large amounts of nutrients (Bai et al., 2018). Green manures from legume crops may also increase soil carbon content, which, according to Chabbi et al. (2017), is essential to meet the goals international on CO2 emission reduction (e.g., Paris Agreement; Glasgow Climate Pact).

Green manure is a clean organic fertilizer source, especially from legumes that can fix nitrogen. Plant species used as green manure, in addition to promoting soil quality improvement, reduce the use of chemical fertilizers (Nascimento et al., 2021). Although the practice of green manure was little used, due to the easy availability and low cost of inorganic fertilizers (Egbe et al., 2022), recently, the price of inorganic fertilizers has doubled, due to the impacts of the war between Russia and Ukraine (Hassen and Bilali, 2022). In this context, the use of green manure is an effective alternative to help farmers, besides promoting positive impacts on the economy, especially in Northern Brazil. In view of the above, this study aims to test the following hypotheses: (i) green manure improves soil fertility, chemical properties, and exchangeable cation concentrations; (ii) legume green manure treatments increase soil organic carbon (SOC), whereas removal of legume residues leads to SOC depletion; and (iii) green manure can contribute to in-creasing crop yield in acidic, low-fertility soils. For this, we evaluate the influence of legume green manures on soil nutrient content, SOC, and agronomic variables of cassava grown in a clayey oxisol in a tropical climate region. Our results are expected to contribute to the management of cassava crop on Brazilian soils.

Results

Effect of green fertilization on soil active acidity, exchangeable acidity, and aluminum saturation

Soil pH H_2O ranged from 4.73 (beginning of crop cycle) to 5.67 (end of crop cycle) with legume green manure application. CR green manure increased pH H_2O by 0.94 pH compared with JB and CP green manures ($p < 0.05$). No differences in pH H_2O were observed between CR and NF treatments ($p < 0.05$). Green manure application did not significantly influence pH KCl ($p < 0.05$). Values ranged from 4.73 (NF) to 4.75 (CR), indicating that pH KCl remained stable compared with pH H_2O. The results show that pH H_2O (active acidity) was influenced over time by the use of legume green manure (Fig. 1).

ΔpH is calculated as the difference between pH H_2O and pH KCl (Fig. 2). ΔpH values revealed an abundance of negative charges in NF and CR treatments as well as near-zero values in JB and CP treatments. The increase in the number of negative charges was highest in the CR treatment (−0.922), which did not differ significantly from that in the NF treatment (−0.884), indicating a predominance of negative charges ($p < 0.05$). JB and CP treatments also did not differ in ΔpH values, which were close to zero, indicating that soil under these treatments tended to retain cations and anions in the same amount and proportion ($p < 0.05$).

The results for exchangeable acidity (represented by Al^{3+}) indicate a predominance of Al^{3+} in JB as compared with the other treatments. Exchangeable Al^{3+} contents ranged from 0.16 to 0.34 $cmol_c\ dm^{-3}$, with a difference of 0.18 $cmol_c\ dm^{-3}$ between CR (0.16 $cmol_c\ dm^{-3}$) and JB (0.34 $cmol_c\ dm^{-3}$) ($p < 0.05$, Fig. 3), representing a 53% increase. There were no significant differences in exchangeable Al^{3+} between the other treatments ($p < 0.05$, Fig. 3).

Similar results were observed for aluminum saturation, indicating that both variables followed the same pattern. There was higher saturation with Al^{3+} ions in JB (4.40%) than in other treatments, suggesting a potentially toxic effect of this fertilizer source on plant crops ($p < 0.05$, Fig. 3). The other treatments did not influence aluminum saturation, which remained stable ($p < 0.05$).

Influence of green manures on soil exchangeable cations and CEC

Exchangeable nutrient concentrations were strongly influenced by green manure treatments. The green manure application influenced soil K^+ and Ca^{2+} contents; however, Mg^{2+} content was not affected ($p < 0.05$, Fig. 4). K^+ content ranged from 0.08 $cmol_c\ dm^{-3}$ (NF) to 0.13 $cmol_c\ dm^{-3}$ (JB); these values are low for cassava crop, particularly for plants under NF. Green manure treatment was able to increase K^+ by 39% compared with NF ($p < 0.05$). Ca^{2+} was the cation with the highest content, which was higher in all green manure treatments (CR, JB, and CP) than in NF ($p < 0.05$). CP green manure increased soil Ca^{2+} content by 1.37 $cmol_c\ dm^{-3}$ compared with NF, representing an increase of 18%. For Mg^{2+}, soil contents did not differ between green manure treatments ($p < 0.05$, Fig. 4). In general, the findings revealed a hierarchy of exchangeable cations, with $Ca^{2+} > Mg^{2+} > K^+$, a result likely associated with nutrient absorption by cassava plants.

SB ranged from 6.62 to 8.19 $cmol_c\ dm^{-3}$; the highest SB was obtained by treatment with CP green manure. This treatment increased SB by 1.57 $cmol_c\ dm^{-3}$ or 19% compared with NF (Fig. 4). Green manures (CR, JB, and CP) increased the input of bases to soil compared with NF ($p < 0.05$, Fig. 4). A similar pattern was observed for CEC: all legume treatments (CR, JB, and CP) enhanced the parameter compared with NF ($p < 0.05$), although, as shown by absolute values, CEC was highest in CP (8.38 $cmol_c\ dm^{-3}$). Thus, it is likely that the increase in SB influenced CEC values. Overall, the data show that non-application of green manure may lead to loss of soil nutrients, resulting in reduced SB and CEC in the soil–plant system.

Contribution of green manure quality to soil organic carbon

After a short period of treatment with legume green manures, there was a subtle increase in SOC in the 0-20 cm layer. To better understand these results, it was necessary to draw a control line, allowing to observe an increment in SOC. SOC values ranged from 15.15 to 16.47 $g\ kg^{-1}$, and the highest value was observed in JB (Fig. 5), which increased SOC by 8% (1.3 $g\ kg^{-1}$) compared with NF ($p < 0.05$, Fig. 5). Overall, application of JB green manure increased SOC, whereas NF led to SOC depletion in the studied soil layer.

Effect of short-term fertilization on cassava yield

Cassava yield parameters were consistently influenced by green manure quality ($p < 0.05$). Cassava diameter was influenced by treatments. JB-treated plants exhibited the smallest diameter (15.59 mm) ($p < 0.05$). A reduction of 2.26 mm or 12% in diameter was promoted by JB compared with NF ($p < 0.05$, Fig. 6). No significant differences in diameter were observed between the other treatments. Interestingly, plant height was increased by 1.14 m with JB treatment, resulting in a total height of 3.59 m, although this effect did not differ from those of other treatments ($p < 0.05$, Fig. 6). In summary, JB treatment increased plant height and reduced diameter.

Yield parameters differed according to the green manure treatment applied ($p < 0.05$). Root yield ranged from 8.60 to 13.77 $t\ ha^{-1}$. CP green manure increased yield by 1.96 $t\ ha^{-1}$ or 14% compared with NF. On the other hand, JB green manure resulted in a low yield: a reduction of 5.17 $t\ ha^{-1}$ or 38% was observed in comparison with CP ($p < 0.05$, Fig. 6). Thus, it was observed that JB green manure reduced plant diameter and root yield but enhanced plant height.

Relationship between the evaluated attributes

To gain a better understanding of the influence of legume green manure treatments on cassava crops, we subjected the experimental data to PCA and correlation analysis. PCA results are depicted in Figure 7. PC1 and PC2 explained 33.8% and 21.6% of the variance in the dataset, respectively.

PCA results clearly showed the influence of treatments on the variables. JB strongly influenced aluminum saturation, Al^{3+}, and ΔpH, which were correlated with PC2. CP treatment, however, acted more broadly on the variables.

Pearson correlation analysis revealed direct relationships between soil attributes, agronomic variables, and SOC (Fig. 8). Aluminum saturation was positively and linearly correlated with Al ($r = 0.93$; $p < 0.05$) and negatively correlated with SB ($r = -0.64$; $p < 0.05$), Ca ($r = -0.60$; $p < 0.05$), and CEC ($r = -0.58$; $p < 0.05$). Ca^{2+} significantly influenced SB ($r = 0.98$; $p < 0.01$) and CEC ($r = 0.97$; $p < 0.01$). Among crop variables, it was observed that plant diameter had a positive linear correlation with root yield ($r = 0.79$; $p < 0.05$).

Discussion

Response of active acidity, exchangeable acidity, and aluminum saturation to green manures

The pH H_2O and pH KCl values were low for all treatments. Such a result was expected, given that Brazilian soils are known to exhibit strong acidity (Santos et al., 2018; Silva et al., 2018). Values of active acidity are related to the concentration of H^+ in soil solution; this characteristic is intrinsic to soil formation processes (Jenny, 1941). In the case of the study soil, strong weathering caused by climatic conditions led to a loss of bases and an increase in acids, resulting in an acidic soil (Lu et al., 2015; Jiang et al., 2018).

In assessing the effects of JB and CP on soil, we found an increase in H^+ concentration in soil solution, likely associated with the increase in biomass input on the surface soil. The presence of plant residues resulted in the formation of organic matter, which contains different functional groups that can release H^+, tending toward acidification of already acidic soils (Torabian et al., 2019). It is noteworthy that, as plants absorb exchangeable bases (Ca^{2+}, Mg^{2+}, and K^+), the concentration of these elements in soil solution decreases, causing an imbalance. Thus, the solid phase recovers these elements to maintain balance, thereby increasing the negative charges that can be occupied by H^+. Another factor related to acidification is the increase in soil microbial populations, stemming from an increase in nitrogen (Averill and Waring, 2018) from legume decomposition and enhanced root exudation, which releases H^+ (Pegoraro et al., 2018).

Green manure application influenced soil charges. The soil was naturally electro-negative (NF), attributed to the adsorption of anions onto soil mineral colloids (D'Acqui et al., 1999). We had hypothesized that there would be a greater contribution of positive charges in soil, given that tropical soils are highly weathered, leading to the retention of a large amount of iron and aluminum oxides in the clay fraction (Ramos et al., 2018). JB and CP treatments resulted in ΔpH values close to zero, indicating the ability of soil to retain cations and anions at the same ratio. These findings are in agreement with those of Benites and Mendonça (1998), who found that changes in the soil system may alter soil charge, favoring an increase in variable charges. The reduction in pH observed in JB and CP treatments might be associated with the increase in positive charges.

The increase in Al^{3+} and aluminum saturation in JB treated plots compared with other treatments can be related to the reduction in pH. Al^{3+} is an acid cation adsorbed onto soil colloids by electrovalence; therefore, if the concentration of Al^{3+} increases, pH tends toward acidification, as observed in our results (Pimentel et al., 2020). In fact, determination of Al^{3+} content is essential to better understand crop performance in acidic soils (Tandzi et al., 2018), as Al^{3+} may be toxic to plants. The results indicate that the effective CEC of soil (SB + Al^{3+}) was mainly represented by Al in the JB treatment.

Response of soil exchangeable cations, SB, and effective CEC to green manures

The reduction of K^+ content in the NF treatment at the end of the experiment confirmed that cassava plants absorb large amounts of K^+ during the crop cycle (Fig. 4), in agreement with previous reports showing that K^+ is one of the major nutrients absorbed by cassava (Fernandes et al., 2017; Biratu et al., 2018). K^+ content increased by up to 39% with green manure application compared with NF, resulting in an intermediate soil K^+ content (Cravo et al., 2020). Thus, the use of legume green manure allowed meeting the crop's K^+ requirement. Accumulation of excess K^+ in soil results from fertilization and indicates that crop requirements were met (Rós et al., 2013).

Cassava absorbs large amounts of both K^+ (Xie et al., 2020) and Mg^{2+} (Howeler, 2002); it was therefore expected that soil would have lower contents of these nutrients at the end of the crop cycle in NF plots (Chua et al., 2020). Furthermore, K^+ is monovalent and can be easily lost by leaching, a common phenomenon in tropical regions (Pimentel et al., 2020). This highlights the importance of applying green manure to soil. Ca^{2+} levels were considered high in all green manure treatments (Byju and Suja, 2020), attributed to the low rate of release of this nutrient from legume decomposition (Perin et al., 2010). Because Ca^{2+} is bivalent, it is more strongly retained in soil colloids compared with K^+, resulting in minimum losses.

Green fertilizers were efficient in increasing SB and CEC (Fig. 4). The highest values were obtained with CP treatment, explained by the high quality and biomass input of this green manure. CP shows potential as a green manure for cassava because it grows under similar climatic, edaphic, and ecological conditions, in addition to fixing nitrogen (Suja et al., 2021). The contribution of legumes to SB and CEC is related to their role in nutrient cycling (Fernandes et al., 2021). Thus, the results suggest that green manure treatments increase Ca^{2+} and Mg^{2+} contents, consequently enhancing SB and CEC values (Ambrosano et al., 2005).

Green manures have the potential to increase SOC

Understanding how small changes in crop management may result in the accumulation or depletion of SOC is of utmost importance. Soil is the main reservoir of SOC in the terrestrial ecosystem; it can store 1505 Pg (1 Pg = 109 t) of SOC at depths of up to 1 m (Lal, 2018). Carbon participation in the soil–plant–atmosphere system is dynamic, influenced by photosynthetic and respiration processes (Paustian et al., 2019). Therefore, small changes can contribute to the overall balance of carbon, reducing atmospheric CO_2 levels.

Our findings revealed a slight contribution of legumes to the increase in SOC. According to (Cotrufo et al., 2013), stabilization of SOC from legumes might be related to their low C/N ratios; residues are transformed into labile fractions when added to soil, reducing loss of SOC to the atmosphere because of the efficiency of the microbial substrate. The authors also reported that labile residues have greater ability to stabilize SOC over time in comparison with recalcitrant residues (high C/N ratio).

Table 1. Characterization of soil chemical and physical attributes before cassava planting in the layer 0-20 cm.

Soil property	Value
pH $CaCl_2$	5.4
pH H_2O	6.1
P (mg dm^{-3})	4.0
K (mg dm^{-3})	43.9
Ca^{2+} ($cmol_c$ dm^{-3})	3.4
Mg^{2+} ($cmol_c$ dm^{-3})	1.2
H + Al ($cmol_c$ dm^{-3})	4.0
SB ($cmol_c$ dm^{-3})	4.8
CEC ($cmol_c$ dm^{-3})	8.7
BS (%)	54.5
Sand (g kg^{-1})	173
Silt (g kg^{-1})	168
Clay (g kg^{-1})	659
OM (g dm^{-3})	37.8

P= phosphorus; K= potassium; Ca= calcium; Mg= magnesium; H= hydrogen; Al= aluminum; SB= sum of bases; CEC= cation-exchange capacity; BS= base saturation; OM= organic matter.

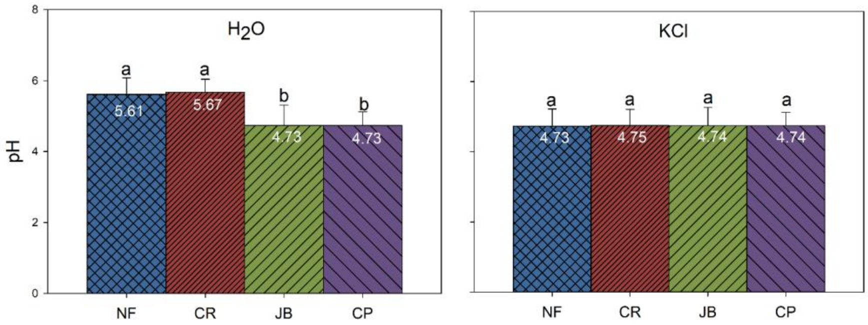

Fig 1. pH H_2O and pH KCl values of 0–20 cm depth soil under cassava crops subjected to different green manure treatments. NF, no fertilization; CR, Crotalaria; JB, jack bean; CP, cowpea. Different letters above bars indicate significant differences by Tukey's test ($p < 0.05$).

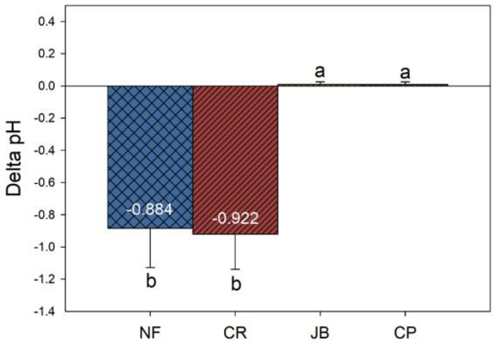

Fig 2. Net charge (ΔpH) of 0–20 cm depth soil under cassava crops subjected to different green manure treatments. NF, no fertilization; CR, Crotalaria; JB, jack bean; CP, cowpea. Different letters above bars indicate significant differences by Tukey's test ($p < 0.05$).

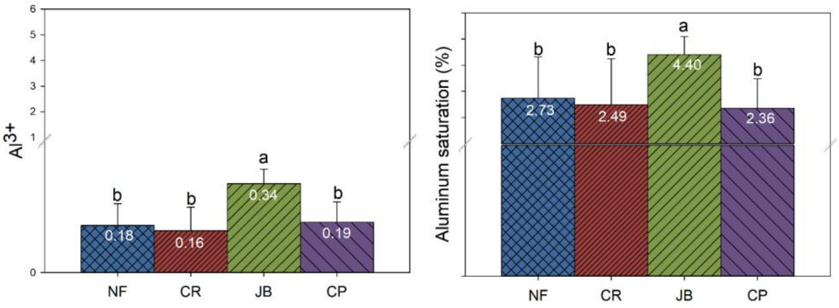

Fig 3. Exchangeable acidity (Al^{3+}) and aluminum saturation (%) of 0–20 cm depth soil under cassava crops subjected to different green manure treatments. NF, no fertilization; CR, Crotalaria; JB, jack bean; CP, cowpea. Different letters above bars indicate significant differences by Tukey's test ($p < 0.05$).

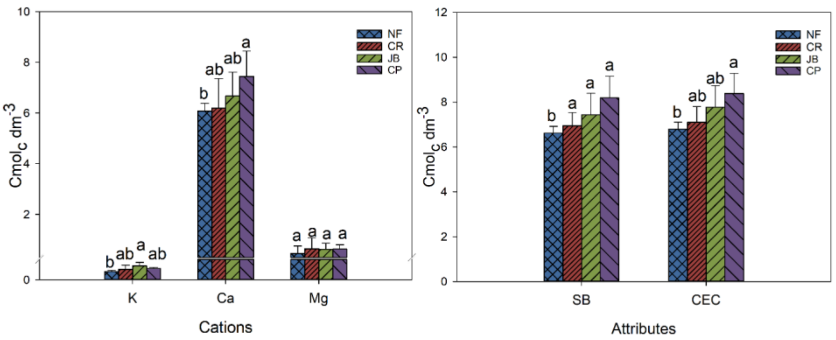

Fig 4. Soil exchangeable cations (K, Ca, and Mg), sum of bases (SB), and effective cation-exchange capacity (CEC) in the 0-20 cm layer under cassava crops subjected to different green manure treatments. NF, no fertilization; CR, Crotalaria; JB, jack bean; CP, cowpea. Different letters above bars indicate significant differences by Tukey's test ($p < 0.05$).

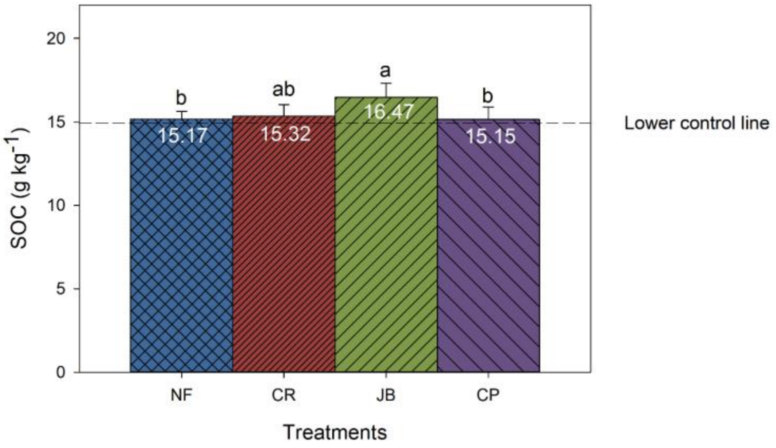

Fig 5. Soil organic carbon (SOC) contents in the 0–20 cm layer under cassava crops subjected to different green manure treatments. NF, no fertilization; CR, Crotalaria; JB, jack bean; CP, cowpea. Different letters above bars indicate significant differences by Tukey's test ($p < 0.05$). The dashed line rep-resents the lower control value, determined based on the NF treatment.

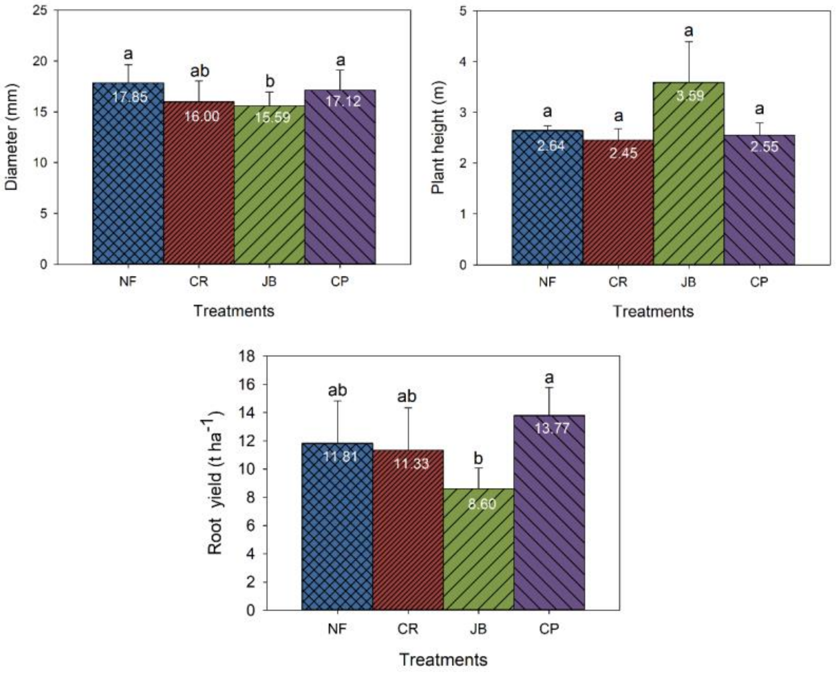

Fig 6. Diameter (mm), height (m), and root yield of cassava crops (t ha^{-1}) under different green manure treatments. NF, no fertilization; CR, Crotalaria; JB, jack bean; CP, cowpea. Different letters above bars indicate significant differences by Tukey's test ($p < 0.05$).

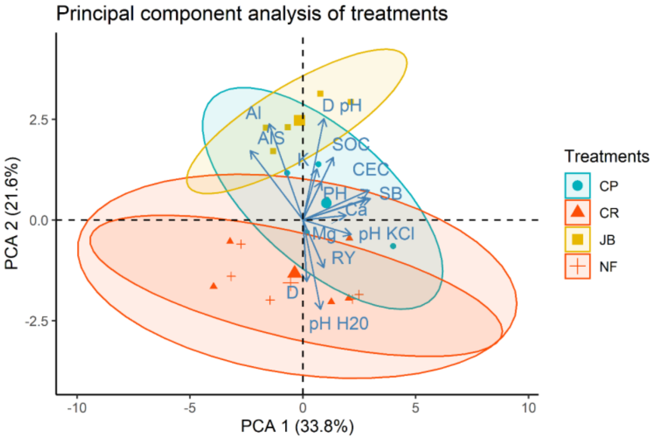

Fig 7. Principal component analysis of soil properties and plant characteristics for cassava crops under different green manure treatments. NF, no fertilization; CR, Crotalaria; JB, jack bean; CP, cowpea; D pH, ΔpH; Al, exchangeable aluminum; AlS, aluminum saturation; SOC, soil organic carbon; CEC, effective cation-exchange capacity; PH, plant height; SB, sum of bases; Ca, calcium; Mg, magnesium, RY, root yield; D, diameter.

pH H20													
0.63	pH KCl												
-0.71	0.10	D pH											
-0.48	-0.20	0.43	Al										
-0.41	-0.36	0.20	0.93	AlS									
-0.13	0.17	0.32	0.12	-0.06	SOC								
-0.22	0.29	0.54	0.15	0.06	0.38	K							
0.04	0.51	0.41	-0.31	-0.60	0.31	0.02	Ca						
0.16	0.35	0.12	-0.26	-0.44	0.51	0.22	0.29	Mg					
0.07	0.55	0.41	-0.34	-0.64	0.41	0.09	0.98	0.49	SB				
0.03	0.55	0.46	-0.26	-0.58	0.43	0.11	0.97	0.49	1.00	CEC			
0.13	0.10	-0.07	-0.27	-0.19	-0.37	0.03	-0.06	-0.06	-0.07	-0.09	D		
0.07	0.32	0.20	0.37	0.15	0.06	-0.05	0.31	0.09	0.30	0.34	0.01	PH	
0.10	0.21	0.06	-0.37	-0.35	-0.07	0.25	0.08	0.20	0.13	0.10	0.79	0.04	RY

Fig 8. Pearson correlation matrix for soil properties and cassava crop characteristics. D pH, ΔpH; Al, exchangeable aluminum; AlS, aluminum saturation; SOC, soil organic carbon; CEC, effective cation-exchange capacity; PH, plant height; SB, sum of bases; Ca, calcium; Mg, magnesium, RY, root yield; D, diameter. Blue and red squares indicate positive and negative correlations, respectively. Smaller squares and lighter colors represent weaker correlations, whereas larger squares and darker colors represent stronger correlations.

Tropical soils represent an opportunity in SOC sequestration, as they are below the storage limit when compared to temperate soils (Six et al., 2002), associated with this, the protection mechanisms of SOC (recalcitrance, occlusion, and association with minerals) assist in the storage over time (Lützow et al., 2006). However, it is emphasized that different types of soil have different potentials to store SOC; for instance, clay soils, such as the clayey oxisol of the current study, exhibit greater potential (Amelung et al., 2020). In addition, the increase in SOC in the JB treatment might be associated not only with the input provided by green manure but also with the biomass of the aerial part of cassava, given that JB enhanced plant height (Fig. 6). Plant residues may contribute to the accumulation of organic matter in soil (Pimentel et al. 2021). In general, covering soil with green manure may promote an increase in SOC level compared with lack of green manure application.

Response of crop yield to green manures and correlation between of the study variables

As expected, given that the study soil had low fertility, treatment with green manure substantially increased yield (Moura-Silva et al., 2017). Low crop yields are associated with inadequate supply of plant nutrients (Imakumbili et al., 2019). CP treatment was the most efficient in increasing crop yield, resulting in a value of 13.77 t ha^{-1}, which is higher than the overall average yield of cassava crop (10.71 t ha^{-1}) (Fao, 2016). By contrast, JB treatment reduced cassava yield (Fig. 6), a result attributed to the high Al^{3+} and aluminum saturation, leading to higher occupation of CEC by acid cations (Fig. 3). Al^{3+} toxicity tends to be more severe in acidic soils (Byju and Suja, 2020). Thus, although JB provided higher levels of SB and CEC than NF, this effect does not necessarily result in higher yields (Matos et al., 2021).

The increase in plant height by JB was associated with decreased yield. Similar results were reported by Misganaw and Bayou (2020) in an experiment with different cassava varieties. The authors found that root number decreased with increasing plant height, probably because assimilates were redirected to vegetative growth rather than root development. JB treatment reduced the formation of tuberous roots, indicating the occurrence of stress, which may reduce cell differentiation and result in delayed development of the root apical meristem (Shan et al., 2018).

Whereas CP enhanced yield, NF and CR treatments resulted in intermediate yield levels. Cassava is a rustic plant that can grow in low fertility soils under drought, an attractive feature for farmers (Adu et al., 2018). However, fertilization is known to increase yield. Our results show that the use of CP green manure increased crop yield, attributed to several direct and indirect factors such as those mentioned by Madembo et al. (2020), namely good nitrogen fixation ability, weed reduction, and soil cover.

SB, CEC, and Ca^{2+} contributed greatly to PC1, whereas acidity attributes contributed to PC2, indicating that soil related characteristics were important to explain the variance in the data. It can be inferred that soil fertilization influences crop yield (Kintché et al., 2017), positively by increasing SB, CEC, and Ca^{2+} and negatively by increasing soil acidity. Acidity attributes were clearly associated with JB. Low nutrient content and the presence of toxic elements may compromise the formation of tuberous roots (Ezui et al., 2016; Kintché et al., 2017).

Correlation analysis complemented the results of PCA, demonstrating that soil bases may increase SB and CEC, which was related to the high Ca^{2+} content provided by green manures (Araújo et al., 2019). Thus, high Ca^{2+} content is associated with increased SB and CEC, whereas high Al^{3+} content is associated with increased aluminum saturation (Pimentel et al., 2020). Correlation coefficients between variables contribute to the understanding of data, as they relate to PCA loadings (Adu et al., 2018). It is important to analyze the attributes that most influence crop yield for informed decision-making about fertilization.

Material and methods

Experimental site

A field experiment was conducted between 2017 and 2018 in Santarém (2°44'S 54°31'W, 145 m elevation), Pará State, Brazil. The chosen site is located in a major cassava-producing region. The soil was classified as a "Latossolo Amarelo", according to Brazilian Soil Classification System (Santos et al., 2018), this is, "oxisol", according to Soil taxonomy (Soil Survey Staff, 2014).

Description of the field experiment

Prior to the installation of the experiment, soil physicochemical properties were determined according to the methods described by Teixeira et al. (2017) (Table 1). Liming was performed based on the results of soil analysis. Harrowing was performed to improve soil physical structure. Cassava cuttings were planted in March 2017 and harvested in July 2018.

The cultivar used was 'Bem-Te-Vi', the most common genetic clone planted in the region. The experimental area was 35 × 28 m, totaling 980 m², with a spacing of 1 × 1 m between cassava plants. Legume residues were left on the soil surface. We used a block design with four treatments and five replications, totaling 20 experimental plots. Each plot measured 36 m² (6 × 6 m). Treatments were as follows: no green fertilization (NF), Crotalaria (CR), jack bean (JB), and cowpea (CP). Biomass management was carried out manually by intercropping the legumes with cassava, as recommended Cravo et al. (2020).

Soil sampling and determination of chemical properties and soil organic carbon

At the end of the cassava crop cycle, soil samples were collected from the 0-20 cm depth layer to assess soil chemical properties and SOC. Disturbed samples were used for determination of pH H_2O, pH KCl, ΔpH, K^+, Ca^{2+}, Al^{3+}, Mg^{2+}, sum of bases (SB), effective cation-exchange capacity (CEC), and aluminum saturation (Teixeira et al., 2017). For SOC determination, soil samples were air-dried, divided into 10 g aliquots, ground, and passed through an 80-mesh sieve. Carbon concentration was measured by wet oxidation with potassium dichromate (Yeomans and Bremner, 1988).

Determination of crop characteristics

After harvest, plant height was measured by using a graduated ruler and stem diameter was determined at the median part of plants by using a digital caliper. Root yield (t ha^{-1}) was calculated from the weight of tuberous roots, which was measured on a digital scale at the end of the crop cycle.

Statistical analysis

Data were analyzed for homogeneity of variance by Bartlett's test and for normality by the Shapiro -Wilk test. Analysis of variance (ANOVA) at the 5% significance level was used to assess the effect of green fertilizers on soil chemical properties, SOC, and crop characteristics. When treatment effects were significant by the F-test ($p < 0.05$), means were compared by Tukey's test ($p < 0.05$). Statistical analyses were performed using a randomized block design. Principal component analysis (PCA) and Pearson correlation analysis were used to compare responses between study variables. All statistical analyses were performed using R software (R core team, 2020).

Conclusion

Application of green fertilizers improved soil fertility and cassava root yield. After a crop cycle, we observed that JB green manure treatment promoted an increase in acid cations but also enhanced carbon incorporation into soil. CP green manure application was the most effective in increasing crop yield. Overall, the results showed that exchangeable soil cations, SB, and CEC were important for obtaining high crop yields. In comparing the results of managed and unmanaged soils, we concluded that, although cassava crops can develop well in acidic conditions, root yield is higher with green manure treatment. However, given that these observations were based on a short-term field experiment, we emphasize that more research is needed to understand the long-term effects of green manure practices on cassava crop and soil fertility.

References

Adiele JG, Schut AGT, Ezui KS, Pypers P, Giller KE (2021) Dynamics of N-P-K demand and uptake in cassava. Agron Sustain Dev. 41:1–14.

Adu MO, Asare PA, Asare-Bediako E, Amenorpe G, Ackah FK, Afutu E, Amoah MN, Yawson DO (2018) Characterising shoot and root system trait variability and contribution to genotypic variability in juvenile cassava (*Manihot esculenta* Crantz) plants. Heliyon. 4:e00665.

Agbede TM (2018) Effect of Green Manure Application on Cassava (*Manihot esculenta* Crantz) Growth, Yield Quantity and Quality in Degraded Alfisols. Pertanika J Trop Agric Sc. 41:1757–1777

Ambrosano EJ, Trivelin PCO, Cantarella H, Ambrosano GMB, Schammass EA, Guirado N, Rossi F, Mendes PCD, Muraoka T (2005) Utilization of nitrogen from green manure and mineral fertilizer by sugarcane. Sci Agric. 62:534–542.

Amelung W, Bossio D, de Vries W, Kögel-Knabner I, Lehmann J, Amundson R, Bol R, Collins C, Lal R, Leifeld J, Minasny B, Pan G, Paustian K, Rumpel C, Sanderman J, van Groenigen JW, Mooney S, van Wesemael B, Wander M, Chabbi A. (2020) Towards a global-scale soil climate mitigation strategy. Nat Commun. 11:1–10.

Araújo FS, Barroso JR, Freitas L de O, Teodoro MS, de Souza ZM, Torres JLR (2019) Chemical attributes and microbial activity of soil cultivated with cassava under different cover crops. Rev Bras Eng Agrícola e Ambient. 23:614–619.

Averill C, Waring B (2018) Nitrogen limitation of decomposition and decay: How can it occur? Glob Chang Biol. 24:1417–1427.

Bai Z, Caspari T, Gonzalez MR, Batjes NH, Mäder P, Bünemann EK, de Goede R, Brussaard L, Xu M, Ferreira CSS, Reintam E, Fan H, Mihelič R, Glavan M, Tóth Z (2018) Effects of agricultural management practices on soil quality: A review of long-term experiments for Europe and China. Agric Ecosyst Environ. 265:1–7.

Benites VM, Mendonça ES (1998) Propriedades eletroquímicas de um solo eletropositivo influenciadas pela adição de diferentes fontes de matéria orgânica. Rev Bras Ciência do Solo. 22:215–221.

Biratu GK, Elias E, Ntawuruhunga P, Sileshi GW (2018) Cassava response to the integrated use of manure and NPK fertilizer in Zambia. Heliyon. 4:e00759.

Burns A, Gleadow R, Cliff J, Zacarias A, Cavagnaro T (2010) Cassava: The Drought, War and Famine Crop in a Changing World. Sustainability. 2:3572–3607.

Byju G, Suja G (2020) Mineral nutrition of cassava. Adv Agron. 159:169–235.

Chabbi A, Lehmann J, Ciais P, Loescher HW, Cotrufo MF, Don A, SanClements M, Schipper L, Six J, Smith P, Rumpel C (2017) Aligning agriculture and climate policy. Nat Clim Chang. 7:307–309.

Chua MF, Youbee L, Oudthachit S, Khanthavong P, Veneklaas EJ, Malik AI (2020) Potassium Fertilisation Is Required to Sustain Cassava Yield and Soil Fertility. Agronomy. 10:1103.

Cotrufo MF, Wallenstein MD, Boot CM, Denef K, Paul E (2013) The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? Glob Chang Biol. 19:988–995.

Cravo MS, Souza BDL, Cardoso EMR, Botelho SM (2020) Mandioca. In: Brasil EC, Cravo MS, Viégas IJM, argitaratzaileak. Recomendações de calagem e adubação para o estado do Pará, 2 ed. Embrapa. Brasília: 251–255.

D'Acqui LP, Churchman GJ, Janik LJ, Ristori GG, Weissmann DA (1999) Effect of organic matter removal by low-temperature ashing on dispersion of undisturbed aggregates from a tropical crusting soil. Geoderma. 93:311–324.

Egbe EA, Soupi NMS, Awo ME, Besong GA, Egbe EA, Soupi NMS, Awo ME, Besong GA (2022) Effects of Green Manure and Inorganic Fertilizers on the Growth, Yield and Yield Components of Soybean (Glycine max (L.) Merr.) in the Mount Cameroon Region. Am J Plant Sci. 13:702–21.

El-Sharkawy MA (1993) Drought-tolerant Cassava for Africa, Asia, and Latin AmericaBreeding projects work to stabilize productivity without increasing pressures on limited natural resources. Bioscience. 43:441–451.

Ezui KS, Franke AC, Mando A, Ahiabor BDK, Tetteh FM, Sogbedji J, Janssen BH, Giller KE (2016) Fertiliser requirements for balanced nutrition of cassava across eight locations in West Africa. F Crop Res. 185:69–78.

Fernandes AM, Gazola B, Nunes JG da S, Garcia EL, Leonel M (2017) Yield and nutritional requirements of cassava in response to potassium fertilizer in the second cycle. J Plant Nutr. 40:2785–2796.

FAO (2016) O que é a agricultura familiar [Internet]. Available from: https://www.fao.org/family-farming/detail/es/c/454156/

FAO (2020) Food and Agriculture Organization of the United Nations [Internet]. Available from: https://www.fao.org/faostat/en/#data/QCL

Fernandes AM, Ribeiro NP, Assunção NS, Geibel da Silva Nunes J, Sorroche CP, Leonel M (2021) Impact of nitrogen and green manure on yield and quality of sweet potato in sandy soil: A Brazilian case study. J Agric Food Res. 4:100131.

Hassen, TB, Bilali HE (2022) Impacts of the Russia-Ukraine War on Global Food Security: Towards More Sustainable and Resilient Food Systems?. Foods. 11: 2301.

Howeler R, Lutaladio N, Thomas G (2013) Save and grow Cassava: a guide to sustainable production intensification. FAO. Rome.

Howeler RH (2014) Sustainable soil and crop management of cassava in Asia: a reference manual. International Cente…. Cali.

Howeler RH (2002) Cassava mineral nutrition and fertilization. Cassava: biology, production and utilization. CABI: 115–47.

Imakumbili MLE, Semu E, Semoka JMR, Abass A, Mkamilo G (2019) Soil nutrient adequacy for optimal cassava growth, implications on cyanogenic glucoside production: A case of konzo-affected Mtwara region, Tanzania. PLoS One. 14:e0216708.

Jenny H (1941) Factors of Soil Formation, a System of Quantitative Pedology. Dover Publication. New York.

Jiang J, Wang YP, Yu M, Cao N, Yan J (2018) Soil organic matter is important for acid buffering and reducing aluminum leaching from acidic forest soils. Chem Geol. 501:86–94.

Kintché K, Hauser S, Mahungu NM, Ndonda A, Lukombo S, Nhamo N, Uzokwe VNE, Yomeni M, Ngamitshara J, Ekoko B, Mbala M, Akem C, Pypers P, Matungulu KP, Kehbila A, Vanlauwe B (2017) Cassava yield loss in farmer fields was mainly caused by low soil fertility and suboptimal management practices in two provinces of the Democratic Republic of Congo. Eur J Agron. 89:107–123.

Lal R (2018) Digging deeper: A holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems. Glob Chang Biol. 24:3285–3301.

Lu X, Mao Q, Mo J, Gilliam FS, Zhou G, Luo Y, Zhang W, Huang J (2015) Divergent responses of soil buffering capacity to long-term N deposition in three typical tropical forests with different land-use history. Environ Sci Technol. 49:4072–4080.

Lützow M V., Kögel-Knabner I, Ekschmitt K, Matzner E, Guggenberger G, Marschner B, Flessa H (2006) Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions – a review. Eur J Soil Sci. 57:426–4245.

Madembo C, Mhlanga B, Thierfelder C (2020) Productivity or stability? Exploring maize-legume intercropping strategies for smallholder Conservation Agriculture farmers in Zimbabwe. Agric Syst. 185:102921.

Malik AI, Kongsil P, Nguyễn VA, Ou W, Sholihin, Srean P, Sheela MN, López-Lavalle LAB, Utsumi Y, Cheng C, Kittipadakul P, Nguyễn HH, Ceballos H, Nguyễn TH, Gomez MS, Aiemnaka P, Labarta R, Chen S, Amawan S, Sok S, Youabee L, Seki M, Tokunaga H, Wang W, Li K, Nguyễn HA, Nguyễn VĐ, Hàm LH, Ishitani M (2020) Cassava breeding and agronomy in Asia: 50 years of history and future directions. Breed Sci. 70:145–166.

Matos LV, Donato SLR, Kondo MK, Lani JL, Aspiazú I (2021) Soil attributes and the quality and yield of 'Gigante' cactus pear in agroecosystems of the semiarid region of Bahia. J Arid Environ. 185:104325.

Misganaw CD, Bayou WD (2020) Tuber Yield and Yield Component Performance of Cassava (Manihot esculenta) Varieties in Fafen District, Ethiopia. Int J Agron. 2020:5836452.

Moura-Silva AG, Aguiar ACF, Jorge N, Agostini-Costa T da S, Moura EG (2017) Food quantity and quality of cassava affected by leguminous residues and inorganic nitrogen application in a soil of low natural fertility of the humid tropics. Bragantia. 76:406–415.

Nascimento GS, Souza TAF, Silva LJR, Santos D (2021) Soil physico-chemical properties, biomass production, and root density in a green manure farming system from tropical ecosystem, North-eastern Brazil. J Soils Sediments. 21:2203–11.

Oghenejoboh KM, Orugba HO, Oghenejoboh UM, Agarry SE (2021) Value added cassava waste management and environmental sustainability in Nigeria: A review. Environ Challenges. 4:100127.

Paustian K, Collier S, Baldock J, Burgess R, Creque J, DeLonge M, Dungait J, Ellert B, Frank S, Goddard T, Govaerts B, Grundy M, Henning M, Izaurralde RC, Madaras M, McConkey B, Porzig E, Rice C, Searle R, Seavy N, Skalsky R, Mulhern W, Jahn M (2019) Quantifying carbon for agricultural soil management: from the current status toward a global soil information system. Carbon Manag. 10:567–587.

Pegoraro RF, Neta MN de A, da Costa CA, Sampaio RA, Fernandes LA, Rodrigues MN (2018) Chickpea production and soil chemical attributes after phosphorus and molybdenum fertilization. Ciência e Agrotecnologia. 42:474–483.

Perin A, Santos RHS, Caballero SSU, Guerra JGM, Gusmão LA (2010) Acúmulo e liberação de P, K, Ca e Mg em crotalária e milheto solteiros e consorciados. Rev Ceres. 57:274–281.

Pimentel ML, Reis IMS, Castro JS de, Portela VS, Romano MLPC, Aguilar Vildoso CI, Gasparin E, Sia EF De (2021) Cassava yield indicators and total organic carbon in tropical soils under different fertilization treatments. Aust J Crop Sci. 15:1325–1331.

Pimentel ML, Reis IMS, Portela VS, Romano MLPC, Aguilar Vildoso CI, Gasparin E, Sia EDF (2020) Effect of Different Sources of Fertilization on Chemical Properties of Soil Under Cassava Cultivation in Western Pará, Brazil. J Agric Sci. 12:106–114.

Pypers P, Bimponda W, Lodi-Lama JP, Lele B, Mulumba R, Kachaka C, Boeckx P, Merckx R, Vanlauwe B (2012) Combining Mineral Fertilizer and Green Manure for Increased, Profitable Cassava Production. Agron J. 104:178–187.

Ramos FT, Dores EF de C, Weber OL do. S, Beber DC, Campelo JH, Maia JC d. S (2018) Soil organic matter doubles the cation exchange capacity of tropical soil under no-till farming in Brazil. J Sci Food Agric. 98:3595–3602.

Rós AB, Silva Hirata AC, Narita N (2013) Produção de raízes de mandioca e propriedades química e física do solo em função de adubação com esterco de galinha. Pesqui Agropecuária Trop. 43:247–54.

R core Team (2020) R: A language and Environment for Statistical computing; The R Project for Statistical Computing: Vienna, Austria [Internet]. Available from: https://www.r-project.org/

Santos, H.G.; Jacomine, P.T.; Anjos, L.H.C.; Oliveira, V.A.; Lumbreras, J.F.; Coelho, M.R.; Almeida, J.A.; Araujo Filho, J.C.; Oliveira, J.B.; Cunha, T.J.F (2018) Sistema Brasileiro de Classificação de Solos, 5th ed.; Embrapa: Brasília, Brazil.

Santos DR, Tiecher T, Gonzatto R, Santanna MA, Brunetto G, da Silva LS (2018) Long-term effect of surface and incorporated liming in the conversion of natural grassland to no-till system for grain production in a highly acidic sandy-loam Ultisol from South Brazilian Campos. Soil Tillage Res. 180:222–231.

Sarma JS, Kunchai D (1991) Trends and prospects for cassava in the developing world. | IFPRI : International Food Policy Research Institute. IFPRI. Wahington, DC.

Shan Z, Luo X, Wei M, Huang T, Khan A, Zhu Y (2018) Physiological and proteomic analysis on long-term drought resistance of cassava (*Manihot esculenta* Crantz). Sci Rep. 8:17982.

Silva GBP da, Zanella CM, Delatorre CA, Chaves MS, Martinelli JA, Federizzi LC (2018) Organic acid carriers in tolerance to toxic aluminum in wheat. Ciência Rural. 48:e2018106.

Six J, Conant RT, Paul EA, Paustian K (2002) Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. Plant Soil. 241:155–176.

Soil Survey staff (2014) Keys to soil taxonomy, 12th ed.; USDA: Washington, DC, USA. https://scholar.google.com/scholar_lookup?title=Keys+to+Soil+Taxonomy&author=USDA&publication_year=2014

Suja G, Sreekumar J, Byju G, Jyothi AN, Veena SS (2021) Weed cloth, an option for integrated weed management for short-duration cassava. Agron J. 113:1895–1908.

Tandzi LN, Mutengwa CS, Ngonkeu ELM, Gracen V (2018) Breeding Maize for Tolerance to Acidic Soils: A Review. Agronomy. 8:84.

Teixeira, P.C.; Donagemma, G.K.; Fontana, A.; Teixeira, W.G (2017) Manual de métodos de análise de solo, 3rd ed.; Embrapa: Brasília, Brazil.

Torabian S, Farhangi-Abriz S, Denton MD (2019) Do tillage systems influence nitrogen fixation in legumes? A review. Soil Tillage Res. 185:113–121.

Wasonga DO, Kleemola J, Alakukku L, Mäkelä PSA (2020) Growth Response of Cassava to Deficit Irrigation and Potassium Fertigation during the Early Growth Phase. Agronomy. 10:321.

Xie X, Machikowa T, Wonprasaid S (2020) Fertigation based on a nutrient balance model for cassava production in two different textured soils. Plant Prod Sci. 23:407–416.

Yeomans JC, Bremner JM (1988) A rapid and precise method for routine determination of organic carbon in soil. Commun Soil Sci Plant Anal. 19:1467–1476.