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Genotype x environment interaction for morpho-agronomic traits and color parameters in cassava in the Central Amazon

E.I. Costa[1], **C.A. Ticona-Benavente**[2] and **D.F. da Silva Filho**[2]

[1]Instituto Federal de Educação, Ciência e Tecnologia do Amazonas, IFAM, Lábrea, AM, Brasil
[2]Instituto Nacional de Pesquisas da Amazônia, Laboratório de Melhoramento de Plantas, Manaus, AM, Brasil

Corresponding author: C.A. Ticona-Benavente
E-mail: cesar.benavente@gmail.com

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ABSTRACT. The Amazon harbors numerous bitter cassava genotypes, of which only a few have been studied agronomically. We evaluated the genotype x environment interaction (GxE) displayed by seven traditional varieties found in the Brazilian municipalities of Lábrea-AM, 07°14’83.5”S, 64°44’70”W, (Cobiçada, Minerva, and Flecha-Amarela) and Manaus-AM, 02º59’00”S, 60º01'00”W, (Mana, Trairinha, Nanica, and Jurará), to determine the landraces best adapted to both sites. A randomized block design, with seven treatments and four replications with eight plants per plot, was adopted at each site. We evaluated commercial root number, length, diameter, length/diameter ratio, mass, dry matter, peel thickness, pulp coloring, plant height, stem diameter, and aerial part mass. GxE interaction analysis revealed GxE interaction for plant height and root diameter and number, and yield. Jurará was the most adapted variety at both sites for the main agronomical characteristics. It showed 43.7 and 26.5 t ha^{-1} root yield; 39.8 and 43.7 t ha^{-1} aerial mass; 10.8 and 4.8 roots per plant and 331.7 and 316.6 cm plant height, respectively in Lábrea and Manaus, respectively. Therefore, Lábrea and Manaus are suitable sites for making studies of GxE interaction. Jurará can be

recommended for the Amazon region as well and should be tested in other tropical and subtropical regions.

Key words: *Manihot esculenta*; Manioc; Adaptability; Stability; Landraces

INTRODUCTION

Little work on genetic improvement of cassava (*Manihot esculenta*) has been done in the Amazon. Traditional and molecular breeding are little used to increase agronomic performance. But in this region, there are numerous traditional varieties that could be introduced elsewhere to increase productivity. This species has been bred for millennia, producing hundreds of genotypes closely associated with Amazonian inhabitants (Elias et al., 2004; Alves-Pereira et al., 2018); consequently an introduced variety will unlikely be adopted locally.

Even though this crop is well adapted to Amazon, there are some Brazilian Amazonian states with low productivity. For example, Amazonas and Pará states hold one of the lowest yields in Brazil 12,0 and 14,2 t ha^{-1} respectively (IBGE, 2022), meanwhile the mean Brazilian yield in 2021 was 15.0 t ha^{-1} (IBGE, 2022). When just taking other Brazilian Amazonian states into account, one also finds the state of Roraima and Acre to yield in 2021 22.0 and 23.2 t ha^{-1}, respectively (IBGE, 2022). This shows the need to genetically improve this species and to adopt some procedures, such as soil plowing, fertilization, and liming in Amazonas and Pará states.

In Amazonas state, some research studies aiming to increase root yield have been conducted, such as that Dias et al. (2012) in the municipality of Lábrea-AM, which showed that the application of dolomitic limestone in the dose of 2 t ha^{-1} and NPK 30-60-40 fertilization increased root yield by 42% (from 25.7 to 36.6 t ha^{-1}). However, this recommendation is often not followed because these inputs are very expensive and scarce in these regions. Therefore, genetic breeding would be an appropriate procedure for increasing productivity.

There are two types of cassava being cultivated in this region: sweet and bitter, the former, known as “macaxeira” is consumed cooked; and the latter “mandioca” is just used to make flour, *tapioca*, and starch. The municipality of Lábrea-AM stands out for the production of bitter manioc, and 80% of its cultivation is carried out on non-flooded land soil with no fertilization and liming, despite nutrient-poor soils with high aluminum content (Quesada et al., 2011). Even so, its production in 2012 was 30 thousand tons, with a productivity of 11 t ha^{-1} (Dias et al., 2012), surpassing that of the state’s average. Manaus is the state capital and harbors numerous non-flooded land bitter cassava varieties, which could have been introduced by immigrants from several other places in the hinterland.

Testing bitter manioc cultivars in different Amazonian environments may help to select the ones showing to be the most stable on their yield. This kind of study is denominated GxE interaction, which is complemented by adaptability and stability studies. The existence of GxE interaction shows that varieties have different responses to environmental changes, however, adaptability and stability studies help to identify the genotypes that should be selected for a given site (adaptability) and recommended for non-tested ones (stability) (Cruz et al., 2004). Most studies of GxE interaction on cassava have been conducted in Africa (Ssemakula and Dixon, 2007; Akinwale et al., 2011; Maroya et al., 2012; Hamblin et al., 2013; Kundy et al., 2014; Mtunguja et al., 2016; Peprah et al., 2016; Adjebeng-Danquah et al., 2017; Chipeta et al. 2017), some in north-eastern (Morais et al., 2017) and southern (Kvitschal et al., 2009) Brazil, but none in the Brazilian Amazon.

Therefore, the aim of this work was to conduct GxE interaction, adaptability, and stability studies on seven bitter cassava genotypes from two municipalities of Central Amazon in order to select the best options and determine if these sites are appropriate for cassava production.

MATERIAL AND METHODS

Two concomitant trials were run in the state of Amazonas in non-flooded land in the municipalities of Lábrea (07° 14’ 83.5” S, 64° 44’ 70” W) and Manaus (02º 59’ 00” S, 60º 01' 00” W). The sites are 705 km apart, but are joined by the Purus and Solimões Rivers. In Lábrea, a grower’s area was used and in Manaus the Experimental Station of Vegetables at Instituto Nacional de Pesquisas da Amazônia (INPA) was used. Seven bitter cassava genotypes (Register no. A8BB667, SISGEN, Ministry of the Environment, Brazil) were tested. Three from Lábrea: Flecha-Amarela, Cobiçada, and Minerva; and four from the Manaus metropolitan region: Mana, Jurará, Nanica, and Trairinha. Lábrea and Manaus represented the 'Am' and 'Af' climates, respectively, in the State of Amazonas (Alvares et al., 2013). According to this study, 'Am' climate covers 17.6% of the state of Amazonas, with an annual mean temperature of 26.6 °C, precipitation of 2450 mm, and an average altitude of 200 m.a.s.l. (meters above sea level). The ‘Af” climate which is the wettest worldwide, covers 82.3% of the state of Amazonas, at a mean altitude of 100 m.a.s.l., with an annual mean temperature of 25.7°C and precipitation of 2700 mm.

Both areas were prepared in October 2015, receiving two gradations. The planting of the cuttings was carried out the following month. The randomized complete block design, with seven treatments (varieties) and four replications with eight 1 x 1 m spaced plants per plot, was employed. The 10 to 20 cm long cuttings were placed into 10 cm deep pits. Fertilizers and limestone were not applied, but weeding and phytosanitary controls were performed as needed. The chemical analysis of the soils was performed before planting (Table 1).

Table 1. Soil chemical traits in the experimental areas of Lábrea (the farmer’s area) and Manaus (Experimental Station of Vegetables at Instituto Nacional de Pesquisas da Amazônia). Amazonas, 2016.

Depth (cm)	**pH H_2O**	**K^+**	**Ca^{2+}**	**Mg^{2+}**	**Al^{3+}**	**P**	**Fe**	**Zn**	**Mn**
		-------------cmol$_c$ dm^{-3}-------------				-------------mg dm^{-3}-------------			
	Lábrea								
0-20	4.37	0.06	0.13	0.14	5.59	1.73	389.90	0.80	3.80
20-40	4.41	0.05	0.12	0.13	5.77	1.31	144.20	2.10	3.50
	Manaus								
0-20	6.64	0.03	0.36	0.07	0.45	14.26	123.70	314.00	9.30
20-40	6.52	0.02	0.29	0.06	0.45	10.63	144.20	156.00	5.90

Plots at both sites were harvested 12 months after being planted, and the following traits were evaluated: commercial roots number, length, diameter, length-diameter ratio, mass, dry matter, peel (periderm + cortex) thickness, and pulp coloring; plant height, stem diameter, and aerial part mass.

Root pulp coloring was evaluated using the Minolta CR-410 colorimeter, which gives three-dimensional scale values (a*, b*, and L*). With a* ranging from -60 (green) to 60 (red), b* from -60 (blue) to 60 (yellow), and L* measuring the luminosity ranging from 0 (black) to 100 (white). Color saturation ($Croma=\sqrt{a^{*2}+b^{*2}}$), ranging from -60 to 60, and its hue (Hue=arctg (a*/b*)) varying from 0^{o} to 360º, were estimated from these values.

To detect GxE interaction, data were submitted to analysis of variance (ANOVA) at each site and then the joint analysis of variance was performed if Pimentel Gomes criterion is satisfied. This criterion set that (MSE max / MSE min) <7 was achieved. MSE = mean square error being the analysis error at a given site.

To determine stability and adaptability of cassava varieties, GxE interaction decomposition of joint ANOVA was performed considering Environment within each Genotype using software SAS 9.1.3 procedure PROC GLM (SAS Institute Inc, Cary, NC). To observe whether the sites are contrasting, a principal component based (PCA) biplot was made with data standardized using JMP 10 (SAS Institute Inc, Cary, NC). The characters included in the PCA were chosen in order to maximize the variability explained.

RESULTS

Genetic improvement of cassava in the Amazon could be successful by introducing Amazonian cultivars from elsewhere in the Amazon. Cassava has been cultivated in the Amazon for ~10,000 years. During this long period, many varieties have been developed. In 330 km of five tributaries of the Amazon River (Peru), 45 varieties have been found (Wooding and Payahua, 2022). In the Medium Negro River Basin 169 varieties were found (Peroni et al., 2007). For this reason, the present work evaluated GxE interaction of some traditional varieties from Lábrea and Manaus municipalities in the same locations in order to select material suitable for both sites and other Amazonian sites.

Joint analysis of variance (Supplementary 1) revealed the importance of three factors: genotype (G), environment (E), and GxE interaction in the variability of all morphological traits found in cassava except for root peel thickness.

Regarding root length, we only found significance in the genotype effect. Yet, there may be other specific-GxE interactions. These are detected in the GxE interaction decomposition when the environment effect is isolated within genotype i (E/genotype i). Thus, E/Minerva showed to be the only significant case, which indicates this genotype's roots length to be affected by the environment, with 8 cm being the difference between Manaus (33.25 cm) and Lábrea (25.60 cm) (Table 2).

Should elongated roots be desired, Jurará would be the most adapted one, since it gave the highest mean root length both in Lábrea (33.15 cm) and Manaus (32.50 cm). Jurará was the longest in both environments, with no significant effect on E/Jurará decomposition (Supplementary 1). Therefore, Jurará is the most stable for this trait.

As to root diameter, ANOVA revealed the genotype and GxE interaction effects significance. Root diameter ranged from 5.34 cm (Trairinha) to 6.86 cm (Jurará) in Lábrea and 5.32 to 7.65 cm (Nanica) in Manaus (Table 2). The environmental effect decomposition within each genotype showed no significance on Cobiçada, Minerva, Mana, Trairinha and Jurará genotypes, showing them to have a stable performance in both environments. If the largest diameter equals the best performance, Jurará with diameters of 6.86 (Lábrea) and

6.29 cm (Manaus) (Table 2) is the most stable genotype, and Jurará (6.29 cm) and Nanica (7.65 cm) are the most adapted ones to Lábrea and Manaus, respectively.

Table 2. Trait means of seven genotypes of bitter cassava (*Manihot esculenta*) in the municipalities of Lábrea and Manaus, Amazonas. 2016.

Site	Cobiçada†	Flecha-amarela†	Minerva†	Genotypes Mana§	Trairinha§	Nanica§	Jurará§
				Root Length (cm)			
Lábrea	29.05 AB[1]	27.35 ABC	25.60 BC	31.37 AB	27.20 ABC	21.05 C	33.15 A
Manaus	29.60 AB	32.60 AB	33.25 A	33.65 A	23.45 C	24.10 BC	32.50 AB
				Root Diameter (cm)			
Lábrea	6.15 ABC	5.43 BC	5.85 ABC	6.64 AB	5.34 C	6.35 ABC	6.86 A
Manaus	5.32 C	7.04 AB	6.01 BC	6.20 BC	5.59 C	7.65 A	6.29 BC
				Root Length-Diameter Ratio			
Lábrea	4.71 A	5.03 A	4.36 A	4.76 A	5.24 A	3.32 B	4.85 A
Manaus	5.57 AB	4.56 AB	5.68 A	5.35 AB	4.23 BC	3.13 C	5.13 AB
				Stem Diameter (cm)			
Lábrea	2.11 C	2.29 BC	2.52 AB	2.51 AB	2.50 AB	2.27 BC	2.66 A
Manaus	2.30 B	2.66 AB	2.62 AB	2.84 A	2.81 AB	2.20 B	3.06 A
				Root Peel thickness (mm)			
Lábrea	1.99 A	1.54 A	2.20 A	2.53 A	2.03 A	1.87 A	2.02 A
Manaus	2.04 A	2.07 A	2.22 A	2.02 A	2.09 A	1.91 A	2.48 A
				Commercial roots number (Unit)			
Lábrea	8.92 B	5.06 D	6.74 C	8.66 B	8.13 BC	6.69 C	10.76 A
Manaus	3.57 AB	3.72 AB	3.91 AB	3.00 B	3.59 AB	2.52 B	4.78 A
				Root yield (t ha^{-1})			
Lábrea	36.20 B	17.00 D	27.90 C	35.70 B	27.30 C	23.40 CD	43.70 A
Manaus	17.31 A	25.46 A	25.80 A	21.24 A	15.99 A	17.19 A	26.45 A
				Major-cutting yield (t ha^{-1})			
Lábrea	5.94 B	3.73 C	5.78 B	8.11 A	7.04 AB	4.17 C	8.22 A
Manaus	6.81 A	4.51 A	10.97 A	4.80 A	4.46 A	4.35 A	13.43 A
				Plant aerial yield (t ha^{-1})			
Lábrea	26.28 CD	17.32 D	29.81 BC	42.23 A	45.06 A	22.31 CD	39.82 AB
Manaus	22.58 B	26.16 AB	32.94 AB	32.19 AB	30.08 AB	16.60 B	43.68 A
				Plant total yield (t ha^{-1})			
Lábrea	68.47 B	38.09 D	63.45 BC	86.06 A	79.37 AB	49.84 CD	91.74 A
Manaus	46.70 AB	56.13 AB	69.72 AB	58.22 AB	50.54 AB	38.15 B	83.56 A
				Root dry matter (%)			
Lábrea	36.43 A	30.68 AB	29.36 B	26.50 B	32.00 AB	26.33 B	31.82 AB
Manaus	34.70 A	24.32 B	29.52 B	26.75 B	28.86 B	26.93 B	35.97 A
				Plant height (cm)			
Lábrea	45.08 D	247.46 D	264.85 C	307.56 B	297.46 B	224.58 E	331.66 A
Manaus	46.63 B	285.17 AB	238.01 BC	259.86 B	268.34 B	198.44 C	316.64 A

[1]Means followed by the same letters in line do not differ among themselves by the Duncan test (P<0.05).
† Varieties originally found in Lábrea.
§ Varieties originally found in Manaus.

As to the length-diameter ratio, ANOVA revealed genotype effect as the single factor to be significant (Supplementary 1), suggesting its great importance regardless of the site. E/genotype decomposition revealed there to be no significant effect on most genotypes, indicating them to be stable. Only E/Minerva showed to be significantly affected, indicating its shape to depend on the site where it is cultivated, with it being longer in Manaus (5.68 cm) than in Lábrea (4.36 cm). Values ranged from 3.32 cm (Nanica) to 5.24 cm (Trairinha) in Lábrea, and 3.13 cm (Nanica) to 5.68 cm (Minerva) in Manaus. Considering the longer varieties to be the ones that performed the best, the cultivar Cobiçada (Lábrea=4.71 cm, Manaus=5.57 cm) is the most stable. Yet, the cultivars most adapted to Lábrea and Manaus are Trairinha (5.24 cm) and Minerva (5.68 cm), respectively.

Genotype and environment showed to be significant for mean stem diameter (Supplementary 1). E/genotype decomposition revealed not to be significant on all genotypes, showing this trait to be stable. Values were higher in Manaus (2.65 cm) than in Lábrea (2.41 cm), and ranged from 2.11 cm (Cobiçada) to 2.66 cm (Jurará) in Lábrea, and 2.20 cm (Nanica) to 3.06 cm (Jurará) in Manaus (Table 2). Hence, one may infer Jurará to bear the thickest stem and to be the most stable and adapted to both environments.

No factor showed any significance for cassava roots peel thickness (Supplementary 1), and no significant variability was found for it (Table 2). Therefore, all genotypes are stable on this trait, as well as adapted to both environments.

These three factors showed to be significant as to the number of roots, showing it to be influenced by genotype, environment, and GxE interaction (Supplementary 1). It ranged from 5.06 (Flecha Amarela) to 10.76 (Jurará) in Lábrea, and 2.52 (Nanica) to 4.78 (Jurará) in Manaus. These data showed the number of roots to be higher in Lábrea than in Manaus. GxE decomposition just showed to be non-significant on E/Flecha Amarela showing the stability of this genotype, bearing 5.06 and 3.72 roots per plant in Lábrea and Manaus, respectively.

The three factors also showed to be significant on root yield, showing it to be influenced by genotype, environment, and GxE interaction. The yield was higher in Lábrea (30.2 t ha^{-1}) than in Manaus (21.3 t ha^{-1}) (Table 2). And it ranged from 17.0 (Flecha Amarela) to 43.7 t ha^{-1} (Jurará) in Lábrea and 16.0 (Trairinha) to 26.5 t ha^{-1} (Jurará) in Manaus. GxE interaction decomposition revealed Flecha Amarela, Minerva, Trairinha, and Nanica genotypes to have a similar performance on both environments (Supplementary 1) suggesting these genotypes to be stable, but taking the means into account (Table 2) Minerva would be the most stable one (Lábrea 27,9 t ha^{-1}, Manaus 25,8 t ha^{-1}). Given its high root yield, Jurará would be the most adapted genotype for both environments.

Just the genotype effect was significant for the plant aerial part (stems + leaves) yield (Supplementary 1). GxE decomposition was just significant for E/Trairinha, showing a different performance between both environments (Lábrea= 45.06 t ha^{-1}, Manaus= 30.08 t ha^{-1}). In Lábrea, this trait ranged from 17.32 (Flecha Amarela) to 45.06 t ha^{-1} (Trairinha), and in Manaus 16.60 (Nanica) to 43.68 t ha^{-1} (Jurará). Therefore, taking all these findings into account, Jurará would be the most stable genotype yielding 39.8 t ha^{-1} in Lábrea and 43.68 t ha^{-1} in Manaus, and Trairinha in Lábrea and Jurará in Manaus showed to be the most adapted genotypes.

Just the genotype factor showed to be significant for the total mass of the plants (roots + aerial mass). The genotypes ranged from 38.68 (Flecha Amarela) to 91.74 t ha^{-1} (Jurará) in Lábrea, and 38.15 (Nanica) to 83.56 t ha^{-1} (Jurará) in Manaus. This showed the adaptability and stability of the Jurará genotype.

Cassava roots dry matter rate was just affected by the genotype ($P<0.05$), showing it to be more important than the environment and GxE interaction. This trait ranged from 26.33 (Nanica) to 36.43% (Cobiçada) in Lábrea, and 24.32 (Flecha Amarela) to 35.97% (Jurará), showing Cobiçada and Jurará to be the most adapted genotypes in Lábrea and Manaus, respectively. GxE interaction decomposition revealed all genotypes excluding Flecha Amarela to be stable (Supplementary 1). Hence, Cobiçada is the most stable genotype with 36.43% and 34.70% in Lábrea and Manaus, respectively (Table 2).

Genotype, environment, and GxE interaction accounted for the height of the plants (Supplementary 1). Plant heights ranged from 224.58 cm (Nanica) to 331.66 cm (Jurará) in Lábrea, and from 198.44 (Nanica) to 316.64 cm (Jurará) in Manaus (Table 2). This demonstrates the Jurará cultivar to be the most adapted one to both environments if high plants were to be desired. However, if one were to desire low ones, the Nanica genotype would be the most adapted to both environments. GxE decomposition revealed Nanica and Jurará to be stable as well. Therefore, these genotypes may be recommended for other sites.

The fresh root pulp coloring was evaluated using five variables (L*, a*, b*, Chroma, and Hue) (Table 3). For L*, the environment and the genetic effect showed to be important. Values of a* and Hue showed the genetic effect to be the only important one, and for b* and Chroma, only the effect from the environment was important. These findings show genotype and environment, but not GxE interaction, to be important. Since the color of the roots is white, the luminosity (L*) had higher values (Lábrea 42.97 and Manaus 36.24) than a*, b* and Chroma. According to the CIELAB color scale, Hue varies in degrees, with it being 0º= Red, 90º= Yellow, 180º= Green, and 270º= Blue. Thus, the Hue angle of 91.56° shows the coloring yellow. GxE decomposition showed E/Cobiçada and E/Jurará to have significant effects on L*, b*, and Chroma, which suggests these roots color to be unstable in these genotypes. Jurará was lighter in Lábrea (L*=48.54) than in Manaus (L*=38.62). Trairinha (L*=37.0 and Hue 89.4º) and Nanica (L*=37 and Hue=96º) showed to be the most stable genotypes for the five-color parameters (Table 3). They can be recommended for other sites with no risk of having their yellowish color changed.

Table 3. The means of the color components of the genotypes of bitter cassava (*Manihot esculenta*) in the municipalities of Lábrea and Manaus, Amazonas. 2016.

				Genotypes			
Site	**Cobiçada**	**Flecha-amarela**	**Minerva**	**Mana**	**Trairinha**	**Nanica**	**Jurará**
				L*			
Lábrea	52.02 A	43.15 AB	37.18 B	44.68 AB	38.47 B	39.02 B	48.54 AB
Manaus	36.60 A	36.67 A	32.00 A	37.86 A	36.13 A	35.81 A	38.62 A
				a*			
Lábrea	-0.62 BC	-0.16 AB	0.16 AB	-1.57 C	0.59 A	-1.58 C	-0.93 BC
Manaus	-0.19 B	0.18 AB	0.92 A	-1.21 CD	-0.31 BC	-1.44 D	0.07 AB
				b*			
Lábrea	19.75 A	17.42 AB	16.04 AB	16.71 AB	16.19 AB	14.72 B	19.42 A
Manaus	14.03 A	13.24 A	13.19 A	13.40 A	13.62 A	13.38 A	14.81 A
				Chroma			
Lábrea	19.76 A	17.42 AB	16.06 AB	16.80 AB	16.20 AB	14.81 B	19.45 A
Manaus	14.03 A	13.25 A	13.22 A	13.46 A	13.67 A	13.46 A	14.82 A
				Hue angle			
Lábrea	91.82 B	90.55 BC	89.53 BC	95.40 A	87.82 C	95.88 A	92.53 AB
Manaus	90.81 B	89.06 BC	86.05 C	95.19 A	91.06 B	96.12 A	90.04 BC

[1]Means followed by the same letters in line do not differ among each other by the Duncan test ($P<0.05$)

Biplot based on principal components (PCA) using morpho-agronomic characteristics and L* explained 65% of total variation (Figure 1). This figure showed the contrast between Lábrea and Manaus (Figure 1). Lábrea was strongly associated with high values of root yield, roots number and L*. However, root length, peel thickness, aerial yield, plant height, L/D ratio and total yield (aerial + root yield) were not useful to differentiate the two sites.

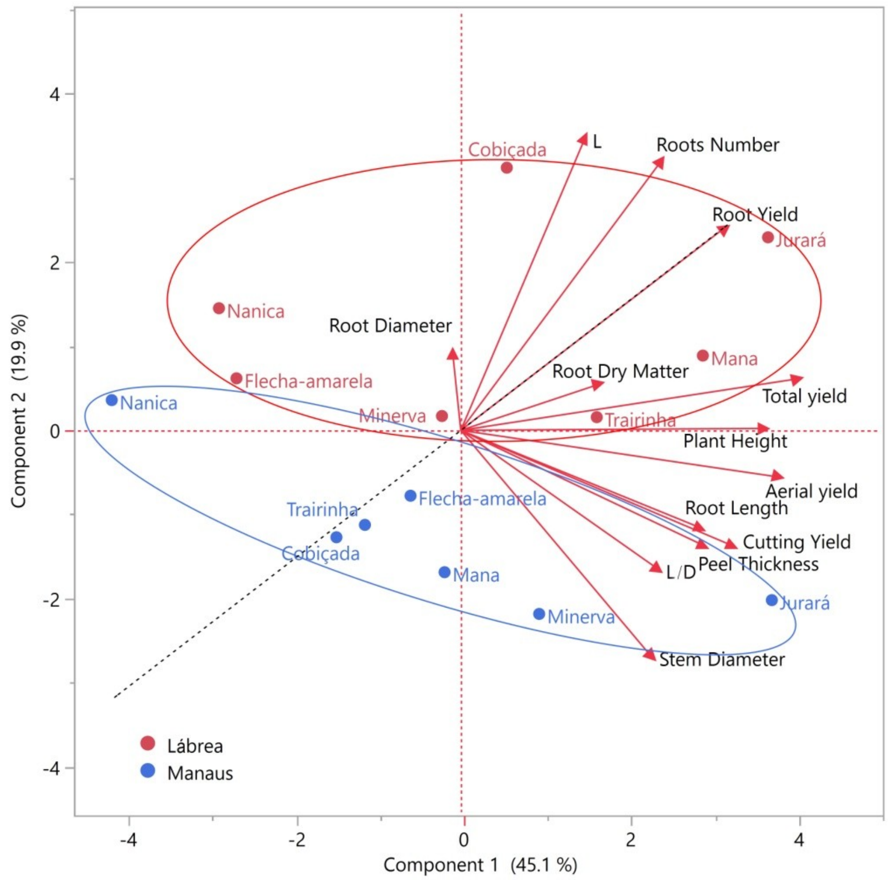

Figure 1. Biplot based in principal components shows agronomic characteristics of cassava varieties in Lábrea and Manaus municipalities. 2016.

DISCUSSION

Obtaining varieties that can be recommended is a process that should always take GxE interaction into account. Since many genotypes are successful in one site but not necessarily in another. Thus, identifying genotypes bearing stable performance assures their adoption at several sites. That is why promising genotypes must be tested in at least two contrasting environments. In the present work we considered Labrea-AM and Manaus-AM, because the former holds a Am climate and acid soils (pH=4.4), and the latter holds Af climate and neutral soils (pH=6.5).

Regarding root length, the present work has only shown the importance of genetic effects. Malawi (Africa), where the altitude was the main difference between the environments (70 and 606 m), showed the importance of the genetic, environmental, and GxE interaction effects (Chipeta et al. 2017). However, the present work was conducted on sites the altitudes of which were not that different (Manaus 56 m and Lábrea 76 m). Therefore, altitude might influence root length. As long roots are the most desired for processing, the Jurará genotype is recommended to both environments.

Despite being an important yield component with a correlation of 0.64 Babu Rao et al. (2012) and 0.78, Mulualem and Ayenew (2012), the root diameter is poorly studied in the GxE interaction context. Yet it showed to be valid for Jurará, but not for Nanica. Their diameters and yields showed to be 6.5 and 7.0 cm and 35.0 and 15.2 t ha^{-1}, respectively. The environmental effect showed not to be significant for this trait. Therefore, testing these genotypes in non-Amazonian environments would be necessary to find out, up to what extent, the environment is not important.

The length-diameter ratio indicates the root shape, which is only accounted for by the genetic effect. Literature has given little emphasis to this trait. Yet, it is of the paramount importance for processing since the industry prefers elongated roots.

The plant stem diameter supports branches and leaves development while indicating its maturity degree, as well. The genotype and environment effects control this trait, agreeing with previous studies (Adjebeng-Danquah et al., 2017; Kundy et al., 2014), but the former author found the GxE interaction effect to have done it as well. The Jurará genotype held the largest diameter in both environments, coinciding with its high root yield. The strong association between these two traits was described (Mulualem and Ayenew, 2012) who found their genetic correlation. Babu Rao et al. (2017) found the phenotypic correlation to be 0.41. Hence, the selection of the plants aiming at the root yield should take their stem diameter into account.

The peel together with skins and tips of the roots may reduce their weight by up to 25% (Viana et al., 2010), yet the present work shows there to be no variability for peel thickness. This may be because of the small number of assessed genotypes. Hence, studies on other genotypes will be needed to ascertain this subject.

The commercial roots number was affected by three effects. Previous works showed just GxE interaction (Chipeta et al., 2017), or only environment and genotype (Peprah et al., 2016) or all three (Akinwale et al., 2011), to be important. This shows that the commercial roots number should be included in the studies on the GxE interaction in ‘Af’ and ‘Am’ climates. Jurará held the highest values for both environments (Lábrea 10.76 and Manaus 4.78 units), adding one more positive trait.

The root yield showed to be controlled by three effects. Previous works found similar results (Adjebeng-Danquah et al., 2017; Akinwale et al., 2011; Chipeta et al., 2017; Kundy et al., 2014; Maroya et al., 2012; Mtunguja et al. 2016; Ssemakula and Dixon, 2007), and another one found no effect from the GxE interaction (Peprah et al., 2016). This shows root yield to depend on the three factors, therefore, it is necessary to use several sites to evaluate it. The Jurará genotype originating from Manaus stood out on account of its high yield both in Lábrea (43.7 t ha^{-1}) and Manaus (26.5 t ha^{-1}). This also demonstrates the cassava yield improvement to be possible in Lábrea, as long as this genotype is introduced.

This root yield in Lábrea is like that of the most productive country in the world: Guyana, whose yield was 47,6 t ha^{-1} in 2020 (FAO, 2022). This indicates that Jurara genotype should to be tested elsewhere in the Amazon to rapidly increase the productivity per unit area.

The aerial part productivity was only controlled by the genetic effect. Other studies reported the importance of the three effects (Peprah et al., 2016; Chipeta et al., 2017). This may have occurred because of the environments used in this study not being contrasting in altitude, as in the case of these authors, who used sites bearing climates ranging from a forest to savannah. The Jurará genotype mass was again the highest in both environments (Lábrea 39.8 t ha^{-1} and Manaus 43.68 t ha^{-1}).

The total mass of the plants is not much considered in the GxE interaction studies, but it gives a logical notion of the capacity of accumulation of organic matter. The present work shows it to only depend on genotype, with Jurará being the one holding the best performance (Lábrea 91.74 t ha^{-1} and Manaus 83.56 t ha^{-1}).

Root dry-matter (DM) indicates roots productivity after being processed. The present work demonstrates this trait to be controlled only by the genetic effect. Other works found the three factors (Ssemakula and Dixon, 2007; Akinwale et al., 2011; Maroya et al., 2012; Adjebeng-Danquah et al., 2017) or only the environment (Chipeta et al., 2017) to be important. Our findings indicate the Amazonian environment does not affect DM, but that other environments might do it. Cobiçada (36.43%) and Jurará (35.97%) genotypes stood out in Lábrea and Manaus, respectively. But, since Jurará has shown the highest root yield, it must be the one to be preferred at both sites.

Just as root yield, plant height is controlled by the three factors, as well. This agrees with the work (Adjebeng et al., 2017). Showing that it should be assessed at several sites to make a suitable selection. Jurará held the greatest heights in both environments (Lábrea 331.6 cm; Manaus 316.6 cm). Although tall plants are considered to be propitious to lodging, they may be suitable for increasing population density, eliminating invasive plants, getting a larger amount of cutting-seed, and making mechanized harvesting (Rós et al., 2011; Passos et al., 2014). Thus, Jurará could be tested in narrower than 1 x 1 m spacing when using mechanized harvest.

The root pulp coloring showed to be affected by the genetic and environmental effect with no GxE interaction. This trait is not usually investigated to make the selection but should be considered, judging by the results it has presented. The results showed the evaluated roots to be yellowish, and suitable for making "farinha d'água" (flour made from cassava roots that have previously been kept immersed in water overnight before being peeled and grated, the taste of which is much appreciated in the northern region of Brazil). Trairinha (L*=37 and Hue=90º) and Nanica (L*=37.5 and Hue=96º) showed to be the most stable genotypes showing they could be used for having their coloring standardized even when being cultivated in different environments.

Considering the results of PCA, Lábrea and Manaus should be used for carrying out GxE studies in order to select cassava's most productive genotypes to non-flooded land in Central Amazon. How these two sites represent the main climates (Af and Am) and soils of the Central Amazon is possible Jurará genotype to be well adapted to this region. Meanwhile, other sites seem adequate to be tested in Amazon, such as Terra Preta soils and all flooded land.

CONCLUSIONS

In non-flooded soils of Central Amazon, the Genotype x Environment (GxE) interaction affect cassava root yield, root number, root diameter and plant height. In contrast, GxE do not affect aerial mass, stem diameter, root dry matter and root pulp color.

Jurará genotype should be adopted in Lábrea to increase the production of flour. It can produce up to 44 t ha^{-1} of fresh root in acid and poor nutrient soils.

Lábrea and Manaus are useful sites for carrying out cassava GxE interaction, adaptability, and stability studies in the Central Amazon.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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