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Adaptability and stability of sweet potato genotypes in Western São Paulo

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ABSTRACT

Sweet potato (*Ipomoea batatas* L.) have great genetic variability that contribute to higher production and root quality. Sweet potato farmers in the Western region of São Paulo state, Brazil, plant during the four seasons and have used the same genotypes for two decades. Thus, research is needed to evaluate new genotypes and indicate the most promising ones. Therefore, the objective of this study was to identify the adaptability and stability of sweet potato genotypes in six planting seasons: September 2019, January 2020, April 2020, September 2020, October 2020, and December 2020 in Western São Paulo using the linear regression methodology proposed by Eberhart & Russell (1966) and the centroid method. We evaluated 17 genotypes, two experimental genotypes from the germplasm bank of the University of Western São Paulo and two genotypes that have been cultivated for more than two decades by farmers (Canadense and Ligeirinha Paulista). The results show that Canadense, IAPAR 69, and SCS 272 Marina can be considered widely adapted in the Western region of São Paulo (favorable and unfavorable environments). In turn, the genotypes UBD 01 and UBD 02 are indicated exclusively for unfavorable environments, while Ligeirinha Paulista, INIA Arapey, SCS 369 Águas Negras, BRS Rubissol, Brazlândia Branca, Brazlândia Roxa, and BRS Amélia are indicated for favorable environments.

Keywords: *Ipomoea batatas* L., superior genotypes, genotype x environment interaction, genotypic performance.

RESUMO

Adaptabilidade e estabilidade de genótipos de batata-doce no Oeste de São Paulo

A batata-doce (*Ipomoea batatas* L.) possui grande variabilidade genética que contribui para maior produção e qualidades das raízes. Os agricultores de batata-doce do Oeste Paulista, Brasil, plantam durante as quatro estações e utilizam há duas décadas os mesmos genótipos. Desse modo, são necessárias pesquisas que visem avaliar novos genótipos e indicar os mais promissores. Portanto, objetiva-se identificar a adaptabilidade e estabilidade de genótipos de batata-doce em seis épocas de plantio: Setembro de 2019, Janeiro de 2020, Abril de 2020, Setembro de 2020, Outubro de 2020 e Dezembro de 2020 no Oeste Paulista, por meio da metodologia da regressão linear proposta por Eberhart & Russell (1966) e pelo método Centróide. Avaliou-se 17 genótipos, dois genótipos experimentais do Banco de Germoplasma da Universidade do Oeste Paulista e dois genótipos que são cultivados há mais de duas décadas pelos agricultores (Canadense e Ligeirinha Paulista). A partir dos resultados obtidos, os genótipos Canadense, IAPAR 69 e SCS 272 Marina, podem ser considerados como de ampla adaptação na região Oeste Paulista (ambientes favoráveis e desfavoráveis). Por sua vez, os genótipos UBD 01 e UBD 02 são indicados exclusivamente para ambientes desfavoráveis, enquanto que Ligeirinha Paulista, INIA Arapey, SCS 369 Águas Negras, BRS Rubissol, Brazlândia Branca, Brazlândia Roxa e BRS Amélia são indicados para ambientes favoráveis.

Palavras-chave: *Ipomoea batatas* L., genótipos superiores, interação genótipo x ambiente, desempenho genotípico.

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Sweet potato (*Ipomoea batatas* L.) has high potential, as it is a rustic plant with certain tolerance to drought and produces roots with high energy and food potential (Leal *et al*., 2021). Sweet potato has gained prominence in production in several regions of Brazil, as it is a key crop for family farming (Perrud *et al*., 2021).

However, in Brazil, sweet potato yield only reaches 14.6 t/ha (IBGE, 2021), a level well below the potential for the crop, which can exceed 30 t/ha (Leal *et al*., 2021).

Currently, there exist 51 official records of sweet potato cultivars in Brazil (MAPA, 2024). From these, more than 20 are indicated for the production of roots intended for human consumption. However, studies that aim to select cultivars adapted to each region are still scarce (Leal *et al*., 2021; Zeist *et al*., 2022). Additionally, cultivars selected in South, Midwest, and Northeast Brazil and in other parts of the world have not yet been tested in most of the main producing regions of Southeast Brazil, such as Western São Paulo. In this region, sweet potato is cultivated in the four seasons of the year, with some irrigated plantations in autumn and winter and the vast majority without irrigation. Thus, genotypes that adapt and are stable in the face of climatic variations that occur throughout the year are necessary.

Western São Paulo is a national reference in the production of sweet potato roots for human consumption (Montes & Pantano, 2013). Nevertheless, even though the yield is higher than the national average, it only reaches 17.0 t/ha (IBGE, 2021). Reduced yields may be due to the low level of technology adopted specifically regarding the use of genotypes that are not very responsive to the improvement of cultivation techniques and technologies (Leal *et al*., 2021; Zeist *et al*., 2022). The region is characterized by the use of local accessions, whose exact origin is generally unknown, such as "Canadense" and "Ligeirinha Paulista". In turn, these genotypes have never been compared with other genotypes regarding yield performance or tested for adaptability and temporal stability under local conditions.

An important tool used in genetic improvement programs is evaluating the interaction of genotypes with environments (G x E). This evaluation allows the selection of superior genotypes. However, a cultivar may perform differently in different environments, such as locations or seasons (Carvalho *et al*., 2017). The environment influences phenotypic expression, providing the G × E interaction, where a specific environment can affect environmental selection (Andrade *et al*., 2016). The interaction between genotype and environment can be observed through the study of adaptability and stability (Carvalho *et al*., 2017).

Adaptability refers to the ability of a genotype to take advantage of environmental variations, and stability is the ability of genotypes to exhibit predictable behavior according to environmental variations (Andrade *et al*., 2016; Carvalho *et al*., 2017). Additionally, with the estimation of the phenotypic adaptability and stability of different genotypes, it is possible to indicate with greater precision which cultivar performs best (Carvalho *et al*., 2017). Therefore, adaptability and stability analyses are essential to identify cultivars with predictable behavior that are adaptable to different environments (Cruz *et al*., 2012).

Several methodologies can be used to determine adaptability and stability, varying according to the degree of precision, the statistics used, the number of environments, and other information involved (Cardoso *et al*., 2021). The most adopted method is the one proposed by Eberhart & Russell (1966) (Pelúzio *et al*., 2015; Rezende *et al*., 2021), which, through simple linear regression, uses the regression coefficient to estimate the adaptability and variance of the standard deviation to estimate stability (Rezende *et al*., 2021). The centroid method has also gained prominence because it is easy to interpret, allowing the analysis of several genotypes simultaneously (Lin & Binns, 1988). This method compares Cartesian distance values between genotypes and four ideotypes: maximum general adaptability, maximum specific adaptability to favorable or unfavorable environments, and minimum adaptability (Nascimento *et al*., 2009).

Identifying genotypes with high productive potential is essential to strengthen sweet potato cultivation in the main producing regions of Brazil. Furthermore, when referring to cultivation in the four seasons of the year, as in Western São Paulo, it is also necessary to identify genotypes that specifically adapt to each growing season. Thus, obtaining reliable estimates of genetic parameters based on adaptability and stability analysis is extremely relevant (Rosado *et al*., 2019). Therefore, this work aimed to identify the adaptability and stability of sweet potato genotypes in Western São Paulo in six planting seasons using the linear regression methodology proposed by Eberhart & Russell (1966) and the centroid method.

MATERIAL AND METHODS

Experimental sites and planting dates

The experiments were carried out on six planting dates in Western São Paulo: September, 2019 (spring-summer cycle) without irrigation; January, 2020 (summer-autumn cycle) without irrigation; April, 2020 (autumn-winter cycle) with irrigation; September, 2020 (winter-summer cycle) with irrigation; October, 2020 (spring-summer cycle) without irrigation; and December, 2020 (summer-autumn cycle) without irrigation. The experiments set up on September, 2019; January, 2020, and September, 2020 were conducted in the experimental area of the Center for Studies in Olericulture and Fruticulture of the University of Western São Paulo, in the municipality of Presidente Prudente-SP (22°7'39"S; 51°23'20"W, altitude 430 m). The experiments that started on April, 2020; October, 2020, and December, 2020 were located at a rural property in the municipality of Álvares Machado-SP (22°5'6"S; 51°28'44"W). The two locations are close together, approximately 6 km apart. According to Köppen's classification, the climate of these regions is Aw, with an average annual temperature of 25°C and precipitation of 1,400 to 1,500 mm, respectively, characterized by hot and humid summers and dry mild winters. The soil is classified as medium-textured dystrophic Red Argisol (Embrapa, 1999).

Plant material and experimental design

Twenty-one sweet potato genotypes were evaluated (Table 1), including 17 cultivars introduced in Western São Paulo, two experimental genotypes from the Germplasm Bank of the University of Western São Paulo (UBD coding), and two genotypes that have been cultivated for over two decades by farmers from this region. A randomized block design was used. The experimental unit consisted of 18 plants, spaced 0.33 m between plants within the planting line and 1.00 m between lines. The nine central plants of each plot were used in the evaluations. The blocks consisted of three rows represented by the planting lines. For planting, selected and standardized vines containing 12 buds were used, coming from young plants kept in nurseries and free from arthropod pests and pathogens.

Table 1. Peel color (PC), flesh color (FC), root shape (RS), and origin of the sweet potato genotypes tested in the six planting seasons in Western São Paulo. Presidente Prudente, UNOESTE, 2019-2020.

Genotypes	PC	FC	RS	Origin
INIA Arapey***	Pink	White	Round elliptic	INIA, Uruguay
BRS Rubissol*	Red	Cream	Round elliptic	EMBRAPA, Brazil
BRS Amélia*	Light pink	Orange	Long elliptic	EMBRAPA, Brazil
Beauregard*	Purpulish-red	Orange	Elliptic	LSU AgCenter, EUA
Princesa*	Cream white	Cream	Long	EMBRAPA, Brazil
Brazlândia Branca*	White	Light cream	Long	EMBRAPA, Brazil
Brazlândia Rosada*	Pink	Cream	Long	EMBRAPA, Brazil
Brazlândia Roxa*	Purple	Cream	Long	EMBRAPA, Brazil
Coquinho*	White	Light cream	Round	EMBRAPA, Brazil
SCS367 Favorita*	Light yellow	Orange	Long	EPAGRI, Brazil
SCS368 Ituporanga*	White	Cream	Round	EPAGRI, Brazil
SCS369 Águas Negras*	Purple	Cream	Long	EPAGRI, Brazil
SCS370 Luiza*	Purple	Purple	Elliptic	EPAGRI, Brazil
SCS371 Katiy*	Purple	White	Long elliptic	EPAGRI, Brazil
SCS372 Marina*	Purple	Yellow	Round elliptic	EPAGRI, Brazil
IAPAR 69*	Cream white	Yellow	Round	IAPAR, Brazil
Rainha Branca°	White	White	Long	Espírito Santo, Brazil
UBD 01**	Purple	Purple	Long	Unoeste, Brazil
UBD 02**	Purple	Purple	Elliptic	Unoeste, Brazil
Canadense$^+$	Pink	Cream	Elliptic	Farmes, Brazil
Ligeirinha Paulista$^+$	Purpulish-red	Light cream	Long elliptic	Farmes, Brazil

*Commercial cultivars with official registration in MAPA, Brazil. °Genotype without official registration cultivated in Espírito Santo and introduced in Western São Paulo by Professor Pedro Veridiano Baldotto. **Genotypes from the germplasm bank of the University of Western São Paulo that are in the selection phase; ***Cultivar with official registration in Uruguay and widely cultivated in Brazil; +Genotypes made available by producers in Western São Paulo and which have been widely cultivated for over two decades.

Preparation of planting areas and experimental conduction

For the soil preparation, two heavy plowings and three light harrowing rounds were carried out. Then, 0.4-0.5 m-high rows were raised. Before preparing the area and planting, soil samples were collected in the 0-20 cm depth layer to determine chemical attributes, with the following results for the experimental area of Presidente Prudente: pH ($CaCl_2$ 1 mol/L)= 5.1; MO= 8,4 g/dm^3; P_{resin}= 9.7 mg/dm^3; H+Al= 19 mmol$_c$/dm^3; K= 2.0 mmol$_c$/dm^3; Ca= 7.0 mmol$_c$/dm^3; Mg= 3.3 mmol$_c$/dm^3; SB= 12.3 mmol$_c$/dm^3; CEC= 31.3 mmol$_c$/dm^3; base saturation = 34.9%. Based on the soil chemical analysis, liming and base and top dressing were performed according to technical recommendations for sweet potato (Echer *et al*., 2015).

On the planting dates of April 24, 2020 and September 1, 2020, irrigation was performed using a hose with a microdripper installed near each plant. In these planting seasons, in the absence of rain, irrigation was carried out daily for the first ten days after planting the vines and every four days thereafter. Each irrigation lasted approximately 40 min with a flow rate of 1.5 L/h of H_2O per microdripper. Hand weeding was performed. Flutriafol (190 mL/ha) and Kasugamycin (300 mL/100 L of water) were applied preventively to control pest arthropods and diseases (Perrud *et al.*, 2021). During the experimental periods, daily data of average, maximum, and minimum air temperatures were collected in maximum and minimum thermometers, and rainfall was measured in rain gauges located 300 m from the experimental sites.

Harvest and parameters explored

The tuberous roots were harvested approximately 140 days after planting the experiments in spring and summer and approximately 150 days for those initiated in autumn and winter. Then, the tuberous roots were evaluated for commercial root yield, considering as commercial roots those heavier than 80 g, uniformly shaped and without pest damage, diseases, and cracks (Leal *et al.*, 2021).

Statistical analysis

Data were subjected to individual and joint analysis of variance considering the fixed model for genotypes and random model for environments. At the same time, data were tested for normality of errors and homogeneity of residual variances by the Lilliefors & Bartlett tests, respectively. Given the statistical assumptions, the analysis of adaptability and stability of the genotypes was performed using the centroid and Eberhart & Russell (1966) methods.

The centroid approach is a non-parametric method that aims to facilitate genotype indications, as it allows targeting genotypes according to their environmental variation (Lin & Binns, 1988; Pelúzio *et al.*, 2015). Using the centroid method, the proposed environments were classified into favorable and unfavorable using the environmental index proposed by Finlay & Wilkinson (1963):

$$I_j = \frac{1}{g}\sum_i Y_{ij} - \frac{1}{eg}Y_{..}$$

Where: Y_{ij}: mean of genotype i in environment j; Y: total of observations; e: number of environments and g: number of genotypes.

Through the centroid method, the response of each genotype in each environment was evaluated, characterized by negative environmental indices (unfavorable) or positive environmental indices (favorable). After establishing the average values of each ideotype, principal component analysis was carried out with the 21 genotypes and 4 representatives (four centroids), where the dispersion of the other genotypes was carried out around the centroids. From then on, the genotypes were classified into: I= high general adaptability, including the ones that present maximum response in favorable and unfavorable environments; II= specific adaptability to favorable environments, representing the genotypes with maximum response in favorable and minimum in unfavorable environments; III= specific adaptability to unfavorable environments, encompassing the genotypes with maximum response in unfavorable environments and minimum response in favorable environments; and IV= poorly adapted, representing the genotypes of inferior performance in all studied environments (Pelúzio *et al.*, 2015).

The analyses were performed using the statistical program Genes (Cruz, 2016).

$$\overline{Y_i} = \frac{\sum_j Y_{ij}}{e}$$

$$\hat{\beta}_1 = \frac{\sum_j Y_{ij} I_j}{\sum_j I_j^2}$$

$$\text{where } I_j = \frac{\sum_i Y_{ij}}{g} - \frac{\sum_{ij} Y_{ij}}{eg} \text{ (environmental index)}$$

$$\sigma^2_{d_i} = \frac{\left[\sum_j Y_{ij}^2 - \left(\frac{\sum_j Y_{ij}}{a}\right)^2\right] - \left[\left(\frac{\sum_j Y_{ij}}{\sum_j I_j^2}\right)^2 \sum_j I_j^2\right]}{e-2}$$

The method of Eberhart & Russell (1966) provides information about the relative performance of each genotype, as well as the average yield of the genotype (μ_i), its regression coefficient (β_1), and the variance of deviations from this regression (σ^2_{di}). Thus, it identifies the behavior of the genotypes in the environments, whose estimators are given by:

RESULTS AND DISCUSSION

Averages of climate data

In the planting seasons of September 21, 2019; January 31, 2020; April 24, 2020; September 1, 2020; October 30, 2020, and December 28, 2020, the accumulated rainfall was 809.2, 475.8, 439.8, 628.2, 968.6, and 634.8 mm, respectively, and the average air temperatures were 26.4, 23.3, 21.4, 26.2, 21.6, and 24.8°C, respectively (Figure 1A, 1B, 1C, 1D, 1E, and 1F).

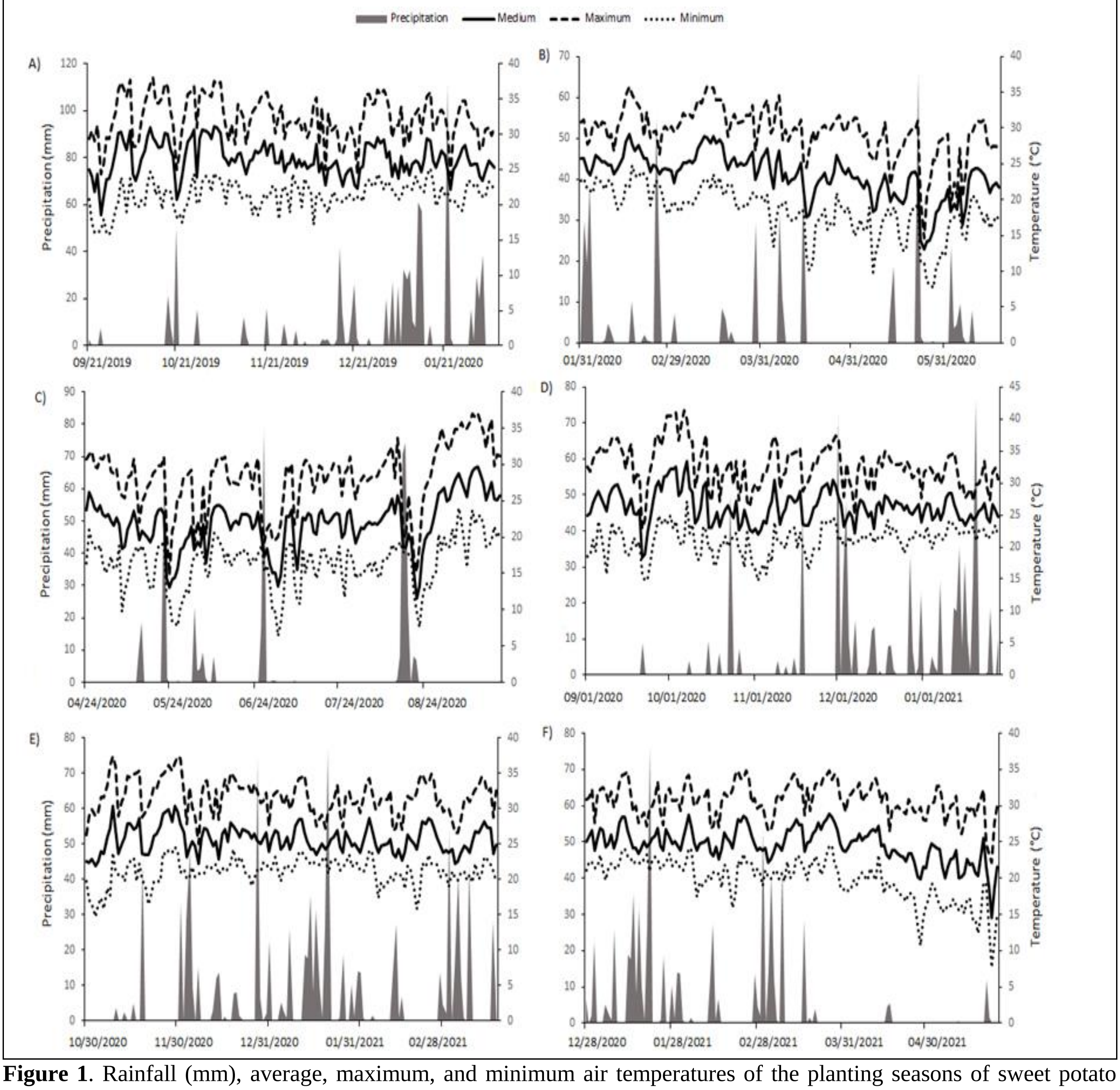

Figure 1. Rainfall (mm), average, maximum, and minimum air temperatures of the planting seasons of sweet potato genotypes in Western São Paulo: (A) September 21, 2019; (B) January 31, 2020; (C) April 24, 2020; (D) September 1, 2020; (E) October 30, 2020, and (F) December 28, 2020. Presidente Prudente, UNOESTE, 2019-2020.

It is noteworthy that the experiments from seasons April 24, 2020 and September 1, 2020 were irrigated. When irrigation was not used, at some moments, there was low accumulated rainfall and irregularity in the rain distribution. In this regard, the following seasons are highlighted: September 21, 2019, in which in the first 27 days after planting the vines, only 10.2 mm of accumulated rainfall occurred (Figure 1A); January 31, 2020, which between the 79th and 103rd days after planting had no rainfall (Figure 1B); and December 28, 2020, which from the 85th day after planting until the time of harvest had only 24.0 mm of accumulated rainfall (Figure 1F).

Favorable and unfavorable environments using the centroid method

Favorable environments were those that obtained the highest yield averages and positive environmental index (Table 2). We identified that in the plantations on January 31, 2020; April 24, 2020, and October 30, 2020, the environmental indices were favorable for the productivity of sweet potato roots (Table 2). This aspect is due to the soil and climate conditions, with temperatures and water availability through irrigation or regular rainfall that best met the needs of the genotypes (Figure 1B, 1C, and 1E). Although the January 31, 2020 season received no irrigation and had a period of no rainfall (between the 79th and 103rd days after planting), there was good water availability in the other periods of the cycle.

Table 2. Classification of planting times of sweet potato genotypes in Western São Paulo based on commercial tuberous root production using the environmental index (Íj) of the centroid method. Presidente Prudente, UNOESTE, 2019-2020.

Date	Environment classification	Mean	Íj	Maximum	Minimum
September 21, 2019	Unfavorable	8,585.2	-10505	24,068.0	852.5
January 31, 2020	Favorable	21,365.6	2274.9	46,186.6	1360.0
April 24, 2020	Favorable	23,930.7	4840	52,320.0	10173.3
September 1, 2020	Unfavorable	18,452.8	-637.8	41,460.0	4170.0
October 30, 2020	Favorable	28,469.0	9378.3	66,693.3	7400.0
December 28, 2020	Unfavorable	13,740.7	-5349.9	33,833.3	1580.0

The water demand of sweet potato from planting to harvesting is approximately 500 mm (Montes & Pantano, 2013; Prabawardani & Suparno, 2015). In turn, the water availability in the first three weeks after planting the vines is the most relevant to define the initial development of plants, while the water condition in the 40-50 days before harvesting is the one with the greatest influence on tuberous root yield (Lewthwaite & Triggs, 2012; Montes & Pantano, 2013). Therefore, it is more important to consider the regularity of rainfall than that accumulated during the sweet potato cycle. The ideal temperature for the development and growth of tuberous roots of sweet potato is close to 25°C. When temperatures below 15°C or above 35°C occur, root growth and development are hampered (Erpen *et al*., 2013). For plantations on January 31, 2020; April24, 2020, and October 30, 2020, with some exceptions regarding temperatures, these aforementioned conditions of rainfall and air temperatures were adequately met, resulting in favorable environments for the sweet potato crop.

The plantations on September 21, 2019; September 1, 2020, and December 28, 2020 were classified as having unfavorable environmental indices (Table 2). This is due to the low rainfall in the first three weeks after planting the vines on September 21, 2019 and the absence of rain in the last two months prior to harvest for cultivation that started on December 28, 2020 (Figure 1A and 1F). For the date September 1, 2020, although irrigation was used, the high air temperatures may have impaired tuberous root yield. In this planting season, the highest temperatures of all experimental periods were observed, with maximum temperatures exceeding 40°C on six occasions (Figure 1D). Temperature events close to 40°C lead to physiological damage that reduces the production of sweet potato tuberous roots (Gajanayake *et al*., 2015).

It is noteworthy that the concept of adaptability and stability used in the centroid method differs from the others present in the literature. This difference occurs because the genotype of maximum specific adaptation is not the one that performs well in groups of favorable or unfavorable environments but the one that has maximum values for a given group of environments (favorable and unfavorable) and minimum values for the other set (Pelúzio *et al*., 2015).

Principal component analysis based on the centroid method

Principal component analysis showed points (genotypes) close to the four ideotypes (Figure 2). The position of the genotypes in relation to the ideotypes in the scatter plot and the Cartesian distance values between the four points established using principal component analysis allow the classification of genotypes in terms of general adaptability or specific stability to a subgroup of environments (Marques *et al*., 2011).

The genotypes Canadense, IAPAR 69, and SCS 372 Marina are close to ideotype I, classified as having high general adaptability. The genotypes INIA Arapey and Brazlândia Roxa are close to ideotype II, characterized by specific adaptability to favorable environments. The genotypes Ligeirinha Paulista, UBD 01, and UBD 02 are close to ideotype III, which has specific adaptability to unfavorable environments. Finally, the genotypes Rainha Branca, SCS 368 Ituporanga, SCS 371 Katiy, SCS 369 Águas Negras, BRS Rubissol, Princesa, Brazlândia Branca, Brazlândia Rosada, Coquinho, SCS

367 Favorita, BRS Amélia, Beauregard, and SCS 370 Luiza were classified as poorly adapted to the tested environments, as they are close to ideotype IV (Figure 2).

Classification of sweet potato genotypes into ideotypes

The highest averages of commercial root production were observed for the Canadense, IAPAR 69, and SCS 372 Marina genotypes, classified as having high general adaptability (ideotype I); that is, they present the maximum values observed for all studied environments. Canadense showed a probability of 29.05%, the cultivar IAPAR 69 showed a probability of 51.58%, and the cultivar SCS 372 Marina showed a probability of 38.33% for the classification as ideotype I (Table 3). Each ideotype has a probability of 25%, so the greater the probability differs from 25%, the greater the reliability of the genotype cluster (Pelúzio *et al*., 2015). Values close to or greater than 50% indicate high confidence in the cluster (Pelúzio *et al*., 2015).

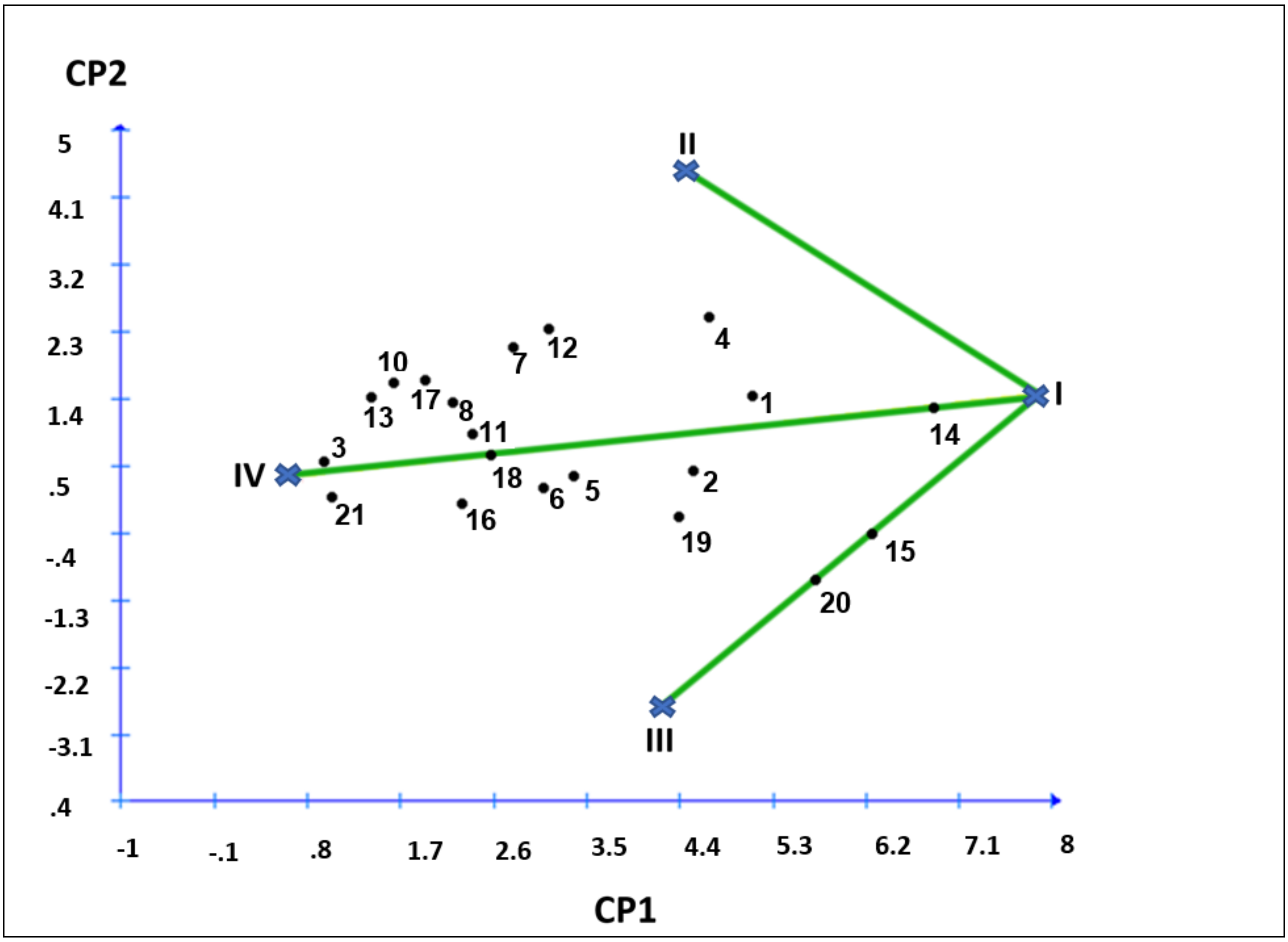

Figure 2. Graphic dispersion of the main components of 21 sweet potato genotypes for commercial tuberous root yield in six growing seasons in Western São Paulo. Centroids: I= high general adaptability, II= specific adaptability to favorable environments, III= specific adaptability to unfavorable environments, and IV= poorly adapted. Genotypes: 1. Canadense; 2. Ligeirinha Paulista; 3. Rainha Branca; 4. INIA Arapey; 5. SCS 368 Ituporanga; 6. SCS 371 Katiy; 7. SCS 369 Águas Negras; 8. BRS Rubissol; 9. Princesa; 10. Brazlândia Branca; 11. Brazlândia Rosada; 12. Brazlândia Roxa; 13. Coquinho; 14. IAPAR 69; 15. SCS 372 Marina; 16. SCS 367 Favorita; 17. BRS Amélia; 18. Beauregard; 19. UBD 01; 20. UBD 02; 21. SCS 370 Luiza. Presidente Prudente, UNOESTE, 2019-2020.

The cultivars INIA Arapey and Brazlândia Roxa with white and cream flesh, respectively, were classified as ideotype II, as they have specific adaptability to favorable environments and are able to respond positively to environmental improvements. Classified as ideotype III, the genotypes Ligeirinha Paulista, UBD 01, and UBD 02 have specific adaptability to unfavorable environments but do not respond positively to environmental improvements (Table 3). Genotypes classified as ideotype III can be indicated for sweet potato producers, who generally employ a low technological level of cultivation.

The genotypes Rainha Branca, SCS 368 Ituporanga, SCS 371 Katiy, SCS 369 Águas Negras, BRS Rubissol, Princesa, Brazlândia Branca, Brazlândia Rosada, Coquinho (white and cream-fleshed genotypes), SCS 367 Favorita, BRS Amélia, Beauregard (orange and yellow-fleshed), and SCS 370 Luiza (purple-fleshed) were classified as poorly adapted (Table 3). These genotypes were classified as ideotype IV because they showed lower values in all studied environments (Pelúzio *et al*., 2015). Most genotypes classified as poorly adapted can be justified through the method of analysis, where the comparison is only made with ideotypes of polarized (extreme) behavior (Nascimento *et al*., 2009). The smaller the difference between any genotype and ideotype I, the smaller the difference between it and the maximum performance genotype in all environments, making general adaptability necessarily associated with better performance (Pelúzio *et al*., 2015).

Table 3. Average yield of commercial tuberous roots of sweet potato genotypes cultivated in six planting seasons in Western São Paulo, classification into ideotypes using the centroid method, and the probability associated with its classification. Presidente Prudente, UNOESTE, 2019-2020.

Genotypes	Means (kg/ha)	Classification	Prob (I)	Prob (II)	Prob (III)	Prob (IV)
White and cream-fleshed genotypes						
Canadense	29,083.2	I	0.2905	0.2419	0.2504	0.2172
Ligeirinha Paulista	25,958.5	III	0.2659	0.2265	0.2704	0.2322
Rainha Branca	6,012.0	IV	0.0487	0.0583	0.0882	0.8047
INIA Arapey	23,390.0	II	0.2935	0.4012	0.1479	0.1574
SCS 368 Ituporanga	18,544.9	IV	0.1769	0.1839	0.3003	0.3390
SCS 371 Katiy	17,836.1	IV	0.1775	0.1879	0.2906	0.3440
SCS 369 Águas Negras	17,682.6	IV	0.1995	0.2733	0.2136	0.3136
BRS Rubissol	14,393.5	IV	0.1589	0.1961	0.2274	0.4177
Princesa	11,579.3	IV	0.1222	0.1458	0.2059	0.5261
Brazlândia Branca	11,734.2	IV	0.1404	0.1811	0.2014	0.4772
Brazlândia Rosada	14,320.4	IV	0.1546	0.1793	0.2466	0.4195
Brazlândia Roxa	19,943.3	II	0.2157	0.3166	0.1987	0.2691
Coquinho	10,925.1	IV	0.1320	0.1652	0.2012	0.5016
Orange and yellow-fleshed genotypes						
IAPAR 69	37,934.6	I	0.5158	0.2151	0.1453	0.1238
SCS 372 Marina	34,915.7	I	0.3833	0.2207	0.2237	0.1723
SCS 367 Favorita	14,008.9	IV	0.1485	0.1567	0.3010	0.3937
BRS Amélia	12,688.8	IV	0.1505	0.1877	0.2191	0.4427
Beauregard	13,713.0	IV	0.1492	0.1705	0.2505	0.4298
Purple-fleshed genotypes						
UBD 01	24,184.4	III	0.2492	0.2306	0.2719	0.2483
UBD 02	29,746.0	III	0.2841	0.1940	0.3181	0.2038
SCS 370 Luiza	6,309.6	IV	0.0558	0.0642	0.1122	0.7678

I= high overall adaptability; II= specific adaptability to favorable environments; III= specific adaptability to unfavorable environments; IV= poorly adapted.

Eberhart & Russell linear regression

The results of the adaptability and stability analysis by the linear regression method of Eberhart & Russell (1966) are shown in Table 4. The adaptability of the genotype is indicated through the regression coefficient (β_{1i}), meaning the capacity of the genotype to respond to environmental improvement (Domingues *et al*., 2013).

According to the methodology of Eberhart & Russell, genotypes with a regression coefficient equal to 1 ($\beta_{1i} = 1$) are considered to have wide adaptability, genotypes with a regression coefficient greater than 1 ($\beta_{1i} > 1$) have specific adaptation to favorable environments, and genotypes with a regression coefficient lower than 1 ($\beta_{1i} < 1$) present specific adaptation to unfavorable environments (Domingues *et al*., 2013).

The genotypes Canadense, Ligeirinha Paulista, INIA Arapey, SCS 369 Águas Negras, BRS Rubissol, Brazlândia Branca, Brazlândia Roxa, IAPAR 69, SCS 372 Marina, and BRS Amélia were classified with specific adaptability to favorable environments due to regression coefficients greater than 1. The other genotypes were classified with specific adaptability to unfavorable environments (β_{1i} <1) (Table 4). These genotypes should be used with caution, as their yields may be reduced in unfavorable environments such as adverse edaphoclimatic conditions and low levels of technology (Pelúzio *et al*., 2015).

Table 4. Range and average of commercial root yield (kg/ha) of sweet potato genotypes cultivated at different planting times in Western São Paulo, estimates of regression coefficients (β_{1i}), regression deviation (σ^2_{di}), and coefficient of determination (R^2) by the method of Eberhart and Russell (1966). Presidente Prudente, UNOESTE, 2019-2020.

Genotypes	Amplitude	Means	β_{1i}	σ^2_d	R^2 (%)
White and cream-fleshed genotypes					
Canadense	13,326.5 ~ 52,320.0	29,083.2	1.21	172386288.20**	33.85
Ligeirinha Paulista	8,085.0 ~ 38,833.3	25,958.5	1.09	68473657.00**	48.75
Rainha Branca	999.0 ~ 12,050.0	6,012.1	0.48	-6550852.31^{ns}	75.57
INIA Arapey	6,613.7 ~ 61,273.3	29,390.0	2.57	52522914.14**	86.82
SCS 368 Ituporanga	13,090.0 ~ 21,333.3	18,544.9	0.38	-8268018.30^{ns}	74.54
SCS 371 Katiy	10,197.0 ~ 26,913.3	17,836.1	0.63	-66352.43^{ns}	69.40
SCS 369 Águas Negras	2,211.0 ~ 37,893.3	17,682.6	1.86	19384.24^{ns}	95.08
BRS Rubissol	1,705.0 ~ 24,376.6	14,393.5	1.07	7996401.98^{ns}	78.99
Princesa	5,753.0 ~ 17,213.3	11,579.3	0.67	-7925835.75^{ns}	89.19
Brazlândia Branca	2,299.0 ~ 27,380.0	11,734.3	1.11	32122098.47**	64.45
Brazlândia Rosada	4,506.6 ~ 20,826.6	14,320.4	0.84	10279292.82^{ns}	67.60
Brazlândia Roxa	3,267.0 ~ 43,346.6	19,943.3	1.96	25501072.67*	86.98
Coquinho	852.5 ~ 25,130.0	10,925.1	0.89	38069691.66**	50.56
Orange and yellow-fleshed genotypes					
IAPAR 69	24,068.0 ~ 51,413.3	37,934.6	1.43	4211184.23^{ns}	89.38
SCS 372 Marina	21,681.0 ~ 66,693.3	34,915.7	1.38	246631420.71**	31.95
SCS 367 Favorita	4,460.0 ~ 29,513.3	14,008.9	0.54	68906491.25**	19.05
BRS Amélia	900.0 ~ 27,700.0	12,688.8	1.09	46984753.84**	56.65
Beauregard	9,466.6 ~ 24,933.3	13,713.0	0.26	31249100.90**	8.94
Purple-fleshed genotypes					
UBD 01	10,173.3 ~ 46,100.0	24,184.4	0.85	122969263.65**	25.43
UBD 02	18,400.0 ~ 41,280.0	29,746.0	0.40	82899371.05**	9.74
SCS 370 Luiza	1,360.0 ~ 12,453.3	6,309.6	0.30	5783165.09^{ns}	24.51
General mean		19,090.7			

β_{1i} =1– wide adaptability; β_{1i} >1– specific adaptability to favorable environments; β_{1i} <1– specific adaptability to unfavorable environments. * and ** significantly different at 5 and 1% probability, respectively, by the F test. ^{ns} = not significant (P>0.05).

The genotypes Rainha Branca, SCS 368 Ituporanga, SCS 371 Katiy, Princesa, Brazlândia Rosada, and Coquinho were classified as having specific aptitude for adverse environment β1i <1 (Table 4). Despite not responding satisfactorily to environments with technological advances, these genotypes maintain their yields under adverse conditions, thus being suitable for cultivation systems that employ low technology (Pelúzio *et al*., 2015).

None of the genotypes showed broad adaptability since, in all of them, the regression coefficient was different from 1 ($\beta_{1i} \neq 1$). On the other hand, the genotypes Canadense, Ligeirinha Paulista, INIA Arapey, Brazlândia Roxa, IAPAR 69, SCS 372 Marina, UBD 01, and UBD 02 showed commercial root yields above the general average. Additionally, the smallest amplitudes were observed for the Rainha Branca, BRS Amelia, and SCS 370 Luiza genotypes; in turn, these last two genotypes produced no more than (12.45 t/ha) in any of the environments (Table 4).

The regression deviation (σ^2_d) indicates the stability of the genotypes, demonstrating the predictability of their behavior facing environmental changes. High stability of behavior is observed when regression deviations show non-significant estimates and are confirmed when high values of the coefficient of determination (R^2) are obtained (Marchiori *et al*., 2015). Thus, we observed that only the genotypes Rainha Branca, SCS 368 Ituporanga, SCS 371 Katiy, SCS 369 Águas Negras, BRS Rubissol, Princesa, Brazlândia Rosada, IAPAR 69, and SCS 370 Luiza showed non-significant regression deviation. Additionally, only the genotypes SCS 369 Águas Negras, BRS Rubissol, Princesa, and IAPAR 69 had higher R^2 values (above 78.99%) (Table 4). A coefficient of determination greater than 80% represents low dispersion in the data, indicating high confidence in the environmental response determined by the regressions (Raizer & Vencovsky 1999). According to Cruz *et al*., (2012), the regression is satisfactorily explained, as it may be used to refer to genotype behavior according to the environment.

Weighting the results based on the two methods

The results found in this work corroborate Silva & Duarte (2006), who pointed out the methods of Eberhart & Russell and Lin & Binns as poorly correlated and, therefore, provide additional information in relation to one another. The simultaneous use of these methods produces estimates with different approaches to the interaction between genotype and environment. Genotypes determined with general adaptability and stability or indicated for favorable or unfavorable environments, regardless of the method, can be considered reliable for recommendation (Cardoso *et al*., 2021; Rezende *et al*., 2021). Additionally, the influence of planting times and climatic conditions on the productivity of commercial tuberous roots for most of the genotypes tested was evident.

Considering that sweet potato planting in Western São Paulo is carried out in all seasons of the year and the scarcity of scientific information on the adaptability and stability of genotypes in the region, this study is crucial to indicate genotypes according to the peculiarities of the region. Based on the centroid method, the Canadense, IAPAR 69, and SCS 372 Marina genotypes can be indicated for planting in all environments tested in this work. At the same time, these genotypes, together with Ligeirinha Paulista, SCS 369 Águas Negras, BRS Rubissol, Brazlândia Branca, and BRS Amélia (by the linear regression method) and the genotypes INIA Arapey and Brazlândia Roxa (based on the two methods used), were indicated for favorable environments.

Using widely adapted genotypes such as Canadense, IAPAR 69, and SCS 372 Marina in a region that carries out continuous cultivation of sweet potato, such as Western São Paulo, facilitates the logistics of maintaining the parent plants and the production of commercial tuberous roots by farmers. At the same time, edaphoclimatic conditions are not always predictable, which makes these widely adapted genotypes even more attractive. On the other hand, for genotypes in which specific adaptation to favorable environments has been identified, they are recommended only when the edaphoclimatic conditions are favorable and predictable. For these, the air temperatures must occur within an ideal range, and it is recommended to use irrigation or to be able to predict whether the rainfall will be regular during the sweet potato development cycle.

We observed that Canadense and Ligeirinha Paulista, already planted throughout the year by farmers in Western São Paulo, have a potential equal to or greater than most of the other genotypes tested. Despite being indicated as adaptable to unfavorable environments by the centroid method, Ligeirinha Paulista had probability values of small variation between ideotypes (0.2659, 0.2265, 0.2704, and 0.2322 for ideotypes I, II, III, and IV, respectively). The commercial cultivars IAPAR 69 and SCS 372 Marina, which showed wide adaptation, have official registration with the Brazilian Ministry of Agriculture, Livestock, and Supply, which facilitates the official production of certified propagation material and that best meets the legislation for the commercialization of the final product. On the other hand, the Canadense and Ligeirinha Paulista genotypes, which have been maintained and planted by farmers in Western São Paulo for over two decades, are of unknown origin, making it challenging to sell certified plants.

Genotypes indicated for unfavorable environments may be relevant for farmers who use low technology and no irrigation or for times of the year when adverse weather conditions are predictable for sweet potato development. For unfavorable environments, the experimental purple-fleshed genotypes UBD 01 and UBD 02 stood out, with commercial tuberous root yield higher than the general average of the genotypes.

Notably, the average productivity of sweet potato in Western São Paulo is 17.0 t/ha (IBGE, 2021). In turn, the yield obtained by most of the genotypes indicated as widely adapted or only suitable for favorable or unfavorable environments was higher than the current average for the region. Thus, it becomes possible to increase sweet potato yield by recommending genotypes identified as superior based on adaptability and stability for each environment.

The linear regression methodology proposed by Eberhart & Russell (1966) and the centroid method used to identify the adaptability and stability of sweet potato genotypes in six planting seasons in Western São Paulo resulted in complementary results.

The Canadense, IAPAR 69, and SCS 272 Marina genotypes were identified as having wide adaptation to the environment and can be indicated for planting at different times in Western São Paulo.

The genotypes Ligeirinha Paulista, INIA Arapey, SCS 369 Águas Negras, BRS Rubissol, Brazlândia Branca, Brazlândia Roxa, and BRS Amélia are suitable for cultivation environments favorable to sweet potato development.

For unfavorable environments, UBD 01 and UBD 02 are recommended. These genotypes were indicated by both methods employed, having commercial tuberous root yields higher than the general average.

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