










RESEARCH ARTICLE

Genetic diversity via REML-BLUP of ex situ conserved macauba [*Acrocomia aculeata* (Jacq.) Lodd. ex Mart.] ecotypes

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Abstract Macauba [*Acrocomia aculeata* (Jacq.) Lodd. ex Mart.], a palm tree native to Brazil, has a high potential as an alternative source for vegetal oil production. It has several applications in the cosmetics, pharmaceuticals and food industries, and for the production of biofuels. The conservation and characterization of its germplasm are essential for progress in genetic improvement. In this sense, a study of genetic divergence was carried out based on predicted genetic values of 88 accessions from the Active Germplasm Bank of Macauba of EMBRAPA (Brazilian

Agricultural Research Corporation). Seven morpho-agronomic characters were observed. The obtained dendrogram generated seven groups. There was a tendency to group accessions according to geographic origin. The graphical dispersion of accession scores plotted in a two-dimensional space showed a pattern correlated to the clusters observed in the dendrogram. The first two principal components (PC1 and PC2) explained 70.4% of the total divergence. The most important traits associated with PC1 and PC2 were the number of fruit bunches and fruit volume, respectively. The application of mixed models in the study of divergence was useful in structuring the germplasm. The structuring of the germplasm is crucial to assist in the choice of parents aiming the selection of recombinant individuals with a superior performance in segregating generations.

Keywords Genetic divergence · Genetic resources · Mixed models · Agroenergy

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Introduction

Macauba [*Acrocomia aculeata* (Jacq.) Lodd. ex Mart.] is a native palm with distribution in the tropics and subtropics of the American continent, with large dissemination in Brazilian regions, especially in the Cerrado (Lorenzi et al. 2010). This resource of the

Brazilian biodiversity stands out for several characteristics of commercial interest, mainly the production of oil with a potential use in the cosmetics, pharmaceuticals and food industries (Callegari et al. 2014; Lescano et al. 2015; Hiane et al. 2005) and for the production of biodiesel (Navarro-Díaz et al. 2014; Michelin et al. 2015; César et al. 2015) and other biofuels, such as biokerosene (Lanes et al. 2014; Falasca et al. 2013), in addition to the use of pulp in natura, which can be processed as flour and used in food products (Aristone and Leme 2006). Several studies have shown the nutritional quality of the pulp (Ramos et al. 2008) and the kernel of macauba (Hiane et al. 2006), and the superiority in macro- and micronutrient contents of the fruit when compared to other tropical fruits in Brazil (Oliveira et al. 2006). In terms of energy, the endocarp is suited for charcoal production (Silva et al. 1986; Evaristo et al. 2016), and the waste biomass is suited for bio-oil production (Cardoso et al. 2016). Vegetal oil extraction residues (pulp and kernel cake) have a potential for animal feed (Rufino et al. 2011; Azevedo et al. 2012; Fonseca et al. 2012). In addition to the evidenced potential of this species in a future scenario of climate change, i.e., an increase in terrestrial temperature, an increase in water deficiency and forecasts of changes in the current agricultural configuration in Brazil for the next decades (Pinto et al. 2008), native species from arid regions, or those occurring in dry seasons, such as macauba, may become viable alternatives in areas with a greater climatic risk for the production of food and renewable energy.

The conservation of genetic resources represents a guarantee of genes for the sustainability of plant improvement works (Wetzel 2006). The improvement process is highly dependent on the existing genetic base, highlighting the need for collection, characterization and conservation of these resources in a germplasm bank, serving as an input for the development of cultivars (Queiroz and Lopes 2007). One of the critical points for the breeder in using accessions from a germplasm bank is the lack of information. The lack of characterization data is a critical and limiting point for the use of accessions in genetic improvement (Tombolato et al. 2004). In this sense, the intensification of activities related to characterization and/or evaluation is critical for the purposes of breeding programs aiming to advance in the selection of superior individuals. Despite advances in cultivation

technology and knowledge generation regarding macauba in the last decade, there is a need to identify promising macauba plants suitable for a production system able to overcome the limitations of this species, which may interfere in cultivation, making it viable for its insertion in the Brazilian agricultural scenario.

The REML (residual or restricted maximum likelihood), developed by Patterson and Thompson (1971), has replaced the ANOVA method in the analysis of experiments and has a wide application in perennial plant species such as fruit trees and agro-industrial fruit trees (Viana and Resende 2014). The use of mixed models with random effects of treatments allows a simultaneous correction of environmental effects and enables the minimization of prediction errors and non-addicted prediction of genetic values (Resende 2004). To eliminate the residual environmental effects embedded in phenotypic data, it is necessary to consider the effects of treatments as random. This occurs through mean shrinkage effect or multiplication of the phenotypic value corrected by a function of the coefficient of genotypic determination associated with the trait (Resende and Duarte 2007). That is, when we apply the mixed model, we consider predicted genetic means rather than phenotypic means. Thus, the lower phenotypic values are disadvantaged by the residual effects of the environment or the higher values that were favored by these effects approach the general average. In this context, the objective of this study is to characterize genetic variability through the prediction of genetic values using mixed models in ecotypes of macauba preserved in an active germplasm bank.

Material and methods

Eighty-eight accessions (half-sibling progenies) of the Active Germplasm Bank of Macauba (BAGMC) of EMBRAPA, kept in an experimental area located in Planaltina, DF, were evaluated. The experimental design was randomized blocks with three replications composed of plots of one to four plants in a spacing of 5 m × 5 m. The study involved accessions from the Federal District and the states of Minas Gerais, Goiás, São Paulo and Pará (Table 1).

The BAGMC area is located at coordinates 15°39'10.0" S 47°44'50.0" W at 1200 m altitude, in

Table 1 Identification of ex situ conserved BAGMC macauba accessions, respective collection locations and geographic regions of origin

Regions of origin/Federal Unit and Köppen-Geiger climate classification	n°	ID accessions	Collection locations
Region of Brasília, Federal District	5	5)DFED-1	Planaltina
Tropical savannah with dry winter (Aw)	6	6)DFED-2	Planaltina
	20	20)DFED-3	Planaltina
	25	25)DFED-4	Paranoá
	26	26)DFED-5	Planaltina
	36	36)DFED-6	Planaltina
	38	38)DFED-7	Planaltina
	40	40)DFED-8	Planaltina
	51	51)DFED-9	Paranoá
	52	52)DFED-10	Planaltina
	64	64)DFED-11	Planaltina
	65	65)DFED-12	Planaltina
	67	67)DFED-13	Planaltina
	68	68)DFED-14	Planaltina
	69	69)DFED-15	Planaltina
	70	70)DFED-16	Planaltina
	71	71)DFED-17	Planaltina
	72	72)DFED-18	Planaltina
	73	73)DFED-19	Planaltina
	74	74)DFED-20	Planaltina
	91	91)DFED-21	Planaltina
92	92)DFED-22	Planaltina	
93	93)DFED-23	Planaltina	
94	94)DFED-24	Planaltina	
95	95)DFED-25	Planaltina	
96	96)DFED-26	Paranoá	
Region of Entorno, Goiás	13	13)ENTO-1	Cabeceiras
Tropical savannah with dry winter (Aw)	22	22)ENTO-2	Formosa
	29	29)ENTO-3	Formosa
	35	35)ENTO-4	Planaltina de Goiás
	37	37)ENTO-5	Formosa
	39	39)ENTO-6	Formosa
	48	48)ENTO-7	Planaltina de Goiás
	88	88)ENTO-8	Formosa
	90	90)ENTO-9	Cabeceiras
	Region of Chapada dos Valadares, Goiás	47	47)CVAL-1
Tropical savannah with dry winter (Aw)	49	49)CVAL-2	Cavalcante
Region of Anápolis, Goiás	2	2)ANAP-1	São Francisco do Goiás
Tropical savannah with dry winter (Aw)	3	3)ANAP-2	São Francisco do Goiás
	34	34)ANAP-3	Jaraguá
	42	42)ANAP-4	Jaraguá
Region of Porangatu, Goiás	7	7)PORA-1	Porangatu
Tropical savannah with dry winter (Aw)	15	15)PORA-2	Porangatu

Table 1 continued

Regions of origin/Federal Unit and Köppen-Geiger climate classification	n°	ID accessions	Collection locations
	19	19)PORA-3	Porangatu
	32	32)PORA-4	Santa Tereza de Goiás
	33	33)PORA-5	Porangatu
	41	41)PORA-6	Campinorte
	43	43)PORA-7	Porangatu
	44	44)PORA-8	Porangatu
	55	55)PORA-9	Estrela do Norte
Region of Ceres, Goiás	45	45)CERE-1	São Luiz do Norte
Tropical savannah with dry winter (Aw)	46	46)CERE-2	São Luiz do Norte
Region of Unaí, Minas Gerais	4	4)UNAI-1	Uruana de Minas
Tropical savannah with dry winter (Aw)	10	10)UNAI-2	Arinos
	17	17)UNAI-3	Arinos
	18	18)UNAI-4	Buritis
	89	89)UNAI-5	Arinos
Region of Montes Claros, Minas Gerais	8	8)MCLA-1	Montes Claros
Tropical savannah with dry winter (Aw)	23	23)MCLA-3	Montes Claros
	54	54)MCLA-4	São João da Lagoa
Region of Belo Horizonte, Minas Gerais	1	1)BHOR-1	Betim
Tropical savannah with dry winter (Aw)	9	9)BHOR-2	Sete Lagoas
	14	14)BHOR-3	Nova Lima
	56	56)BHOR-4	Belo Horizonte
	58	58)BHOR-5	Ouro Preto
	59	59)BHOR-6	Betim
	60	60)BHOR-7	Sabará
Region of Alto Parnaíba, Minas Gerais	12	12)APAR-1	Uberaba
Temperate climate with dry winter and hot summer (Cwa)	63	63)APAR-2	Córrego Dantas
	76	76)APAR-5	Córrego Dantas
	78	78)APAR-7	Carmo do Parnaíba
	79	79)APAR-8	Carmo do Parnaíba
	80	80)APAR-9	Carmo do Parnaíba
	83	83)APAR-12	Carmo do Parnaíba
	85	85)APAR-14	Lagoa Formosa
Region of Lavras, Minas Gerais	16	16)LAVR-1	Ingaí
Temperate climate with dry winter and warm summer (Cwb)	27	27)LAVR-2	Ingaí
	28	28)LAVR-3	Ingaí
	50	50)LAVR-4	Itutinga
	53	53)LAVR-5	Ingaí
Region of Ituverava, São Paulo	21	21)ITUV-1	Buritizal
Temperate climate with dry winter and warm summer (Cwb)	24	24)ITUV-2	Buritizal
	30	30)ITUV-3	Buritizal
	31	31)ITUV-4	Buritizal
	97	97)ITUV-5	Buritizal
	98	98)ITUV-6	Igarapava
Region of Marabá, Pará	57	57)MARA-1	Marabá
Tropical savannah with dry winter (Aw)	99	99)MARA-2	Marabá

soil classified as Ferralsols (WRB 2015), with clayey texture and low natural fertility, previously covered by vegetation typical of the Cerrado biome. According to the Köppen-Geiger classification, the local climate is Aw (Equatorial savannah with dry winter) with an average annual accumulated precipitation of 1400 mm, concentrated between October and March, and a dry and colder period of 5–6 months. Table 2 presents meteorological data for the years corresponding to the period of field evaluations.

Seven traits were evaluated: precocity (PRE: number of months from planting to first flowering), number of spaths (NSP: average number of spaths/year; three harvests: 2016/17, 2017/18 and 2018/19), number of fruit bunches (NFB: average number of fruit bunches/year; three crops: 2016/17, 2017/18 and 2018/19), number of fruits (NFR: average number of fruits/year; two crops, 2017/18 and 2018/19), fruit volume (FRV: cm³, sample of five fruits/plant; two harvests: 2017/18 and 2018/19), fruit mass (FRM: g, wet base corrected to 40% of moisture; sample of five fruits/plant; two harvests: 2017/18 and 2018/19), and average fruit productivity (PRD: ton/ha, wet base corrected to 40% moisture; density 400 plants/ha; two harvests: 2017/18 and 2018/19). The fruits were harvested in a staggered manner after the beginning of the natural fall of the fruits for each germplasm bank accession, this being the point of natural maturation. All data were obtained at the plant level (individual).

The analysis followed the statistical model number 1: $y = Xr + Za + Wp + e$, where “y” is the data vector, “r” is the vector of the replication effects

Table 2 Meteorological informations from the BAGMC area corresponding to the period of 2016–2019, Planaltina, Federal District, Brazil

Year	APP mm	RH _{max} %	RH _{min}	RH _{mea}	T _{max} °C	T _{min}	T _{mea}
2016	1112	85.0	40.9	66.0	28.4	14.0	21.2
2017	967	85.2	40.9	64.3	27.8	14.2	20.7
2018	1136	86.4	43.0	67.2	28.4	17.0	21.8
2019	1096	83.4	38.9	63.3	29.4	17.8	22.9

Accumulated pluviometric precipitation (APP), maximum value of relative humidity (RH_{max}), minimum value of relative humidity (RH_{min}), mean air relative humidity (RH_{mea}), maximum temperature (T_{max}), minimum temperature (T_{min}) and mean temperature (T_{mea})

(assumed as fixed) added to the general mean, “a” is the vector of individual (random) additive genetic effects, “p” is the vector of plot (random) effects, and “e” is the vector of errors or residues (random). Capital letters represent the incidence matrices for these purposes. Based on the average (BLUP) and variance (REML) components obtained by the model, the predicted additive genetic values “u + a” were estimated. Data were analyzed using the Selegen-REML/BLUP software (Resende 2007).

For the cluster analysis, a distance matrix was generated by dissimilarity measures obtained via generalized Mahalanobis distance (Selegen, Model 104) based on the predicted additive genetic values of the evaluated characters using mixed models (Selegen, Model 1). A dendrogram was constructed using the grouping obtained by the UPGMA hierarchical method (Unweighted Pair Group Method with Arithmetic Mean) using the NTSYS software (Rohlf 2000). The Mantel test, based on 10,000 re-samples, was applied to analyze the correlation between the original distance matrix and the graphic matrix in order to analyze the consistency of the grouping and its graphic representation in a dendrogram. The principal component analysis (Selegen, Model 103) was applied considering only the matrices of predicted additive genotypic values and the correlations between variables. In this case, the principal component analysis is equivalent to the canonical variates technique since the residual dispersion matrix is already considered when predicting genotypic values (Resende 2007). A two-dimensional graph was plotted based on the scores obtained from the first two principal components using the PAST software, version 3.26 (Hammer et al. 2001).

Results and discussion

The generated dendrogram showed the formation of seven groups, using the cut-off point as a criterion for visual analysis of branches of the dendrogram. The cut was established at points where there is an abrupt change in the branch (Fig. 1).

There is a tendency to group accessions according to geographic origin and, but at the same time, accessions of the same origin were distributed among subgroups, which indicates an existing variability. The group 1 was composed mainly of accessions from

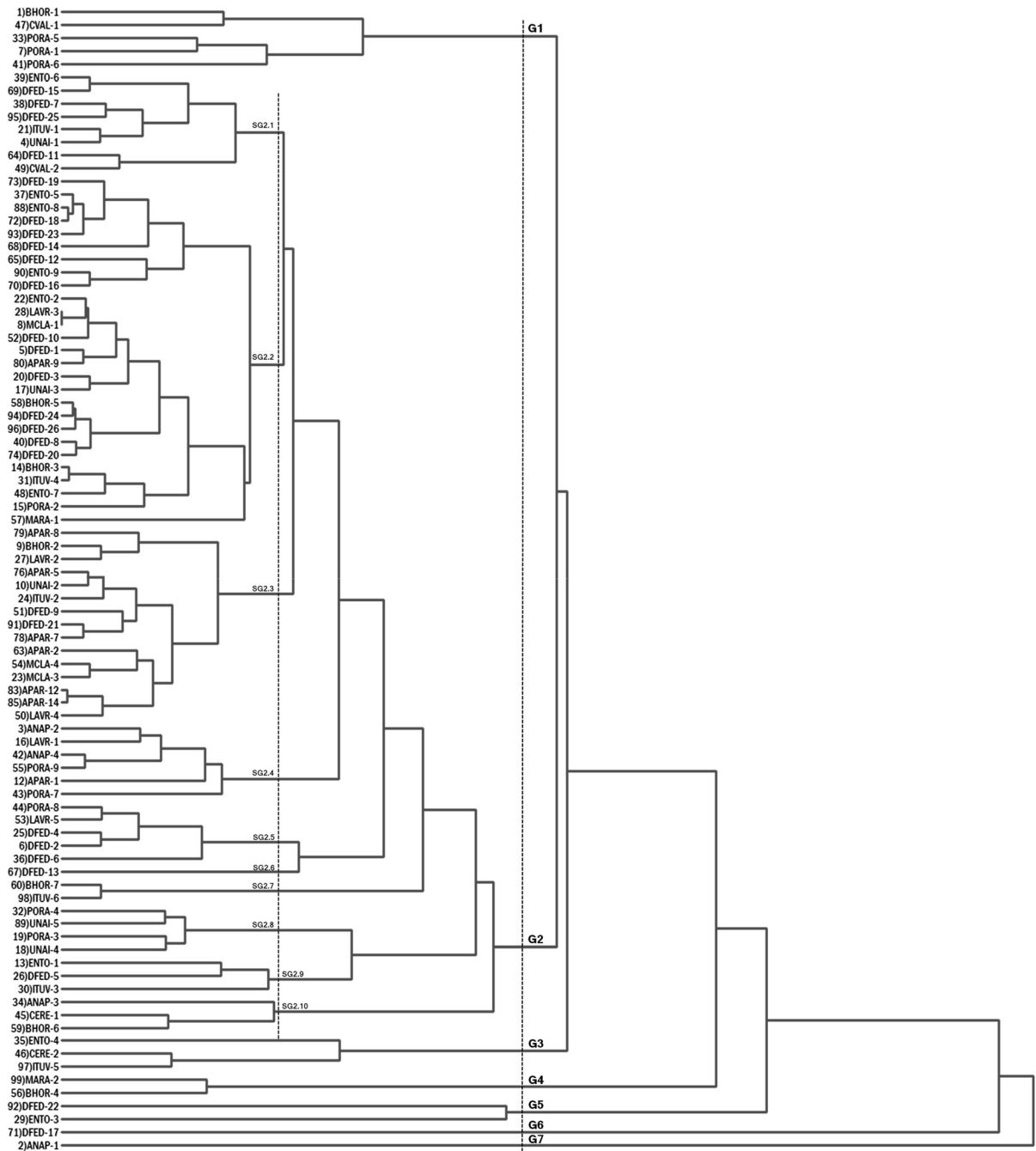


Fig. 1 Dendrogram of the cluster obtained using the UPGMA hierarchical method generated from the generalized Mahalanobis distance based on predicted additive genetic values of the traits precocity (PRE), number of spaths (NSP), number of

fruited bunches (NFB), number of fruits (NFR), fruit volume (FRV), fruit mass (FRM), and productivity (PRD) observed in 88 accessions of the BAGMC. Planaltina, Federal District, Brazil, 2016–2019

Table 3 Additive genetic values predicted for the traits precocity (PRE), number of spaths (NSP), number of fruited bunches (NFB), number of fruits (NFR), fruit volume (FRV), fruit mass (FRM), and productivity (PRD) observed in 88 accessions of the BAGMC

ID Accessions	PRE months	NSP	NFB	NFR	FRV cm ³	FRM g	PRD ton/ha
5)DFED-1	75.8	3.63	1.47	148.4	33.7	34.2	2.41
6)DFED-2	80.8	3.72	1.67	254.0	26.0	28.8	3.50
20)DFED-3	72.6	3.71	1.67	204.3	29.6	31.5	3.59
25)DFED-4	75.3	4.04	1.82	274.5	27.4	28.2	3.75
26)DFED-5	70.3	3.60	1.54	233.3	29.3	31.8	4.24
36)DFED-6	87.2	3.62	1.77	289.5	28.7	31.7	3.84
38)DFED-7	84.3	3.27	1.37	148.7	23.5	24.7	1.83
40)DFED-8	85.5	3.16	1.28	147.4	27.6	30.3	2.42
51)DFED-9	87.2	3.37	1.55	162.1	32.2	32.0	2.69
52)DFED-10	74.5	3.38	1.42	136.7	31.8	33.3	2.69
64)DFED-11	80.9	3.67	1.36	113.3	20.9	23.2	1.56
65)DFED-12	77.7	4.08	1.60	135.5	28.0	28.3	1.82
67)DFED-13	91.3	3.45	1.80	309.4	20.4	24.1	3.67
68)DFED-14	82.8	3.72	1.40	173.0	23.3	22.5	1.93
69)DFED-15	90.9	3.14	1.44	123.7	27.8	30.8	2.12
70)DFED-16	75.8	3.73	1.57	130.9	24.6	26.3	1.93
71)DFED-17	96.7	2.94	1.50	258.8	31.9	33.8	5.95
72)DFED-18	79.4	3.94	1.51	188.0	25.7	27.1	2.60
73)DFED-19	76.8	4.04	1.58	209.4	27.9	26.6	2.72
74)DFED-20	86.0	3.23	1.26	108.0	27.9	30.4	1.91
91)DFED-21	83.1	3.23	1.45	148.6	35.5	34.4	2.27
92)DFED-22	74.5	4.20	1.35	145.2	34.3	27.0	2.00
93)DFED-23	80.2	3.87	1.48	142.1	25.0	27.2	2.00
94)DFED-24	87.2	3.16	1.31	132.4	29.7	32.2	2.11
95)DFED-25	93.7	3.20	1.30	124.1	28.4	27.9	1.54
96)DFED-26	79.9	3.25	1.30	124.1	30.5	32.1	1.91
13)ENTO-1	78.2	3.82	1.64	239.8	29.6	32.0	4.93
22)ENTO-2	72.8	3.44	1.38	128.2	30.4	30.9	2.08
29)ENTO-3	80.1	4.63	1.62	221.8	24.8	27.6	3.01
35)ENTO-4	54.7	3.22	1.50	121.7	30.9	35.7	1.93
37)ENTO-5	76.4	3.99	1.55	181.4	24.9	26.5	2.26
39)ENTO-6	87.0	3.36	1.55	168.4	22.3	26.7	2.58
48)ENTO-7	81.3	3.37	1.53	234.7	26.2	28.3	3.15
88)ENTO-8	76.6	3.81	1.46	165.5	26.8	27.4	2.30
90)ENTO-9	72.7	3.77	1.51	137.3	25.6	26.9	2.00
47)CVAL-1	63.9	3.51	1.45	216.7	26.4	22.2	2.58
49)CVAL-2	78.9	3.47	1.24	104.8	24.0	24.3	1.69
2)ANAP-1	54.4	3.58	1.58	142.7	52.6	39.8	2.91
3)ANAP-2	60.1	3.81	1.80	227.8	29.8	26.4	3.19
34)ANAP-3	55.4	3.77	1.97	223.7	28.6	30.7	4.31
42)ANAP-4	64.2	3.20	1.70	248.9	30.7	28.3	3.49
7)PORA-1	73.3	3.20	1.87	442.0	24.0	21.4	5.62
15)PORA-2	74.2	3.20	1.64	275.1	25.2	27.0	4.34

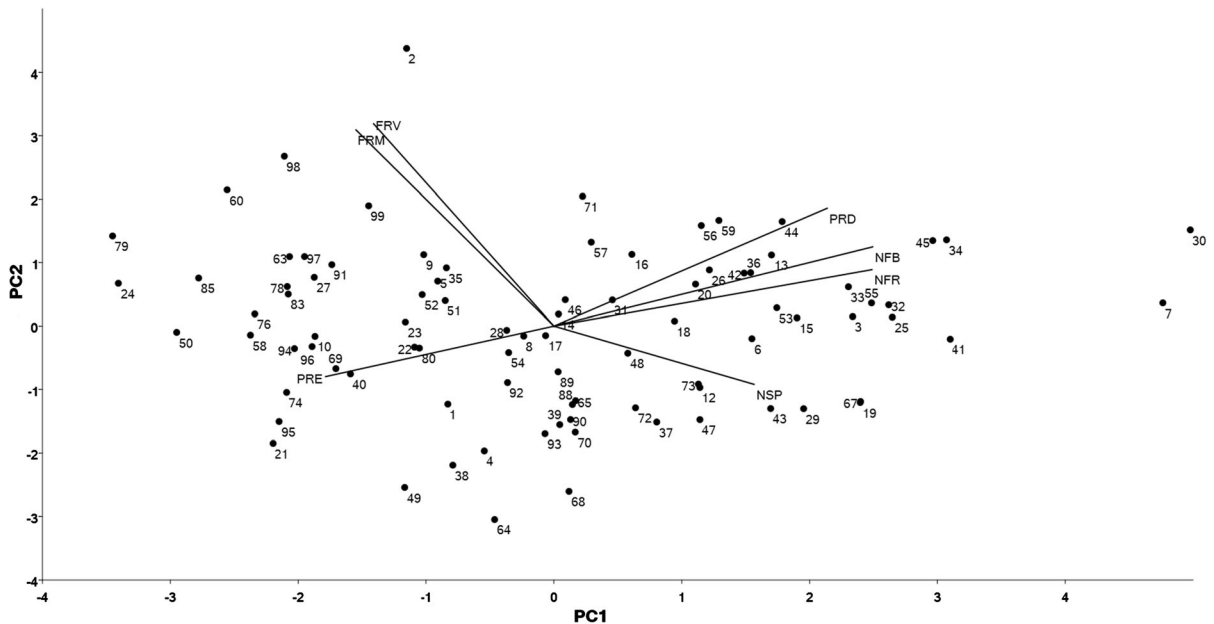
Table 3 continued

ID Accessions	PRE months	NSP	NFB	NFR	FRV cm ³	FRM g	PRD ton/ha
19)PORA-3	66.7	3.40	1.62	241.9	22.5	21.8	3.95
32)PORA-4	70.2	3.49	1.77	254.3	25.6	27.0	4.69
33)PORA-5	71.4	3.30	1.69	320.1	30.8	25.4	4.09
41)PORA-6	63.6	3.18	1.70	324.8	23.0	23.9	4.32
43)PORA-7	70.6	3.46	1.69	219.8	25.8	21.8	2.75
44)PORA-8	74.6	3.58	1.78	273.4	32.6	32.0	4.18
55)PORA-9	65.8	3.47	1.77	277.3	27.8	26.6	3.84
45)CERE-1	58.8	3.50	1.96	263.5	27.7	30.6	4.10
46)CERE-2	59.9	3.45	1.51	169.0	30.4	31.8	2.48
4)UNAI-1	84.1	3.25	1.42	142.8	23.2	24.9	2.28
10)UNAI-2	83.9	3.11	1.41	116.8	31.0	31.5	2.05
17)UNAI-3	81.5	3.59	1.50	176.7	28.7	30.5	3.05
18)UNAI-4	76.5	3.29	1.50	220.1	27.5	27.6	4.33
89)UNAI-5	74.0	3.34	1.49	151.4	25.7	28.2	2.94
8)MCLA-1	74.2	3.57	1.50	157.5	29.5	30.6	2.56
23)MCLA-3	80.2	3.21	1.43	152.2	33.3	29.6	2.38
54)MCLA-4	81.3	3.24	1.51	185.0	29.6	27.9	2.49
1)BHOR-1	85.5	2.99	1.31	202.0	27.2	25.4	2.49
9)BHOR-2	86.2	3.17	1.46	201.3	35.6	32.6	3.07
14)BHOR-3	78.7	3.28	1.49	216.3	30.3	29.4	3.09
56)BHOR-4	76.2	3.61	1.84	226.4	37.3	30.3	3.43
58)BHOR-5	87.3	3.10	1.25	135.8	31.5	32.7	2.08
59)BHOR-6	68.2	3.59	1.77	228.2	32.2	33.9	3.65
60)BHOR-7	89.8	3.12	1.37	146.7	37.3	40.4	2.95
12)APAR-1	75.0	3.52	1.67	217.7	24.9	26.2	2.48
63)APAR-2	82.4	3.12	1.38	140.5	39.1	32.6	2.39
76)APAR-5	90.8	2.92	1.40	125.3	33.3	31.9	2.10
78)APAR-7	92.2	3.13	1.40	151.1	34.3	33.8	2.42
79)APAR-8	99.6	2.78	1.20	142.6	38.0	36.5	2.89
80)APAR-9	82.7	3.57	1.43	144.9	29.6	31.8	2.18
83)APAR-12	92.2	3.05	1.40	150.9	35.1	32.1	2.41
85)APAR-14	97.4	2.94	1.37	137.9	37.4	33.0	2.25
16)LAVR-1	65.5	3.39	1.73	186.4	33.5	31.3	2.84
27)LAVR-2	94.8	2.90	1.31	198.0	34.5	32.2	3.13
28)LAVR-3	75.0	3.62	1.49	150.7	30.9	30.6	2.55
50)LAVR-4	96.3	2.88	1.30	119.1	35.8	30.0	1.91
53)LAVR-5	76.2	3.50	1.71	263.6	28.5	27.6	3.75
21)ITUV-1	88.2	2.96	1.29	99.9	27.0	25.9	1.49
24)ITUV-2	92.6	2.76	1.30	105.3	35.4	35.0	1.83
30)ITUV-3	62.1	3.82	1.88	366.8	27.1	26.8	6.51
31)ITUV-4	74.5	3.32	1.54	217.0	30.1	29.7	3.39
97)ITUV-5	69.1	3.33	1.33	123.3	38.1	34.5	1.94
98)ITUV-6	83.8	3.05	1.48	157.1	39.6	40.0	3.00
57)MARA-1	74.2	3.61	1.56	216.7	36.4	31.8	3.34

Table 3 continued

ID Accessions	PRE months	NSP	NFB	NFR	FRV cm ³	FRM g	PRD ton/ha
99)MARA-2	75.1	3.42	1.70	112.9	44.5	33.1	1.79

Planaltina, Federal District, Brazil, 2016–2019

**Fig. 2** Scatter plot of the scores of 88 accessions of the BAGMC associated with the principal components 1 and 2 (PC1 and PC2) in a two-dimensional space. Planaltina, Federal District, Brazil, 2016–2019

Goiás (CVAL-1, PORA-5, PORA-1 and PORA-6), as well as group 3 (ENTO-4 and CERE-2). The group 2, formed by 84% of the accessions, allocated practically all accessions from Minas Gerais and the Federal District. According to the visual analysis, it was possible to divide this large group into ten subgroups by performing a second cut. The subgroup 2.2 contained mostly accessions from the Federal District (13/27) and the subgroup 2.3 contained mostly accessions from Minas Gerais (11/15). The subgroup 2.4 was composed mainly of accessions from Goiás (4/6). The rest of the groups and subgroups were formed by accessions from different regions. Other studies of genetic diversity of macauba based on quantitative or molecular variables have shown such grouping tendency according to geographical origin (Oliveira et al. 2008; Bellon et al. 2009; Manfio et al. 2012; Conceição et al. 2015). The correlation between the dissimilarity matrix and the cophenetic matrix was 0.74, highly significant by applying the Mantel test

($p < 0.0001$), evidencing an adjustment between the distance matrix and the graphical representation and showing consistency in the observed grouping.

By examining Table 3 together with the dendrogram (Fig. 1), additional information can be highlighted. Most accessions allocated in group 1 had small fruits with a low volume and less mass (CVAL-1, PORA-1 and PORA6). The subgroup 2.2 was composed of accessions that are among the most productive ones, with the largest number of clusters and the largest number of fruits (DFED-14, DFED-16, DFED-18, DFED-20, ENTO-5 and ITUV-4). The subgroup 2.3 was formed mainly by late accessions, with a longer period between planting until the first flowering, such as APAR-5, APAR-8, APAR-14, BHOR-2 and ITUV-2. The subgroup 2.6, formed only by the DFED-13 accession, presents plants with small and not very productive fruits, similar as accessions of the subgroup 2.8 (PORA-3, PORA-4, UNAI-4 and UNAI-5). The accessions BHOR-7 and ITUV-6,

Table 4 Estimate of eigenvalues and percentage of explained variance (%) of the six principal components (PC) and respective eigenvectors (weighting coefficients) associated

with the traits precocity (PRE), number of spaths (NSP), number of fruited bunches (NFB), number of fruits (NFR), fruit volume (FRV), fruit mass (FRM), and productivity (PRD)

PC	Eigenvalue	% Variance	PRE	NSP	NFB	NFR	FRV	FRM	PRD
1	3.30	47.20	− 0.3437	0.3013	0.4798	0.4788	− 0.2714	− 0.2978	0.4114
2	1.63	23.25	− 0.1532	− 0.1768	0.2403	0.1710	0.6136	0.5949	0.3576
3	1.12	16.04	0.5370	− 0.6170	− 0.0963	0.3583	− 0.1930	− 0.1336	0.3717
4	0.48	6.87	0.6927	0.6606	0.0522	0.0690	0.0117	0.2403	0.1354
5	0.22	3.12	0.2704	− 0.0902	0.4994	0.1276	0.5059	− 0.4559	− 0.4351
6	0.18	2.64	− 0.1049	0.2287	− 0.6446	0.2606	0.4879	− 0.4087	0.2194
7	0.06	0.88	− 0.0782	0.0185	− 0.1873	0.7240	− 0.1358	0.3271	− 0.5557

Planaltina, Federal District, Brazil, 2016–2019

which form the subgroup 2.7, are the two accessions with the highest fruit volume. The accessions of group 3 (CERE-2, ENTO-4 and ITUV-5) and group 7 (ANAP-1) presented plants with large fruits in both mass and volume. The accession MARA-2, belonging to group 4, despite having a high fruit mass, is among the least productive and latest accessions. Crosses between plants of accessions of the subgroup 2.2 and the groups 3 and 7 may be promising in obtaining recombinant with a high production in bunches with larger fruits, resulting in high productivity.

The principal component analysis revealed that the dispersion of scores associated with accessions in a two-dimensional space showed a pattern similar as the grouping observed in the dendrogram (Figs. 1, 2). The first two principal components (PC1 and PC2) explained 70.4% of the total variation between the accessions analyzed. The traits number of fruits and number of fruited bunches showed the highest eigenvectors associated with the component with the highest eigenvalue (PC1), responsible for 47.2% of the variation, indicating that they are the traits of greatest contribution to variability between accessions. The variation found for the traits number of fruits and number of fruit bunches, among the accessions, are important for selection work aiming to increase productivity, as these traits are considered components of yield. The characters fruit volume and fruit mass are strongly associated with PC2, which explains 23.2% of the total variation (Fig. 2, Table 4). The variability for these characters can be important in the selection of plants with a higher pulp yield, and consequently, a greater volume of oil. Previous studies

indicate a high positive association between fruit mass and mesocarp (Ciconini et al. 2013; Conceição et al. 2015; Sá et al. 2019). In addition, the mesocarp is the part that stores most of the oil in the fruit.

Regarding other palm trees, such as tucum (*Astrocaryum vulgare* Mart.), in a divergence analysis study, fruit yield per grouping was one of the most important traits to differentiate 29 germplasm accessions conserved in the Amazon region (Flores et al. 2012). In a diversity study of açai palm (*Euterpe oleracea* Mart.), in which thirty progenies were evaluated, the relative contribution of the traits total number of bunches and total bunch weight proved to be important for total divergence (Yokomizo et al. 2017).

Conclusions

This study demonstrates the existence of variability in morpho-agronomic characters of importance related to objectives for macauba improvement (productivity and oil yield). The use of mixed models was useful in characterizing the variability and structuring of macauba germplasm. Thus, based on this structure, crosses between superior plants from distant accessions may be promising in order to obtain recombinant with superior performances.

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Data availability Quantitative data available in Science Data Bank (ScienceDB) at the link <http://www.scidb.cn/en/s/pymUVNf>

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Informed consent Consent to submit has been received explicitly from all co authors, as well as from the requisite authorities.

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