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Root distribution of cultivated macauba trees

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ABSTRACT

Macauba (*Acrocomia aculeata* Mart.) is a palm tree native to tropical regions in the Americas. This species has been the subject of several studies in the last decade because of its high yields and potential as a new global source of vegetable oil. However, the root system of this plant species has not yet been described. An evaluation of the root distribution in the soil is essential to improving crop productivity. Moreover, the root distribution pattern directly affects the cultivation practices of future plantations because it is strongly associated with crop nutrition, water use, and plant anchorage in the soil. Thus, the objective of this study was to promote the first evaluation of the horizontal and vertical distribution of the root system of macauba trees of different ages. The effective (> 80% of the roots) depth and distance from the stem of the root system of macauba trees grown for 1.6, 4.8, and 9.0 years were evaluated using the excavation method and the monolith technique, with the collection of soil and root samples in the crown projected area. The root distribution of macauba seedlings cultivated for 3 and 8 months in nurseries was also evaluated. The total root mass of all evaluated plants was measured. The results indicated that the root mass increased with as the age of the plant increased, and varied from 0.0006 kg in seedlings (3 months) to 80.73 kg in adult plants (9 years). The effective depth of the root system also increased with as the age of the plant increase, reaching 0.4 m (1.6 years), 0.6 m (4.8 years), and 1.0 m (9.0 years). The effective distance of the roots from the plant stem coincided with the crown projection area. An important and unprecedented identified characteristic of young macauba plants was that their root system is concentrated in the direction of the tuberous region of a saxophone stem. The effective depth of macauba roots increases with as the age of the plant increase and the effective distance of the macauba roots coincides with the crown projection area. These features are relevant to crop production, as they can be used for fertilization and irrigation purposes.

1. Introduction

Macauba (*Acrocomia aculeata* (Jacp.) Lodd. ex Mart) is a palm species native to the tropical regions of the American continent (Dransfield et al., 2008) and is found across the entire Brazilian territory, except for the southern region (Mota et al., 2011). This plant species is an alternative to the cultivation of oil palm (*Elaeis guineenses*) (Pimentel et al., 2011a; Motoike et al., 2013), which supplies most of the global demand for vegetable oil and is the crop with the fastest growing cultivation area worldwide (Levermann and Souza, 2014). Despite high yields, the cultivation of oil palm contributes to the deforestation of large areas of tropical forests, which are rich in biodiversity and serve as carbon sinks (Vijay et al., 2016). For this reason, the environmental impact of macauba plantations shows relatively smaller potential impact because this palm is typical of savanna regions.

The advantages of macauba over other species are it oil composition and yield, which are similar to those of the oil palm. These characteristics and a lower water requirement arouse interest in plant exploitation worldwide (Pimentel et al., 2011a; Motoike et al., 2013).

The oil obtained from macauba fruit can be used in the pharmaceutical, food, and cosmetic industries and is a source of raw material for producing biodiesel (Dias et al., 2011). Biodiesel stands out as a renewable fuel and has a lower environmental impact than petroleum products. A number of studies have assessed the possibility of using macauba oil to produce biokerosene, a fuel used in aviation (Boeing and Fapesp, 2013; Cortez et al., 2014; MME, 2017).

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Several studies were the basis for increasing the productive potential of macauba on a commercial scale, including aspects related to reproductive biology (Scariot et al., 1991), anatomy and the histology of seeds (Moura et al., 2010), seedlings (Ribeiro et al., 2012) and fruits (Castro et al., 2017), ecophysiological aspects (Pires et al., 2013), genetics and plant breeding (Abreu et al., 2011; Lopes et al., 2018), plant propagation (Granja et al., 2018), harvesting and post-harvest procedures (Evaristo et al., 2016; Costa et al., 2017); oil production potential (Colombo et al., 2018), and oil extraction processes (Silva e Andrade, 2013). These studies are relevant to efforts to reduce the extractive exploitation of this palm, which is still common in the Americas. In addition, macauba plants can be cultivated together with other crops and may be used in reclamation of degraded area projects and agroforestry systems aimed at increasing farmer income per cultivated area (Viana et al., 2011; Montoya, 2016; Moreira et al., 2018).

The majority of studies on macauba were published in the last decade, reflecting the recent global interest in this palm. The results of these studies have attracted agricultural entrepreneurs and indicated the need for future work to focus on increasing yield. From this perspective, this study aimed to evaluate the root distribution of macauba, a key and fundamental aspect of crop management. The root distribution pattern affects the cultivation of future plantations because it is directly associated with crop nutrition, water use, and plant anchorage in the soil.

Studies of root distribution of palms are scarce, and frequently related to the effects of irrigation systems (Bhat and Sujatha, 2008; Ramos et al., 2009; Lopes et al., 2014) or soil management (Yahya et al., 2010). A complete study of root distribution and architecture was carried out by Jourdan and Rey (1997) on oil palm, but no studies have been identified in the specialized literature aimed at evaluating the distribution of the root system of macauba, and the present study appears to be unprecedented and may help improve the productive potential of this crop.

The effective depth and distance of the root system are usually evaluated in studies on the root system distribution. These variables delimited the volume of soil in which at least 80% of the plant roots was concentrated (Klar, 1991; Bernardo et al., 2006). The definition of such indicators is relevant and essential to better managing crop fertilization and irrigation, which is vital to the scope and success of crop production. Furthermore, the knowledge of root distribution in depth (vertical) and distance from the stem (horizontal) is relevant to modeling studies because root distribution data are often used as parameters in models that seek to simulate processes that occur in the soil-plant-atmosphere continuum. In addition, more accurate data from the root system of cultivated crops are necessary for calculating the carbon stock stored in the soil biomass.

The objective of this study was to evaluate the horizontal and vertical distribution of the root system of macauba trees of different ages.

2. Materials and methods

2.1. Study area

The study was carried out at the Araponga Experimental Farm of the Federal University of Viçosa in the municipality of Araponga (20°39′6″ S and 42°32′14″ W; altitude, 839 m), in the state of Minas Gerais, Brazil, with annual average temperature of 18 °C and average rainfall of 1338 mm (Rueda, 2014).

The study site, comprising approximately 10 ha is cultivated with macauba plants. The palms have been grown in 5 × 5 m spacing and received annual fertilization according to the soil analysis and the recommendations of Pimentel et al. (2011b). There was no complementary irrigation in the experimental area. The soil is classified as a dystrophic Yellow Red Latosol, according to the Brazilian Soil Classification System. The soil chemical and physical attributes (0–20 cm) are presented in Table 1.

Table 1

Soil chemical and physical characterization of the substrate (8 months) and experimental area (1.6, 4.8 and 9 years).

	Macauba ages			
	8 months	1.6 years	4.8 years	9 years
pH (H_2O)	6.76	4.47	4.62	5.34
P (mg dm^{-3})	89.0	3.7	8.1	7.6
K (mg dm^{-3})	247	33	79	138
Ca ($cmol_c$ dm^{-3})	3.71	1.99	3.54	5.36
Mg ($cmol_c$ dm^{-3})	1.00	0.32	0.70	1.09
Al ($cmol_c$ dm^{-3})	0.00	0.78	0.29	0.00
H + Al ($cmol_c$ dm^{-3})	0.8	11.1	10.9	8.20
SB ($cmol_c$ dm^{-3})	5.34	2.39	4.44	6.80
CEC (t) ($cmol_c$ dm^{-3})	5.34	3.17	4.73	6.80
CEC (T) ($cmol_c$ dm^{-3})	6.14	13.49	15.34	15.00
V (%)	87.0	17.7	28.9	45.3
m (%)	0.0	24.6	6.1	0.0
Sandy (%)	53	39	34	38
Silt (%)	4	10	5	4
Clay (%)	43	51	61	58
Textural class	Sandy clay	Clay	Clay	Clay

SB: sum of exchangeable bases; CEC: cation exchange capacity effective (t) and at pH 7.0 (T); V (%): base saturation; m (%): aluminum saturation. Soil characterization according to Teixeira et al. (2017). The substrate of 3 months was insufficient for determining its characterization.

The root distribution of the macauba in the field was assessed by selecting areas containing plants cultivated for 1.6, 4.8, and 9.0 years. In addition, two palm seedlings of 3 and 8 months were evaluated. The substrate used for 8 month seedlings was also characterized (Table 1). This older seedling had reached the age deemed sufficient for transplanting to the field.

2.2. Plant selection

Individual macauba plants, representative of 4.8 and 9 years old, were selected for cutting down after a preliminary forest inventory which was carried out on 20 plants of different ages in the center of each plantation area. The following dendrometric parameters were measured: diameter at chest height (1.3 m from the soil) (DCH), crown projection diameter (CPD), and total plant height (TPH). The data obtained for each age area allowed for calculating the mean values of DCH, CPD, TPH and basal area ($BA = \pi (DCH)^2/4$).

The mean basal area was used as a criterion for selecting 4.8 and 9 years olds palms that would be cut down in the field. Only one plant of each age was cut down because of the high labor demand, time, and resources necessary to perform more replicates. Nevertheless, the results are relevant because this study is the first to evaluate the distribution of the macauba root system in the field.

Palms 1.6 years old in the field, and the two seedlings (three and eight months), were selected, taking the mean height as a yardstick, because these plants did not reach the requisite height for DCH measuring (1.3 m).

The mean dendrometric data obtained for the 20 plants per age in the inventory procedure are presented in Table 2. Next, a single representative plant with similar dimensions to those mean values was selected in the field to be cut down.

2.3. Root collection

After cutting down the selected palms (1.6, 4.8 and 9 years) in the field, the root system was evaluated by the soil excavation method. The root system was collected within the limits of the crown projection area of each cut-down palm following the guidelines of Bolte et al. (2004); Nielsen (1995), and Kuhr (1999) with modifications. The root collection procedures considered the division of crown projection area into

Table 2
Dendrometric data from the previous inventory of macauba plants used to select the representative palm to be cut down for analysis in this study.

Age	Total plant height	Crown projection diameter	Diameter at chest height (1.3 m)	Basal area
	(m)	(m)	(m)	(m^2)
3 months	0.19 ± 0.02			
8 months	0.93 ± 0.02	0.72 ± 0.03	—	—
1.6 years	2.80 ± 0.13	4.00 ± 0.22	—	—
4.8 years	7.10 ± 0.86	5.43 ± 0.40	0.350 ± 0.03	0.0962 ± 0.0185
9 years	10.25 ± 0.99	6.25 ± 0.34	0.375 ± 0.04	0.1104 ± 0.0213

Mean values ± standard deviation (N = 20).

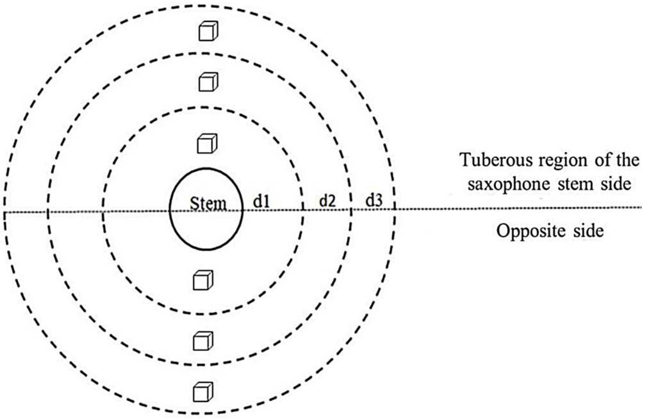

Fig. 1. Sampling representation of macauba root horizontal collection in two sides of the stem.

dimensional vertical and horizontal sections using concentric rings with the stem in the center.

During the root collection, we observed the adhered roots grew predominantly in the side of the tuberous region of saxophone stem. This macauba characteristic has not been described in the literature but was used to define our root collection procedure. Then, each plant was divided into two sides: the tuberous region of the saxophone stem and the opposite one (Fig. 1). The saxophone stem in macauba has been recently described by Souza et al. (2017). For the vertical dimension analyses, soil blocks were sampled in the center of five predefined sections at different depths (0-0.2 m, 0.2-0.4 m, 0.4-0.6 m, 0.6–1.0 m, and 1.0–1.4 m). For the horizontal dimension analyses, soil blocks were sampled in the center of three concentering rings delimited within the border of the crown projection area, which was divided into three equal sections (d1, d2, and d3) (Fig. 1).

Soil blocks for the vertical and horizontal root analyses were sampled using the monolith technique (Bohm, 1979). Soil samples were collected in a box (0.0027951 m^3) with internal dimensions of 0.12 m (width) × 0.11 (height) × 0.21 m (length).

The soil blocks collected were manually disaggregated, and the roots separated from the soil by sieving. The roots were taken to a laboratory, washed with water, and oven-dried at 65 °C. The root dry mass obtained in each block was used to calculate the total roots on each of the two sides of the plant saxophone stem. Next, root density (kg m^{-3}) was estimated at each vertical (depth) and horizontal (distance) section.

The adhered roots of the saxophone stem of macauba (1.6, 4.8 and 9.0 years) were washed and photos were taken to characterize the root distribution compared to the tuberous region of saxophone stem. These roots were dried for mass estimation.

The total root mass considered the total roots collected in the soil and the roots adhered to the saxophone stem. Only the roots collected in the soil were considered in the evaluation of the differential distribution of roots in the soil according to the position of the tuberous region of the saxophone stem.

These data were used to calculate the effective depth and effective distance of the roots from the stem. These values corresponded to the soil volume that contained at least 80% of the plant roots (Klar, 1991; Bernardo et al., 2006). As mentioned above, only the roots collected in the soil blocks were considered in these calculations.

The evaluation of the root system of seedlings (3 and 8 months) was carried out in the nursery after total substrate removal and root washing with tap water. The entire root system was photographed and collected to obtain the root dry mass. Another seedling from 4 to 12 months were selected specifically to certify the preferential root growth from the tuberous region of the saxophone stem. Their root system was washed and photos were taken to record this preferential growth.

3. Results and discussion

There is a consensus that the root system of palm trees is fasciculate, with roots emerging homogeneously and radially from the plant stem (Jourdan and Rey, 1997; Jourdan et al., 2000). However, when looking in the field, this characteristic was not found in macauba in its early stages, because of the influence of the saxophone stem structure described by Souza et al. (2017).

The distribution of the adhered roots of macauba is shown in Fig. 2. In the initial nursery stage, all roots were directed to the tuberous region side (Fig. 2a and b). At the age of 1.6 years (Fig. 2c), the predominance of the adhered roots in the direction of the tuberous region is evident, confirming the field observations. In plants aged 4.8 (Fig. 2d) and 9.0 years (Fig. 2e), the difference in the root system distribution was smaller, and the adhered roots tend to be equally distributed in older plants.

The total root mass, including the roots present in the soil and adhered to the saxophone stem structure, increased with the plant age (Table 3), varying from 0.0006 kg for seedlings (3 months) to 80.728 kg for 9-year-old plants. According to our data, root production (in kg) as a function of macauba age (years) is linear up to 9 years and can be estimated by the equation $\hat{Y} = -5.5456 + 9.5405x$ ($R^2 = 0.996$).

The estimated below-ground biomass of 9-year-old macauba (80.728 kg) was less than the root mass of 12-year-old oil palm trees (213.6 kg per plant) in Malaysia (Kiyono et al., 2015). This result is explained by the greater size of the oil palm in comparison to the macauba palm. This was evident from the comparison of values of DCH (0.38 m) and CPD (6.25 m) of 9-year-old macauba to the oil palm trees (0.71 m and 12.6 m).

In addition to the diversity of products provided by macauba, this palm can also store below-ground carbon. For 9-year-old plants with a population density of 400 plants ha^{-1}, the carbon stock potential is 16.15 ton ha^{-1}, considering an average of 50% of C in the plant biomass. This carbon stock may be higher in commercial crops where a population density up to 460 plants ha^{-1} is used. The below-ground carbon stock determined in the present study is similar to that found for oil palm in southeast Asia (Yuen, 2015). We reviewed 448 studies with oil palm plantations and found the carbon stock in the palm tree root system varied from 3 to 22 ton ha^{-1} of C. The high variability in carbon stock is related to the different methodologies used and different

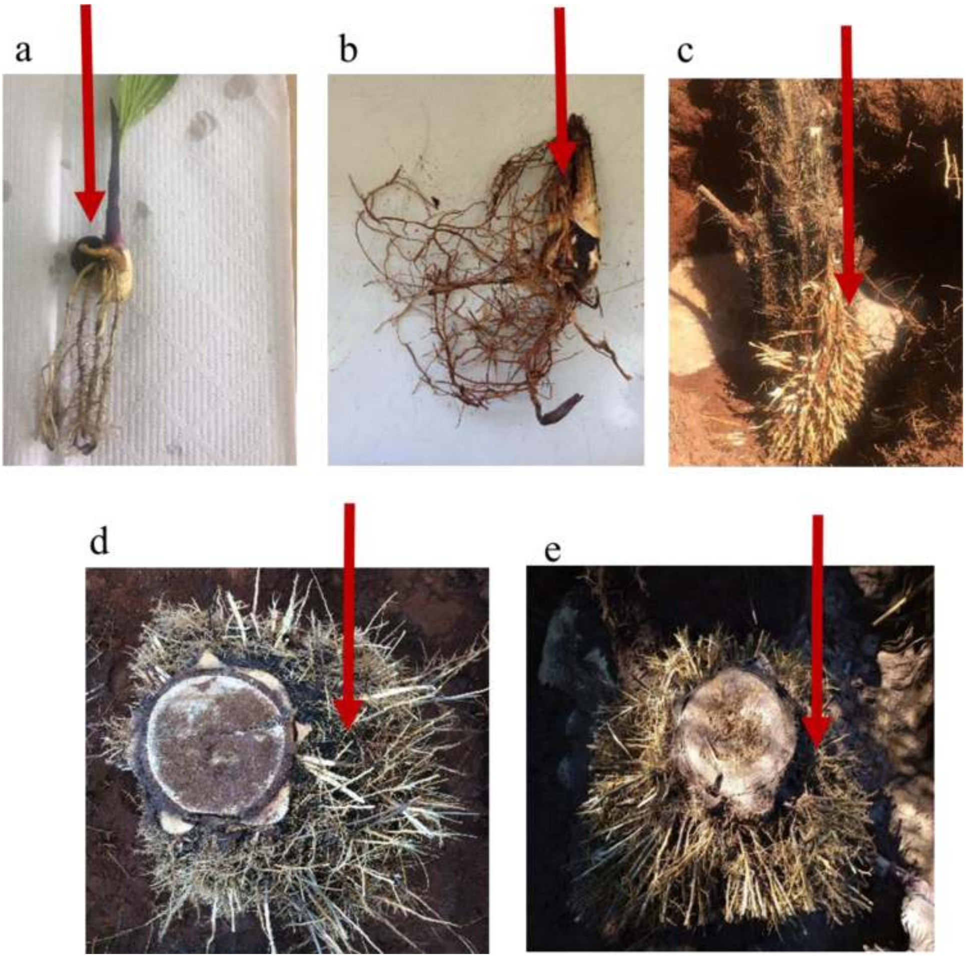

Fig. 2. Representation of adhered roots of macauba palms of different ages, showing the side of the tuberous region of saxophone stem (red arrow): 3-month (a) and 8-month (b) seedlings; and 1.6-year (c), 4.8-year (d), and 9.0-year (e) adult plants.

Table 3
Root biomass of macauba plants of different ages.

Macauba age	Macauba root system (kg)			
	Soil roots[a]	Adhered roots to the saxophone stem	Saxophone stem	Total
3 months	–	0.0002	0.0004	0.0006
8 months	–	0.0166	0.081	0.0977
1.6 years	4.4380	0.450	1.780	6.688
4.8 years	22.7150	5.201	12.510	40.426
9 years	43.5520	10.689	26.487	80.728

[a] Soil roots evaluated up to 1.4 m depth.

Table 4
Effective depth and effective distance of macauba roots from the stem within the palm crown projection area.

Macauba age	Effective depth[a]	Effective distance[a] from palm stem
(years)	(m)	(m)
1.6	0.40	2.00
4.8	0.60	2.71
9	1.00	3.12

[a] Effective depth and effective distance corresponded to the volume of soil that concentrated at least 80% of the plant roots.

population densities and ages.

The effective depth and effective distance of the macauba roots from the palm stem are presented in Table 4. These two variables increased as expected with the increase in plant age. In all plants, the effective distance of the roots from the stem was coincident with the crown projection area, indicating the radial spreading of the root system and the proper use of CPD value in the macauba radicular studies.

Measuring the effective depth and effective distance is essential to crop irrigation and fertilization procedures (Bernardo et al., 2006). However, from the practical point of view, fertilization is carried out on the soil surface and within the crown projection area. The importance of knowing the root density in the most superficial layers should also be taken into consideration. In the present study, the majority of the roots are found in the first soil layer (0–0.2 m): 50.9% (1.6 years), 35.6% (4.8 years), and 18.5% (9 years), which should be taken into account when planning crop fertilization. In 4-year-old dwarf coconut palm (Cocos nucifera) grown under three localized irrigation systems in a Brazilian Argisol, most roots were located at a depth of 0.2–0.6 m (56%) regardless of the irrigation system adopted, and 21% of the roots were found in the 0-0.2 m soil layer (Cintra et al., 2005).

The root density (kg m^{-3}) of macauba at different depths and distances from the stem are shown in Fig. 3. The roots of 1.6-year-old plants grew preferentially from the side of the tuberous region of saxophone stem. This side of the plant concentrated 79% of the roots (Fig. 3a), and root distribution was more uniform in the three depth sections evaluated. This result is relevant and should be considered when managing fertilization and irrigation and suggests that, in the first years of crop cultivation, higher doses of nutrients and water should be applied to the plant side with higher root density.

The 4.8-year-old plants presented roots not concentrated on the

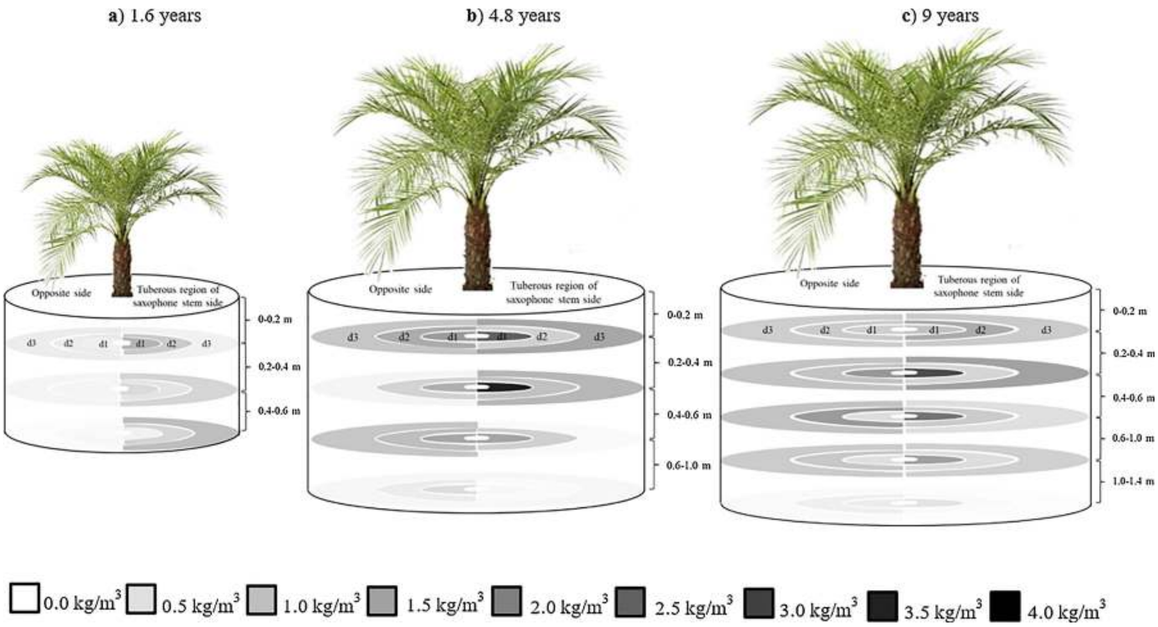

Fig. 3. Root density (kg m^3) of macauba trees aged 1.6 (a), 4.8 (b), and 9 years (c). Distances (d1, d2, d3) from the stem: 1.6 years (0–0.67; 0.67–1.34; 1.34–2 m); 4.8 years (0–0.9; 0.9–1.8; 1.8–2.71 m); and 9 years (0–1.04 m; 1.04–2.08; 2.08–3.12 m).

Fig. 4. Details of the higher root density of macauba seedlings (from 4 to 12 months) coincident to the side with fewer leaves. Red arrows indicate the position of the tuberous region of the saxophone stem which concentrated the adhered roots.

tuberous region of saxophone stem side (Fig. 3b). Roots became more equally distributed across the crown projection area as the years progressed. The tuberous region side comprised 56% of the roots, and 69% of the macauba roots were attached to the first third of the crown projection area (d1) of this site. The root system of 9-year-old macaubas was uniformly distributed, and 50% of the roots grew in the direction of the tuberous region side (Fig. 3c). However, 63% of the roots were located in the first third of the crown projection area on the tuberous region side (d1), while on the other plant side the root distribution was more similar.

The greater root growth in the direction of the tuberous region side during plant development in the field is an unprecedented observation and may support future studies and practices of macauba management, fertilization, and irrigation. Studies addressing fertilization and irrigation of highest root density plant side may be carried out with the aim of improving the productive potential of this palm, obviously taking appropriate care to avoid the adverse effects of chemotropism. Another interesting question for future studies is whether the uniform growth verified in 9-year-old macauba trees was the result of the progress of time over the years and the crop grown, or if the fertilizer distribution in all the crown projection area promoted root development on the opposite side of the tuberous region. Moreover, further studies are necessary to monitor the development of the saxophone stem during cultivation in the field, since this structure was only studied during the early stages of macauba seedlings in a greenhouse study (Souza et al., 2017).

The confirmation of the root predominance in the tuberous region side of macauba seedlings and in young palm trees in the field is especially relevant to the planting layout of seedlings in the field. The planting standardization in a specific cardinal direction may help future fertilization and irrigation management. However, determining the tuberous region side can be complicated because macauba seedlings are grown in polietilene bags and the substrate is not removed for planting. Our observations suggest that the side with relatively fewer seedlings leaves coincided with the higher root density macauba side (Fig. 4). From this observation, we speculated this is a plant strategy to allow for better plant balance and greater soil anchorage.

4. Conclusions

1 The roots of macauba seedlings and young palm trees in the field are concentrated in the tuberous region side and are uniformly distributed in adult plants.

2 The effective depth of macauba roots increases as the plant ages and the effective distance of the macauba roots coincides with the crown projection area.

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