horticulturae

Article

Morphology and Allometry of Juvenile Açaí Palms Under Cultivation Conditions in Central Amazonia

Jhon Paul Mathews Delgado [1], Raimundo Nonato Vieira da Cunha [2], Ronaldo Ribeiro de Morais [2], Maria Teresa Gomes Lopes [1], Santiago Linorio Ferreyra Ramos [1], Maria do Rosário Lobato Rodrigues [2], Nathalia Maíra Cabral de Medeiros [3], Carlos Henrique Salvino Gadelha Meneses [3], Edson Barcelos [2] and Ricardo Lopes [2,*]

[1] Faculty of Agricultural Sciences, Federal University of Amazonas, Avenue Rodrigo Otávio, 3000, Manaus 69060-000, AM, Brazil; fedormath@hotmail.com (J.P.M.D.); mtglopes@ufam.edu.br (M.T.G.L.); slfr@ufam.edu.br (S.L.F.R.)

[2] Embrapa Western Amazon, Route AM 10, Km 29, s/n, C.P. 319, Manaus 69010-970, AM, Brazil; raimundo.vieira@embrapa.br (R.N.V.d.C.); ronaldo.morais@embrapa.br (R.R.d.M.); rosario.lobato@embrapa.br (M.d.R.L.R.); edson.barcelos@embrapa.br (E.B.)

[3] Graduate Program in Agricultural Sciences, Department of Biology, Center for Biological and Health Sciences, State University of Paraíba, Campina Grande 58429-500, PB, Brazil; nathaliamaira@ufrn.edu.br (N.M.C.d.M.); carlos.meneses@servidor.uepb.edu.br (C.H.S.G.M.)

* Correspondence: ricardo.lopes@embrapa.br; Tel.: +55-92-99128-6866

Abstract: Two Amazonian species of açaí palm trees (*Euterpe oleracea* and *Euterpe precatoria*) are exploited in the commercial production of açaí pulp or juice. While *E. oleracea* benefits from developed cultivation technologies, *E. precatoria* lacks such advancements. Studies on the morphology and development of açaí palms under cultivation conditions can contribute to increasing the productivity of the species. The aim of this study was to carry out morphological characterization, assess growth and development in the juvenile phase of the plants, and obtain allometric models for *E. precatoria* and *E. oleracea*. Evaluations were conducted between 44 and 48 months post-planting. Allometric equations were formulated to accurately estimate leaf area. The results showed that *E. oleracea* begins reproduction earlier and exhibits greater growth in stem dimensions and leaf areas compared to *E. precatoria*, indicating that *E. precatoria* can be cultivated at higher planting densities. Allometric models, based on leaf length and width, effectively predicted individual leaf areas for both species, demonstrating their utility in optimizing cultivation strategies.

Keywords: *E. oleracea*; *E. precatoria*; açaí cultivation; leaf morphology; allometric equations; Amazonian crops

check for updates

Citation: Delgado, J.P.M.; da Cunha, R.N.V.; de Morais, R.R.; Lopes, M.T.G.; Ramos, S.L.F.; Rodrigues, M.d.R.L.; de Medeiros, N.M.C.; Meneses, C.H.S.G.; Barcelos, E.; Lopes, R. Morphology and Allometry of Juvenile Açaí Palms Under Cultivation Conditions in Central Amazonia. *Horticulturae* **2024**, *10*, 1119. https://doi.org/10.3390/horticulturae10101119

Academic Editor: Diego Rivera-Nuñez

Received: 1 September 2024
Revised: 10 October 2024
Accepted: 18 October 2024
Published: 21 October 2024

1. Introduction

The açaí palms *Euterpe oleracea* and *Euterpe precatoria* belong to the family Arecaceae and are native to the Amazon region, where they are exploited for the commercial production of fruit pulp. Açaí smoothies are an important food for indigenous peoples and riverside populations of the Amazon. In recent decades, they have reached national and international markets. Extractive production has failed to meet the growing market demand, which highly rewards the product, and the areas of cultivated açaí palm have been continuously expanding, predominantly with the species *E. oleracea*. In 2022, the value of açaí production in Brazil (BRL 6.17 billion) was the third highest among fruits produced in the country, surpassed only by oranges (BRL 14.4 billion) and bananas (BRL 11.9 billion) [1]. Brazilian açaí production, including both cultivation and wild harvesting, reached 1.9 million tons of fruit, with the state of Pará contributing 90.5% of this production and Amazonas contributing 7.5% [1].

In Brazil, the species *E. oleracea*, known locally as "açaí-de-touceira" or "açaí-do-Pará", is naturally distributed in the states of Amapá, Goiás, Pará, Tocantins, and Maranhão. In contrast, *E. precatoria*, known as "açaí-solteiro" or "açaí-do-Amazonas", is found in the states of Acre, Amazonas, Pará, Rondônia, and Roraima [2]. Regarding production and natural geographic distribution, it is noteworthy that in Pará, production predominantly comes from *E. oleracea*, while in Amazonas, it mainly comes from *E. precatoria*. However, cultivars of *E. oleracea* are expanding in cultivation areas within Amazonas [3]. The adaptation of *E. oleracea* and *E. precatoria* to their respective geographical regions has led these species to develop distinct morphological characteristics, as well as differing harvest periods and pulp composition [4–7].

E. precatoria has a solitary, erect stem measuring between 3 and 20 m in height and 4 to 25 cm in diameter, with a root cone at its base. The palm features pinnate leaves ranging from 10 to 20, with a closed sheath 0.7 to 1.6 m long, which can be green or green with yellow stripes. Its petiole ranges from 18 to 57 cm in length, and the rachis measures between 2.1 and 4.0 m. The leaflets are regularly distributed along the rachis in the same plane ranging from 43 to 91 on each side of the rachis, measuring 62 to 88 cm in length and 1 to 4 cm in width in the midsection of the leaf [8,9].

E. oleracea has a clumping stem structure, with up to 25 stems per clump, which can be erect or inclined, measuring from 3 to 20 m in height and 7 to 18 cm in diameter, with a cone of reddish aerial roots at the base. The leaves are also pinnate, ranging from 8 to 14 per stem; the sheath is 0.65 to 1.50 m long and greenish in color. The petiole measures 17 to 50 cm in length, and the rachis is 1.5 to 3.7 m long. Like *E. precatoria*, the leaflets are long acuminate and distributed along the rachis in the same plane, with 40 to 80 leaflets on each side of the rachis, measuring 60 to 111 cm in length and 2.0 to 4.5 cm in width in the midsection of the leaf [2,8,9].

Despite the significant economic and social importance of açaí palm cultivation, there have been limited investments in the development of cultivation technologies. Both *E. oleracea* and *E. precatoria* are still in the process of domestication [10,11]. For *E. oleracea*, several important technologies have been developed, notably two cultivars (BRS Pará and BRS Pai d'égua) and a production system, which have yielded significant economic and social benefits [12,13]. There are significant knowledge gaps regarding the morphological and developmental differences between *E. oleracea* and *E. precatoria* under controlled cultivation conditions. Specifically, while *E. oleracea* already has developed cultivation technologies and is widely studied, with cultivars and production systems, *E. precatoria* lacks such advancements. There are no recommended cultivars or production systems for *E. precatoria*, and knowledge about the behavior of this species under local cultivation conditions is quite limited based on the empirical experiences of farmers. This highlights the need for more research to explore the growth, productivity, and morphological responses of *E. precatoria* under agricultural management, with the aim of optimizing production and reducing the non-productive phase of this species, promoting its economic viability [14].

Most studies describing the morphological aspects of açaí palms are based on research conducted on plants from natural populations in uncontrolled environmental conditions, which are heavily influenced by environmental factors [2,8,9]. Understanding morphological characteristics, such as leaf area, stem structure, and growth patterns, is essential to optimize cultivation techniques. These characteristics influence decisions such as plant spacing, irrigation management, and harvesting strategies. For example, plants with larger leaf areas like *E. oleracea* may require wider spacing and more water, while their faster growth and earlier onset of the productive phase favor quicker harvesting. Thus, this information is fundamental for improving productivity and efficiency in managing açaí plantations.

Within the same species, leaf morphology can vary depending on the plant's developmental stage and environmental conditions, with leaves adapting to maximize energy absorption and minimize the negative effects of stress [15]. Consequently, leaves serve as excellent indicators of the impact of environmental variations on plant development, such as spacing, fertilization, and irrigation. Allometric models that estimate leaf area quickly, practically, and non-destructively will enable the use of the leaf area as a parameter in studies examining the effects of cultivation conditions on the development and production of açaí palms. The research primarily aimed to assess the morphological traits and allometric relationships during the juvenile stage of two açaí palm species, *E. oleracea* and *E. precatoria*, cultivated in the Central Amazon region of Brazil. By focusing on these aspects, the study likely sought to understand the growth patterns, size relationships, and developmental stages of these species under specific cultivation conditions. This kind of research is crucial for optimizing cultivation practices, improving yield, and understanding the ecological adaptation of these palms in the Amazonian environment.

2. Materials and Methods

2.1. Study Site and Climate Conditions

The study was conducted on a plantation established in July 2019 at the Experimental Field of Embrapa Western Amazon (2°53′38″ S and 59°59′24″ W), located at kilometer 29 of AM 010, in the city of Manaus, Amazonas State. The region's climate is tropical humid (Af type) according to the Köppen classification, with an average annual temperature of 33.9 °C, relative humidity ranging from 76% to 89%, an annual total sunshine average of 1940 h, and average annual rainfall of approximately 2500 mm. The soil is classified as very clayey dystrophic Yellow Latosol [16,17].

2.2. Soil Preparation and Planting Procedures

For preparing the area for planting, soil samples were collected and analyzed to assess fertility and acidity levels, guiding the need for pH correction and fertilization based on crop requirements. Two months before planting, the area underwent subsoiling, plowing, and harrowing. To correct soil pH, 2 tons of dolomitic limestone per hectare (Relative Total Neutralizing Power—RTNP 70%) were applied before plowing. One week before planting, holes measuring 40 cm × 40 cm × 40 cm were prepared, with a spacing of 5 m between rows and 4 m between plants in the row. The soil in the planting holes was enriched with 3 kg of aged laying hen manure, 300 g of single superphosphate, and 50 g of slow-release micronutrient—FTE (Nutriplant, São Paulo, Brazil). At planting time, the seedlings were approximately 12 months old. The plantation consisted of 14 rows, with the number of plants per row ranging from 14 to 48, covering a total area of 1.2 hectares. Seven rows were planted with the species *E. oleracea* and seven with *E. precatoria*. In total, the plantation included 262 *E. oleracea* plants, of which 242 were the BRS Pará cultivar, and 20 were "Chumbinho", both obtained from seeds purchased from AmazonFlora (https://www.amazonflora.com.br/, accessed on 10 September 2024), and 349 *E. precatoria* plants from seeds collected from 12 different open-pollinated bunches in plantations in the municipalities of Codajás, Anori, and Manaquiri, Amazonas State. Weed control was carried out using herbicides around the plant crowns and mechanical mowing to reduce vegetation between the rows.

2.3. Nutrient Management and Pruning Practices

The same topdressing fertilization was applied to the entire plantation, regardless of species, based on recommendations for *E. oleracea* [18] and visual observations of nutritional deficiencies, as no specific recommendations exist for *E. precatoria*. From planting until the end of the evaluation period (48 months after planting), eight topdressings were performed. Six months after planting, 200 g of NPK 16-10-20 was applied per plant. Twelve months after planting, each plant received 5 kg of aged laying hen manure and 200 g of NPK 16-10-20. The use of aged laying hen manure is due to local availability, the cultivation methods used by regional farmers, and because it is a rich source of essential nutrients, such as nitrogen, phosphorus, and potassium, which improve soil fertility, promote root development, and increase water retention capacity, contributing to plant development. Eighteen months after planting, 200 g of NPK 16-10-20, 30 g of FTE, and 50 g of borax were applied per plant. At 24 months, 200 g of NPK 16-10-20, 30 g of FTE, and 30 g of borax were applied. Thirty months after planting, each plant received 200 g of NPK 16-10-20, 5 kg of aged laying hen manure, and 30 g of borax. At 36 months, 400 g of NPK 16-10-20, 70 g of FTE, 80 g of magnesium sulfate, and 45 g of borax were applied per plant. Forty-two months after planting, 500 g of NPK 16-10-20, 60 g of FTE, 50 g of magnesium sulfate, and 40 g of borax were applied. Finally, 48 months after planting, 400 g of NPK 16-10-20, 50 g of FTE, 60 g of magnesium sulfate, and 40 g of borax were applied per plant.

For *E. oleracea* plants, starting 12 months after planting and every six months thereafter, sucker pruning was performed, leaving the main stem and three offshoots intact.

2.4. Phenotypic Assessments

2.4.1. Nutritional Deficiencies and the Reproductive Stage of Plants

Evaluations were conducted on 227 *E. precatoria* plants and 179 *E. oleracea* plants, including 161 of the BRS Pará plants and 18 of the Chumbinho plants. The cultivars BRS Pará and Chumbinho were used to represent the species *E. oleracea* as they were the only ones available with commercial seed production at the time of the experiment's establishment. These cultivars were primarily selected to increase productivity and early reproductive maturity, characteristics that make them more suitable for intensive cultivation systems. The assessment of nutritional deficiencies was conducted 48 months after planting. Visual symptoms were directly observed on the plants and classified into (a) potassium deficiency and (b) the combined deficiency of potassium and boron. The methodology for identifying these deficiencies involved observing typical symptoms on leaves, such as marginal chlorosis for potassium and growth deformations in young leaves for boron. Additionally, the incidence of plants in the reproductive stage was recorded, counting those that displayed inflorescences or fruit bunches, regardless of whether abortion occurred before or after the assessment. The cultivars BRS Pará and Chumbinho were used to represent the species *E. oleracea* as they were the only ones available with commercial seed production at the time of the experiment's establishment. These cultivars were primarily selected to increase productivity and early reproductive maturity, characteristics that make them more suitable for intensive cultivation systems. The assessments were expressed as a percentage of occurrence within the plantation: (a) plants with potassium nutritional deficiencies, (b) plants with nutritional deficiencies in both potassium and boron, and (c) plants in the reproductive stage. The latter category counted the number of plants displaying an inflorescence or fruit bunch at any developmental stage, regardless of whether there was an abortion of the reproductive organ before or after the evaluation.

2.4.2. Stipe Growth and Number of Leaves on Plants

To assess the growth of the stem and the number of leaves of the plants, 44 randomly selected *E. oleracea* plants, 27 from the BRS Pará cultivar and 17 from the 'Chumbinho' cultivar, and 121 *E. precatoria* plants were examined from the planting area. Plants from the outer rows and the ends of all rows were excluded, as were those exhibiting visual symptoms of nutritional deficiencies, pest attacks, diseases, or any abnormal developmental characteristics.

Evaluations were conducted 44 months after planting and recorded: (a) stem height (m), measured from the base to the bifurcation between the first expanded leaf and the spear leaf with a graduated ruler; (b) stem diameter (cm), measured at the base with a tape measure; (c) internode distance (cm), represented by the average distance between the first five internodes below 1.50 m of the stem height, measured with a graduated ruler; and (d) number of leaves per plant, determined by counting expanded and green leaves, for *E. oleracea*, including the main stem and up to three offshoots when present.

2.4.3. Leaf Morphology

The experiment followed a completely randomized experimental design with three treatments (BRS Pará and Chumbinho cultivars of *E. oleracea* and open-pollinated progeny plants of *E. precatoria*) and three replicates, each represented by three randomly selected plants per treatment from the plantation. Leaf morphology was measured using a destructive method on the third leaf, identified as such by counting from the most recently expanded leaf as the first. In the case of *E. oleracea*, the third leaf from the main stem was used. The following characteristics were measured: (a) petiole length (cm), the distance from the petiole junction with the stem to the base of the first leaflet insertion; (b) rachis length (cm), the distance from the insertion of the first leaflet to the base of the last pair of leaflets; (c) rachis width (cm), measured adjacent to the insertion of the first leaflet; (d) rachis height (cm), measured adjacent to the insertion of the first leaflet; (e) number of leaflets, counted on both sides of the rachis; (f) leaflet length (cm), the distance from the base to the apex of the leaflet, taken from measuring three pairs from the central part of the leaf; (g) leaflet width (mm), measured at the widest part of the leaflet; (h) leaf width (cm), the distance between the apices of the leaflets on opposite sides at the central part of the rachis; (i) distance between leaflets (cm), obtained by dividing the rachis length by the number of pairs of leaflets.

2.4.4. Leaf Area Measurement

The leaf area measurement was conducted through a destructive analysis using three *E. oleracea* plants (BRS Pará cultivar) and three *E. precatoria* plants, harvesting all green and active leaves from each plant. Plants were randomly selected, excluding those from the outer rows and row ends, as well as those with visible symptoms of nutritional deficiencies, phytosanitary issues, or abnormal development. Leaves were collected by cutting the petiole close to its insertion on the stem. In total, 34 leaves from *E. oleracea* and 33 from *E. precatoria* were evaluated. Individual leaf area was determined by measuring the area of each leaflet using a CI-203 Portable Laser Area Meter® (Solfranc Technology, Vila-seca, Tarragona, Spain). The area meter allows for precise and non-destructive measurements of leaf area, which is essential for assessing the photosynthetic capacity of plants. In the study, this tool was used to create allometric models based on simple leaf dimensions, such as leaflet length and width, facilitating rapid and accurate assessment of plant growth.

For leaf area measurement, the CI-203 Portable Laser Area Meter® was used and properly calibrated according to the manufacturer's instructions before each use, to ensure data accuracy. Leaves were harvested destructively, and all leaflets were measured individually. The CI-203 was calibrated at regular intervals to maintain accuracy, and the leaves were carefully handled to avoid any alteration in shape during measurement. To ensure consistency and avoid bias, measurements were carried out by the same trained technician, and any anomalous values or those outside the expected standards were investigated and, if necessary, excluded from the final analysis.

The measurement of leaf morphology followed a completely randomized experimental design with three treatments (BRS Pará and Chumbinho cultivars of *E. oleracea* and *E. precatoria* plants) and three repetitions, with three plants per treatment. Leaf 3 from each plant was used, considering leaf 1 as the most recently expanded leaf of the plant. In addition to individual leaf area, the following measurements were taken for all leaves: (a) petiole length (cm); (b) petiole height (cm); (c) petiole width (cm); (d) rachis length (cm); (e) leaf width (cm); (f) number of leaflets; (g) leaflet length (cm); (h) leaflet width (cm); and (i) distance between leaflets (cm).

A random selection of 44 *E. oleracea* plants (27 from the BRS Pará cultivar and 17 from the Chumbinho cultivar) and 121 *E. precatoria* plants were chosen to assess stem growth and leaf number. Plants from the outer rows and edges were excluded, as were those showing visible symptoms of nutritional deficiencies, pest attacks, or abnormal characteristics. The measured parameters were for stem: (a) stem height (m), measured from the base to the bifurcation between the first expanded leaf and the young leaf, using a graduated ruler; (b) internode distance (cm), calculated from the average of five internodes below 1.50 m in height; and (c) stem diameter (cm), measured at the base with a tape measure; (d) number of leaves per plant, including the main stem and up to three lateral shoots; the measurements for rachis width (cm); and rachis height (cm) were taken using a graduated ruler, with the width measured adjacent to the insertion of the first leaflet and the height measured in the same region. The presence of a yellow stripe on the rachis was visually assessed, noting whether this distinctive trait was present or absent. The shape of the rachis was determined by visual inspection and described based on its geometric characteristics, such as trapezoidal or triangular.

Leaf area was measured using the CI-203 Portable Laser Area Meter®, which provided accurate values by scanning individual leaves. The total plant leaf area (m^2) was calculated by summing the leaf area of all green, active leaves on each plant.

2.4.5. Statistical Analyses

The effect of treatments was evaluated using the non-parametric Kruskal–Wallis test and, when significant ($p < 0.05$), the means were compared using the Mann–Whitney multiple comparisons non-parametric test (adjusted p-value < 0.017) [19]. Pearson's correlation coefficient ($p < 0.05$) between variables was calculated separately for each species. Analyses were performed using IBM SPSS software, version 20.0 [20].

Statistical analyses were conducted using IBM SPSS software, and data normality was verified graphically, as well as the homoscedasticity of standardized residuals in the allometric models developed to estimate leaf area. Outlier values were identified when standardized residuals exceeded ± 2 and were then excluded from subsequent analyses.

2.4.6. Allometric Models for Estimating Leaf Área

In developing allometric models to estimate the individual leaf area of açaí palms, variables such as the average length (Cf) and width (Lf) of the three central pairs of leaflets, the length of the leaf rachis (Cr), and the total number of leaflets per leaf (Nf) were measured in 34 leaves of *E. oleracea* (BRS Pará cultivar) and 33 leaves of *E. precatoria*.

In constructing the linear regression model, initially, all four explanatory variables were included to determine their contribution to explaining the total variation in estimated leaf area (ELA). Subsequently, the explanatory variables were sequentially removed in order of their contribution, from the least to the most, resulting in four linear regression models for each species by the end of the process. The significance of the regression coefficients in these four models was assessed using the t-test ($p < 0.05$), with models having non-significant coefficients excluded from selection. The most accurate models were selected based on those that exhibited the lowest standard error of the estimates (S), the lowest coefficient of variation of the equation (S/average mean), and the highest determination coefficient (R^2).

To validate the accuracy of the models, the estimated leaf area values (ELA) were compared with the observed leaf area values (OLA) obtained from measurements. The standardized residuals (RESZ) for each leaf were calculated from the differences between ELA and OLA, with absolute values greater than 2 considered outliers. Accurate models should produce estimates with an outlier frequency below 5% [19]. To assess the effect of outliers on the model, a new model was generated from the original data, excluding samples that produced outlier estimates. New estimates of leaf area for all samples were obtained from this new model, yielding the adjusted estimated leaf area (AELA). The standardized residuals (RESZAJ) were calculated from the differences between AELA and OLA. The model used to obtain the AELA is considered accurate when the absolute RESZAJ values are less than 1 [19].

The normality and homoscedasticity of the selected allometric models for estimating the leaf area of *E. precatoria* and *E. oleracea* were verified by graphical dispersion between standardized residuals and the adjusted estimated leaf area values. The linearity between leaf area estimates and the model's explanatory variables, the width and length of central leaflets, was assessed through graphical dispersion between standardized residuals and the adjusted leaf area obtained by partial regression for each explanatory variable [19].

3. Results and Discussion

3.1. Impact of Nutritional Deficiencies on Plant Reproductive Development

The nutritional deficiencies observed in *E. precatoria*, particularly increased sensitivity to boron and potassium shortages, have significant implications for its reproductive performance and slow growth compared to *E. oleracea*. In the study, *E. precatoria* exhibited a 13.9% incidence of plants with boron deficiency and 2.4% with potassium deficiency, while *E. oleracea* showed no visual symptoms of these deficiencies. Considering that both species were grown in the same environment and received identical management, these results suggest that *E. precatoria* is more sensitive to deficiencies in boron and potassium. In the topdressing fertilizations, fertilizers containing sources of potassium and boron were used, and remission of boron deficiency symptoms was observed in 17.6% of the *E. precatoria* plants that exhibited symptoms. Boron deficiency affects the formation of young cells and tissues, directly impacting leaf growth and the formation of reproductive organs, while potassium deficiency interferes with water regulation and photosynthesis, impacting the overall health of the plant and its long-term productive capacity. The low productivity and delayed onset of the reproductive phase, due to these deficiencies, may result in slower economic returns for farmers who choose to cultivate *E. precatoria*.

For *E. oleracea*, studies on mineral nutrition have contributed to improved productive and economic performance in commercial plantations of the species [21–28]. However, for *E. precatoria*, research is scarce and limited to the nursery seedling production phase [29–32]. Given these findings, considering the effects of nutritional deficiencies on the plants, the lack of nutritional management recommendations can be considered one of the main constraints to the expansion of commercial plantations of *E. precatoria*. Field experiments with various sources and doses of macro and micronutrients are necessary to establish the needs and fertilization recommendations that offer the best cost–benefit for the cultivation of *E. precatoria*.

At 48 months post-planting, 44.1% of the *E. oleracea* cv. BRS Pará and 77.8% of the "Chumbinho" plants exhibited reproductive structures at some stage of development, compared to only 0.9% of the *E. precatoria* plants. These results demonstrate that under the same cultivation conditions, *E. precatoria* is later maturing than *E. oleracea*. There are currently no published studies providing precise information on the onset of the productive phase of *E. precatoria* under cultivation conditions; therefore, further assessments are necessary to acquire such data. The earlier production in cultivation conditions is a favorable characteristic of *E. oleracea* compared to *E. precatoria*. Research on genetic variability and selection for early productivity in *E. precatoria*, as well as on more suitable management practices under cultivation conditions, could help reduce the non-productive phase, thereby increasing the economic viability of cultivating the species.

To mitigate these impacts and enhance long-term productivity, specific interventions may be necessary. One strategy could be the development of fertilization programs tailored to the specific needs of *E. precatoria*, including the application of fertilizers with higher concentrations of boron and potassium at critical growth stages. Additionally, the use of soil amendments and management techniques that enhance the availability of these nutrients over time, such as the use of slow-release fertilizers or organic compounds rich in micronutrients, can help reduce this species' sensitivity to nutritional deficiencies. Field trials to test different doses and sources of fertilizers would also be useful to adjust fertilization recommendations and maximize the economic return of this species by optimizing its management similarly to what has been achieved with *E. oleracea*. The results of the study clearly indicate that the two species have distinct nutritional requirements, with *E. precatoria* showing greater sensitivity to boron and potassium deficiencies. This sensitivity may be linked to its lower reproductive performance and slower development compared to *E. oleracea*. Thus, the need for specific studies on nutritional management for *E. precatoria* is evident. Further research is essential to develop fertilization strategies that better meet the nutritional demands of this species, thereby increasing its productivity and long-term economic viability. The proposal for tailored fertilization programs and the need for field trials to test different nutrient combinations and dosages align with the knowledge gaps identified in the study.

3.2. Plants' Morphology and Development

For most evaluated characteristics, the effect of treatments was significant (Table 1). According to the classification proposed by Pimentel-Gomes [33], among the nine morphological characteristics evaluated on leaves, the coefficient of variation (CV) was low for rachis length (CV = 9%), high for petiole height (CV = 22%), and very high for petiole length (CV = 47%). For the remaining six characteristics, the CVs were moderate (ranging from 10% to 20%). Therefore, the results indicated greater variability in the data for petiole height and length. When analyzing the CVs for petiole length for each species, the values were classified as very high for both *E. precatoria* (54%) and the *E. oleracea* cultivars BRS Pará (50%) and "Chumbinho" (35%). However, for petiole height, the CV was classified as moderate for *E. precatoria* (17%) and low for the *E. oleracea* cultivars (9%), indicating that variability was greater in *E. precatoria*.

Table 1. Summary of the analysis of variance for biometric leaf characteristics of açaí palm species *E. precatoria* and *E. oleracea*, cultivars BRS Pará and "Chumbinho".

Character Evaluated	F	Coefficient of Variation (%)
Petiole Length (cm)	0.74	47
Petiole Height (cm)	31.16 **	22
Petiole Width (cm)	13.55 **	11
Rachis Length (cm)	1.39	9
Leaf Width (cm)	0.05	13
Number of Leaflets	5.73 **	11
Leaflet Length (cm)	1.86	10
Leaflet Width (cm)	51.72 **	17
Distance Between Leaflets (cm)	8.18 **	12

** Significant using the Kruskal–Wallis test, $p < 0.01$.

At 44 months post-planting, the averages for growth in height and stem diameter, as well as internode distance and leaf number in *E. oleracea* cultivars, did not differ among themselves and were superior to those observed in *E. precatoria* (Table 1). Plant height showed a high and positive correlation with average internode distance (r = 0.73, $p < 0.01$), stem diameter (r = 0.79, $p < 0.01$), and leaf number (r = 0.71, $p < 0.01$) in *E. precatoria*, and a moderate and positive correlation with average internode distance (r = 0.46, $p < 0.05$) and leaf number (r = 0.46, $p < 0.01$) in *E. oleracea* cultivar BRS Pará. No significant correlations were found between the variables in the Chumbinho cultivar. In a study with *E. precatoria* under natural conditions, Avalos and Otarola [34] also observed a significant relationship between growth and plant diameter. The authors reported that the height of the stem in smaller palms (<1 m) increases slowly in relation to the stem diameter; however, in palms taller than 1 m, there is a linear increase in both variables, with height growing 1.5 times faster than diameter. Unlike what was observed in *E. precatoria*, in *E. oleracea* the correlation value between height and stem diameter was negligible (r = 0.29, $p > 0.05$), indicating no correlation. This result may be due to the morphological differences between the species, notably that in *E. oleracea*, measurements were only taken on the main stem, and the species has a clumping habit with up to three offshoots maintained per plant, whereas *E. precatoria* has a solitary stem [34,35].

In natural populations, Henderson [9] reports heights for both açaí palm species ranging from 3 to 20 m, with the stem diameter of *E. precatoria* being larger than that of *E. oleracea*. Thus, Henderson's [9] description of the species in natural conditions contrasts with the results obtained for the species under the same cultivation conditions up to 44 months after planting, where the growth of *E. oleracea* was superior to that of *E. precatoria*.

The species predominantly originate from distinct natural environments, especially in terms of shading and moisture, which could explain the different responses in monoculture conditions. *E. oleracea* is more commonly found in floodable areas with high light intensity [9], while *E. precatoria* originates from shaded environments like the understory of “terra firme” forests [36], thus being more adapted to lower light intensities.

3.3. Morphology and Leaf Area

The *E. oleracea* cultivars did not differ from each other in any of the evaluated leaf characteristics, and except for the number of leaflets, all other characteristics exhibited averages that were superior to those observed in *E. precatoria* (Table 2). The total number of leaflets per leaf found for *E. precatoria* (total 130.2 or 65.1 on each side of the leaf) and *E. oleracea* (total 115.4 or 57.7 on each side for BRS Pará and total 116.8 or 58.4 leaflets on each side of the rachis for Chumbinho) fell within the range cited in the literature: 48 to 91 leaflets per side of the rachis in *E. precatoria* and 40 to 80 leaflets per side of the rachis in *E. oleracea* [2,8,9]. It is notable that in this study, the use of the third leaf was standardized for the characterization of leaf morphology. The results obtained corroborate literature descriptions indicating that the average number of leaflets in leaves of *E. precatoria* may be higher than in *E. oleracea*.

Table 2. Means and standard deviation for stem, leaf, leaf area, and plant leaf area variables, and qualitative characteristics of the leaf rachis for açaí palm species *E. oleracea* and *E. precatoria*.

Variables *	***E. oleracea* cv. BRS Pará**	***E. oleracea* cv. Chumbinho**	***E. precatoria***
Stem			
N	27	17	121
Stipe height	576 ± 93 a	599 ± 86 a	357 ± 101 b
Internode distance	63 ± 8 a	86 ± 3 a	44 ± 13 b
Stem diameter	23 ± 3 a	24 ± 2 a	19 ± 5 b
Number of leaves	26 ± 10 a	26 ± 12 a	10 ± 2 b
Leaf			
N	3	3	3
Petiole length (cm)	13.7 ± 6.8 a	17.3 ± 6.1 a	17.1 ± 9.2 a
Rachis length (cm)	251.7 ± 20.2 a	268.3 ± 23.0 a	255.1 ± 26.7 a
Leaf width (cm)	167.9 ± 26.5 a	171.0 ± 21.5 a	169.5 ± 17.7 a
Number of leaflets (count)	115.4 ± 15.8 b	116.8 ± 7.1 b	130.2 ± 9.9 a
Rachis width (cm)	3.5 ± 0.2 a	3.6 ± 0.3 a	3.0 ± 0.3 b
Rachis height (cm)	2.1 ± 0.2 a	2.1 ± 0.3 a	1.4 ± 0.1 b
Leaflet length (cm)	93.5 ± 6.9 a	93.4 ± 8.3 a	87.0 ± 11.4 a
Leaflet width (cm)	4.1 ± 0.2 a	3.9 ± 0.3 a	2.9 ± 0.3 b
Distance between leaflets (cm)	4.4 ± 0.5 a	4.6 ± 0.4 a	3.9 ± 0.4 b
Yellow stripe on the rachis	Absent	Absent	Present
Rachis shape	Trapezoidal	Trapezoidal	Triangular
Leaf Area			
N	3		3
Plant leaf area (m^2)	25.21 ± 9.23 a	-	16.72 ± 2.76 b
N	34		32
Leaf area (m^2)	5.82 ± 1.47 a	-	4.18 ± 1.19 b

* Means with different lowercase letters in the row differ statistically by the Mann–Whitney test, $p < 0.05$.

For leaflet width, the values found for *E. precatoria* (2.9 ± 0.3) and *E. oleracea* (4.1 ± 0.2 for BRS Pará and 3.9 ± 0.3 for Chumbinho) exceeded the ranges reported in the scientific literature by Henderson [9], who noted 1 to 2 cm for *E. precatoria* and 2.0 to 2.5 cm for *E. oleracea*. Since Henderson’s observations are derived from plants in natural populations of varying ages and environmental conditions, these factors may explain the discrepancies with the higher measurements obtained in this study conducted under controlled cultivation conditions. However, in comparing the species, the literature also indicates that leaflet width in *E. precatoria* surpasses that in *E. oleracea*.

The measurements for rachis height and width in *E. precatoria* were lower than those observed in *E. oleracea*, and there were no references to these characteristics in the scientific literature for either species under cultivation conditions. In studies on peach palm (*Bactris gasipaes*), Clement [37] and Ramos [38] utilized rachis dimensions to estimate leaf biomass, suggesting that these traits might similarly be useful for studies on açaí palms.

In the species *E. precatoria*, a yellow stripe on the abaxial face of the leaf rachis was observed, which is not present in *E. oleracea* (Figure 1B). In the transverse section of the rachis, *E. oleracea* exhibited an approximately trapezoidal shape, distinct from *E. precatoria*, which displayed an approximately triangular shape (Figure 1A,C). Therefore, these characteristics can be included among the morphological features that can be used to distinguish between the species.

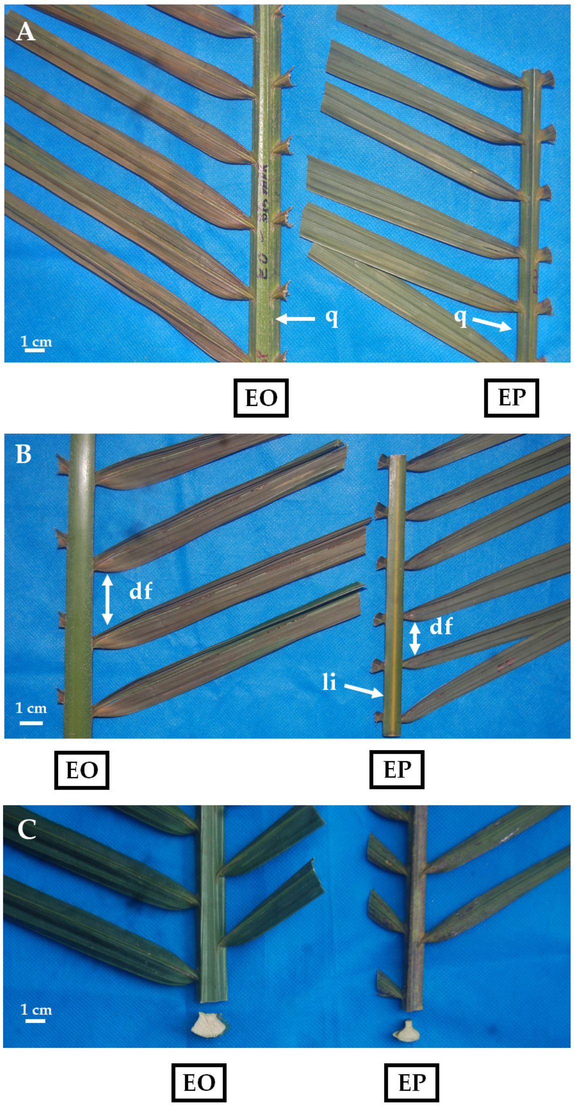

Figure 1. Adaxial (**A**) and abaxial (**B**) views of the leaflets of *E. oleracea* (EO) cv BRS Pará on the left and *E. precatoria* (EP) on the right. Cross-section of the leaf rachis (**C**). Scale bar: 5 cm. q = Ridge on the abaxial phase of the rachis. Li = Yellow stripe on the abaxial phase of the rachis in EP. df = distance between leaflets. P = cross-section of the leaf rachis.

Regarding tillering, as documented in the scientific literature, *E. precatoria* did not exhibit any offshoots [2,9]. In *E. oleracea*, 91% of the plants of the BRS Pará cultivar and 78% of the Chumbinho cultivar displayed offshoots at 44 months after planting. Tillering is a favorable trait for the establishment and survival of the species as if one stem's meristematic region is compromised by physical damage, pest attacks, or diseases, the plant can survive through other healthy offshoots or by producing new offshoots. In contrast, in *E. precatoria*, which is monocaulous, once the meristematic region is compromised, the plant will die. Tillering also allows for the management of plant height, as it is possible to remove taller offshoots, which will be compensated by the emergence of new, lower offshoots. Additionally, tillering enables the dual-purpose use of the plant, allowing for the harvest of some offshoots for palm heart extraction while maintaining others for fruit production [11].

The averages for individual leaf area (ILA) and total plant leaf area (TLA) in *E. oleracea*, BRS Pará cultivar (ILA = 5.82 ± 1.47 m^2 and TLA = 25.21 ± 9.23 m^2), were statistically superior to those observed in *E. precatoria* (ILA = 4.18 ± 1.19 m^2 and TLA = 16.72 ± 2.76 m^2). In this study, both species were cultivated at the same spacing (5 m × 4 m); however, since *E. precatoria* exhibits lower individual and total plant leaf area compared to *E. oleracea*, it is assumed that it could be cultivated at a higher density. Nonetheless, experiments assessing the impact of planting density on growth in height and productivity of the species are necessary to determine the optimal planting densities.

The morphological differences between *E. oleracea* and *E. precatoria* translate into practical benefits for agriculture. The superior stem and leaf growth of *E. oleracea* demonstrates its greater suitability for intensive cultivation, where its rapid development and larger leaf area result in higher photosynthetic capacity and productivity in less time, making it ideal for environments where space optimization and maximizing quick economic returns are priorities. In contrast, *E. precatoria* shows slower growth, smaller leaf area, and greater sensitivity to nutritional deficiencies, such as those of boron and potassium, which can pose challenges in intensive cultivation scenarios. However, *E. precatoria* may be more suitable for low-density environments or agroforestry systems, where less intensive management is feasible, and the pressure for high yields in the short term is lower. These morphological differences should, therefore, guide species selection according to the environment and cultivation objectives, with *E. oleracea* being more suitable for intensive cultivation systems with efficient management, while *E. precatoria* may be better utilized in conditions that favor its slower growth cycle and specific nutritional needs.

3.4. Leaf Allometry

Except for the average leaflet width (Lfm) in the case of *E. precatoria*, there was a high linear correlation between individual leaf area (Af) and the other characteristics measured with a tape measure on the leaves of both açaí palm species (Table 3). The linear regression model, including the explanatory variables leaflet length (Cf) and average width (Lf) of the central leaflets, provided the most precise estimates of individual leaf area, with high R^2 values and low S and CV (%) for both *E. oleracea* and *E. precatoria* (Table 4). For both species, the models incorporating Cf and Lf variables explained 93% (R^2) of the variation in estimated individual leaf area, thus, they are considered accurate. Furthermore, the standard deviations (S) of the models were low (S = 7% for *E. oleracea* and S = 6% for *E. precatoria*). The variables rachis length and total number of leaflets did not significantly contribute to enhancing the accuracy of the predictive models for leaf area in açaí palms.

During model validation, when analyzing standardized residuals (RESZ) calculated from the differences between the estimated individual leaf area (ELA) and the observed leaf area (OLA), only 1 (2.9%) out of 34 in *E. oleracea* and 1 (3.0%) out of 33 in *E. precatoria* were considered outliers (Table S1). According to Field (2013), models that produce fewer than 5% discrepant RESZ demonstrate good precision. The data that generated discrepant RESZ were removed from the model construction, and adjusted individual leaf area estimates (AELA) were obtained with the newly generated model. Among the standardized residuals of the adjusted estimates (RESZAJ) for both species, none were classified as discrepant, considering all absolute values were below 1 [19]. The exclusion of discrepant RESZ allowed for assessing the influence of the models in predicting the identified discrepant cases; however, it had little impact on the precision of the model for the other samples' estimates.

Table 3. Pearson correlation coefficients among variables: mean leaf area (Af), average leaflet length (Cfa), and width (Lfa) measured with a leaf area meter; average leaflet length (Cfm) and width (Lfm) measured with a tape measure; number of leaflets per leaf (Nf), and rachis length (Cr). Values for *E. oleracea* are shown in the lower diagonal and for *E. precatoria* in the upper diagonal.

	Af	**Cfa**	**Lfa**	**Cfm**	**Lfm**	**Cr**	**Nf**
Af	-	0.922 **	0.662 **	0.956 **	0.415 *	0.848 **	0.725 **
Cfa	0.934 **	-	0.712 **	0.940 **	0.339	0.813 **	0.618 **
Lfa	0.622 **	0.538 **	-	0.644 **	0.550 **	0.572 **	0.303
Cfm	0.915 **	0.962 **	0.517 **	-	0.293	0.886 **	0.720 **
Lfm	0.805 **	0.711 **	0.533 **	0.614 **	-	0.025	0.039
Cr	0.911 **	0.925 **	0.544 **	0.912 **	0.752 **	-	0.717 **
Nf	0.745 **	0.729 **	0.380 *	0.699 **	0.575 **	0.716 **	-

**, * Significant at 1 and 5% probability, respectively, by the *t*-test.

Table 4. Allometric equations relating leaf area in açaí palm species *E. oleracea* (AFo) and *E. precatoria* (AFp) to the variables average length (Cf) and width (Lf) of the three central leaflet pairs, rachis length of the leaf (Cr), and total number of leaflets per leaf (Nf).

Model	***t*-Test for Model Parameters**					**S**	**CV (%)**	**R^2**
	t_a	t_{b1}	t_{b2}	t_{b3}	t_{b4}			
AFo = –3.32 + 3.52 Cf + 43.80 Lf − 0.034 Cr + 0.01 Nf	–7.8 **	5.3 **	5.1 **	–0.1 ^{ns}	1.5 ^{ns}	0.15	7	94
AFo = –2.85 + 3.71 Cf + 45.48 Lf + 0.02 Cr	–9.6 **	5.6 **	5.2 **	0.1 ^{ns}		0.15	7	93
AFo = –2.86 + 3.75 Cf + 45.88 Lf	–11.5 **	11.5 **	6.6 **			0.15	7	93
AFo = –2.10 + 5.09 Cf	–6.2 **	12.9 **				0.23	10	84
AFp = –1.77 + 1.90 Cf + 32.61 Lf + 0.17 Cr + 0.004 Nf	–4.2 **	6.7 **	1.3 **	–0.1 ^{ns}	0.79 ^{ns}	0.08	5	94
AFp = –1.43 + 2.11 Cf + 30.26 Lf + 0.19 Cr	–6.3 **	5.8 **	3.7 **	2.0 ^{ns}		0.09	6	94
AFp = –1.21 + 2.78 Cf + 21.67 Lf	–5.8 **	18.4 **	3.0 **			0.09	6	93
AFp = –0.70 + 2.91	–5.5 **	17.9 **				0.10	7	92

** and ^{ns}, significant and non-significant by the *t*-test at 5% probability; S = standard error of the estimate; CV = coefficient of variation; R^2 = coefficient of determination of the regression model.

The graphical dispersion obtained with standardized residuals and standardized adjusted estimates of leaf area demonstrated the normality of residuals and homogeneity of variances for the models across both species (Figure S1). Positive linearity was observed between the explanatory variables width and length of the central leaflets and the leaf area estimates in the selected allometric models for *E. precatoria* and *E. oleracea*, as indicated by the graphical dispersion between standardized residuals and adjusted leaf area obtained through partial regression for each explanatory variable [39]. Therefore, the length and width of the central leaflets proved to be explanatory variables that generated models with high precision for estimating the leaf area of *E. precatoria* and *E. oleracea*.

Leaf area is a determining factor that directly influences photosynthetic capacity, light interception, and the overall vigor of plants, playing a central role in the productive capacity of açaí species. Plants with larger leaf areas, like *E. oleracea*, have a greater ability to capture sunlight, converting it into energy through photosynthesis, which results in greater vegetative and reproductive growth. Conversely, the smaller leaf area observed in *E. precatoria* may limit this capacity, reflecting lower vigor and slower growth. In this context, the allometric models developed to estimate leaf area are valuable practical tools for agricultural management. These models allow for the rapid and accurate estimation of leaf area based on simple measurements, such as the length and width of leaflets, which can be used to optimize planting density, adjust plant spacing to maximize light interception and minimize competition. Additionally, these models are useful for predicting plant responses to environmental stresses, such as variations in light, water, or nutrient availability, allowing for management adjustments, such as changing irrigation regimes or modifying fertilization to better meet the specific needs of the plants. They can also be used to assess the impact of different cultivation practices, such as thinning, on the growth and productivity of plants. The application of allometric models in agricultural practice not only improves the efficiency of açaí cultivation management but also maximizes the productive potential of plants, ensuring better adaptation to environmental conditions and management practices.

4. Conclusions

E. oleracea palm initiates its reproductive phase earlier than *E. precatoria*. This factor is crucial as it suggests a quicker entry into production when cultivated in full sun in Central Amazonia, positively influencing management decisions and species selection for plantations. This precocity can lead to maximized production in shorter production cycles, making *E. oleracea* a preferable choice for producers seeking rapid returns. While the early maturity of the *E. oleracea* species is an initial advantage, it should not be the only aspect considered when choosing a species for planting. Productivity data for fruit yield and pulp output of *E. precatoria* still need to be obtained for an economic analysis of the species considering the lifespan of the plantations. Moreover, the species have distinct harvest periods, which is important for market price stability, considering that price variation is very high due to product scarcity, especially during the off-season of *E. oleracea*.

Among future research efforts to promote the sustainable development of the *E. precatoria* production chain, the development of cultivars with homogeneity in growth, early maturity, and high fruit and pulp productivity is highlighted. The superiority of *E. oleracea* in terms of rapid growth and early onset of the reproductive phase underscores its potential to boost economic growth in the Amazon, making it ideal for intensive, high-productivity cultivations. Its ability to enter production earlier offers quick financial returns, which can attract investments for the expansion of açaí cultivation, which is essential for the local economy. With the use of appropriate management techniques and allometric models, producers can optimize inputs and space, increasing the efficiency and sustainability of the plantations.

The differences in nutritional requirements between *E. oleracea* and *E. precatoria* reinforce the need for specific management practices for each species, with *E. oleracea* being more suitable for intensive systems and *E. precatoria* for agroforestry systems in more sensitive ecosystems. This understanding can diversify agricultural practices and promote environmental preservation. The economic impact can be significant, given the international interest in the açaí market, generating more jobs and income in rural communities, promoting sustainable development, and enhancing the global competitiveness of the region.

To improve the productivity of *E. precatoria*, it is recommended to increase planting density due to its slower growth and smaller leaf area, optimizing the use of space. Additionally, specific nutritional protocols focusing on nutrients such as boron and potassium can mitigate deficiencies and stimulate growth. Controlled-release fertilizers and adjusted irrigation practices can accelerate its development, making its cultivation more competitive and productive.

The analysis of leaf area reveals that *E. precatoria* has a lower individual and total leaf area compared to *E. oleracea*. This finding is significant as it can directly affect photosynthesis and energy conversion efficiency, influencing overall productivity. The allometric relationships based on the length and width of the central leaflets prove to be effective methods for estimating leaf area in the two studied species. The precision of these allometric models facilitates the conduct of rapid and non-destructive leaf area assessments, an essential parameter for physiological and agronomic studies aimed at enhancing cultivation practices.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/horticulturae10101119/s1. Table S1. Value of observed leaf area (AFO), obtained by measuring the area of all leaflets of the leaf; estimated leaf area (AFE), obtained by the allometric model using length and width of the three pairs of central leaflets of the leaf; difference between AFO-AFE and standardized residue (RESZ) of each sample; adjusted estimated leaf area (AFAJ), obtained by allometric model after excluding samples with outliers from the analysis; difference between AFE-AFAJ and standardized residue (RESZAJ) of each sample and Cook's distance (COOK) for the açaí palms *E. oleracea* and *E. precatoria*; Figure S1. Scatterplots between the regression estimate and the residual for mean leaf area per leaf of *E. oleracea* (A) and *E. precatoria* (B). Scatterplots between the partial regression estimate and the residual for leaflet length and leaflet width in *E. oleracea* (A-1, A-2) and *E. precatoria* (B-1, B-2).

Author Contributions: Conceptualization, J.P.M.D., R.L. and M.T.G.L.; methodology, J.P.M.D., R.L., R.N.V.d.C., S.L.F.R., R.R.d.M., E.B. and M.T.G.L.; software, J.P.M.D., N.M.C.d.M. and S.L.F.R.; validation, R.R.d.M., M.d.R.L.R., E.B. and C.H.S.G.M.; formal analysis, R.N.V.d.C., C.H.S.G.M. and N.M.C.d.M.; investigation, J.P.M.D. and R.L.; resources, R.L. and C.H.S.G.M.; data curation, R.L. and J.P.M.D.; writing—original draft preparation, M.T.G.L., R.L. and J.P.M.D.; writing—review and editing, C.H.S.G.M. and N.M.C.d.M.; supervision, M.d.R.L.R. and R.L.; project administration, M.T.G.L.; funding acquisition, C.H.S.G.M., M.T.G.L. and R.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received financial support from Graduate Development Program (PDPG)–Strategic Partnerships in States III, Notice No. 38/2022; Paraiba State Research Foundation (FAPESQ), Grant Agreement No. 397/2023; Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES): PROAP, Emergency Strategic Consolidation of Academic Stricto Sensu Graduate Programs PDPG–CAPES with Scores 3 and 4; and Finance Code 001. Paraiba State University (PRPGP grant #01/2024) partially financed this study. This research was funded by the Amazonas State Research Foundation (FAPEAM), grant numbers 062.01247/2018 and 01.02.016301.03218/2021-92, and the National Council for Scientific and Technological Development (CNPq), grant number 407002/2021-9.

Data Availability Statement: Data are contained within the article.

Acknowledgments: Jhon Paul Mathews Delgado was supported by a scholarship from FAPEAM. The authors thank the National Council for Scientific and Technological Development, Edital CNPq/MCTI no. 23/2020, and Coordination for the Improvement of Higher Education Personnel, Brazil (CAPES), Edital no. 16/2020—PROCAD-SPCF for funding this research. The authors also wish to thank CNPq for providing the research productivity grant that enabled the following to complete this research: Carlos Henrique Salvino Gadelha Meneses (Process no. 313075/2021-2); Santiago Linorio Ferreyra Ramos (Process no. 305280/2022-8); Ricardo Lopes (Process no. 308815/2023-8); and Maria Teresa Gomes Lopes (Process no. 310307/2018-0) and (Process no. 442914/2020-2).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. IBGE (Instituto Brasileiro de Geografia e Estatística-IBGE). Sistema IBGE de Recuperação Automática. Banco de Dados Agregados. Tabela 1613: Área Destinada à Colheita, Área Colhida, Quantidade Produzida, Rendimento Médio e Valor da Produção das Lavouras Permanentes—Açaí. Rio de Janeiro. 2022. Available online: https://sidra.ibge.gov.br/tabela/1613#resultado (accessed on 6 July 2024).
2. Vianna, S.A. Euterpe in Flora e Funga do Brasil. Jardim Botânico do Rio de Janeiro. Available online: https://floradobrasil.jbrj.gov.br/FB22142 (accessed on 30 July 2024).
3. Castro, A.F.; Santos, A.C.; Silva, L.J.S.; Meneghetti, G.A.; Lopes, R. Adoção da cultivar BRS Pará no Amazonas: Um estudo exploratório da expansão de açaizais com tecnologia agropecuária disponibilizada pela Embrapa. In *O Despertar para a Ciência: Contribuições dos Alunos de Iniciação Científica para a Pesquisa Socioeconômica na Amazônia*; Silva, L.J.S., Meneghetti, G.A., Pinheiro, J.O.C., Eds.; Embrapa: Brasília, Brazil, 2022; pp. 17–41. Available online: https://ainfo.cnptia.embrapa.br/digital/bitstream/item/237885/1/Livro-bolsista-final-atual-p17.pdf (accessed on 8 August 2024).
4. Kang, J.; Thakali, K.M.; Xie, C.; Kondo, M.; Tong, Y.; Ou, B.; Jensen, G.; Medina, M.B.; Schauss, A.L.; Wu, X. Bioactivities of açaí (*Euterpe precatoria* Mart.) fruit pulp, superior antioxidant and anti-inflammatory properties to Euterpe oleracea Mart. *Food Chem.* **2012**, *133*, 671–677. [CrossRef]
5. Matos, C.B.; Sampaio, P.; Rivas, A.A.A.; Matos, J.C.S.; Hodges, D.G. Economic profile of two species of Genus Euterpe, producers of açaí fruits, from the Pará and Amazonas States—Brazil. *Int. J.Environ. Agric. Biotechnol.* **2017**, *2*, 1822–1828. [CrossRef]
6. da Silva Melo, G.; da Costa, F.S.; da Silva, L.C. Productivity of Açai Euterpe Precatoria and Production System Management Recommendations in the South Of The Amazonas. *Rev. Gest. Soc. Ambient.* **2024**, *18*, e06972.
7. Lopes, R.; Cunha, R.N.V.; Tavares, M.S.; Raizer, M.D.M.; Santos, C.A.; Silva, E.J.D.; Lopes, M.T.G. Seasonality of fruit production of Euterpe oleracea and E. precatoria açaí palm trees cultivated in the metropolitan region of Manaus (AM). *Agro@mbiente On-Line* **2022**, *16*, e7282. [CrossRef]
8. Henderson, A.; Galeano, G. Euterpe, Prestoea, and Neonicholsonia (Palmae: Euterpeinae). *Flora Neotrop.* **1996**, *72*, 98–103.
9. Henderson, A. *The Palms of the Amazon*, 1st. ed.; Oxford University Press: New York, NY, USA, 1995; p. 101.

10. Clement, C.R.; de Cristo-Araujo, M.; d'Eeckenbrugge, G.C.; Alves Pereira, A.; Picanço-Rodrigues, D. Origin and domestication of native Amazonian crops. *Diversity* **2010**, *2*, 72–106. [CrossRef]
11. Oliveira, M.S.P.; Mochiutti, S.; Farias-Neto, J.T. Domestication and Breeding for Assai Palm. In *Domestication and Breendig: Amazonian Species*; Borém, A., Lopes, M.T.G., Clement, C.R., Noda, H., Eds.; Suprema: Viçosa, Brazil, 2012; pp. 209–236.
12. Nogueira, A.K.M.; Santana, A.C. Benefícios socioeconômicos da adoção de novas tecnologias no cultivo do açaí no Estado do Pará. *Rev. Ceres* **2016**, *63*, 1–7. [CrossRef]
13. Chaves, S.F.S.; Alves, R.M.; Dias, L.A.S. Contribution of breeding to agriculture in the Brazilian Amazon. I. Açaí palm and oil palm. *Crop Breed. Appl. Biotechnol.* **2021**, *21*, e386221S8. [CrossRef]
14. Ayres, M.I.; De Souza, E.I.; Uguen, K.; Alfaia, S.S.; Pereira, H. Dos Santo. Caracterização dos agroecossistemas de açaí-do-amazonas em Codajás, Amazonas—Brasil. *RBA* **2024**, *19*, 167–190. [CrossRef]
15. Fritz, M.A.; Rosa, S.; Sicard, A. Mechanisms underlying the environmentally induced plasticity of leaf morphology. *Front. Genet.* **2018**, *9*, 478. [CrossRef]
16. Moreira, A.; Fagueria, N.K. Potential of Brazilian Amazon Soils for Food and Fiber Production. *Dyn. Soil Dyn. Plant* **2008**, *2*, 82–88.
17. Fisch, G.; Marenco, J.A.; Nobre, C.A. The climate of Amazonia–A review. *Acta Amaz.* **1999**, *28*, 101–126. [CrossRef]
18. Oliveira, M.S.P.; Carvalho, J.E.U.; Nascimento, W.M.O.; Müller, C.H. *Açaí Tree Cultivation for Fruit Production*, 1st ed.; Embrapa: Belém, Brazil, 2002; pp. 6–7.
19. Field, A. *Discovering Statistics Using IBM SPSS Statistics*, 4th ed.; SAGE: London, UK, 2013; pp. 156–215.
20. IBM Corp. *IBM SPSS Statistics for Windows*; Version 20.0.; IBM Corp: Armonk, NY, USA, 2011.
21. Viégas, I.J.M.; Frazão, D.A.C.; Thomaz, M.A.A.; Conceição, H.E.O.; Pinheiro, E. Limitações nutricionais para o cultivo de açaizeiros em Latossolo Amarelo textura media, Estado do Pará. *Rev. Bras. De Frutic.* **2004**, *26*, 382–384. [CrossRef]
22. Viégas, I.J.M.; Gonçalves, A.A.S.; Frazão, D.A.C.; Conceição, H.E.O. Efeito das omissões de macronutrientes e Boro na sintomatologia e crescimento de plantas de açaizeiros (*Euterpe oleracea* Mart.). *Rev. Ciências Agrárias* **2008**, *50*, 129–142.
23. Viégas, I.J.M.; Meireles, R.O.; Frazão, D.A.C.; Conceição, H.E.O. Avaliação da fertilidade de um Latossolo Amarelo textura média para o cultivo do açaizeiro no estado do Pará. *Rev. Ciências Agrárias* **2009**, *52*, 23–36.
24. Cordeiro, R.A.M. Crescimento e Nutrição Mineral do Açaízeiro (*Euterpe oleracea* Mart.), em Função da Idade em Sistemas Agroflorestais no Município de Tomé-Açu, Pará. Ph.D. Thesis, Universidade Federal Rural da Amazônia, Belém, Brazil, 2011.
25. Araujo, F.R.R.; Viegas, I.D.J.M.; Da Cunha, R.L.M.; De Vasconcelos, W.L.F. Efeito da omissão de nutrientes no crescimento e estado nutricional de mudas de açaizeiro. *Pes. Agropec. Trop.* **2016**, *46*, 374–382.
26. Ribeiro, F.O. Estado Nutricional e Produtividade de Açaizeiro Fertirrigado em Função Variabilidade Espacial. Master's Thesis, Universidade Federal Rural da Amazônia, Curió Utinga, Brazil, 2017.
27. Cajueiro, L.R.; Costa, L.G.B.; Feitosa, I.d.L. Adubação orgânica na produção de açaí (*Euterpe oleracea* e E. precatoria), visando à geração de emprego e renda, em pequenas propriedades do estado de Rondônia. *Cad. Agroecol.* **2018**, *13*, 1–6.
28. Lindolfo, M.M.; Matos, G.S.B.; Pereira, W.V.; Fernandes, A.R. Productivity and nutrition of fertigated açaí palms according to boron fertilization. *Rev. Bras. Frutic.* **2020**, *42*, e-601. [CrossRef]
29. Almeida, U.O.D.; Andrade Neto, R.D.C.; Lunz, A.M.P.; Nogueira, S.R.; Costa, D.A.D.; Araújo, J.M.D. Environment and slow-release fertilizer in the production of Euterpe precatoria seedlings. *Pesqui. Agropecu. Trop.* **2018**, *48*, 382–389. [CrossRef]
30. Araújo, C.S.; Lunz, A.M.P.; dos Santos, V.B.; Neto, R.D.C.A.; Nogueira, S.R.; dos Santos, R.S. Uso de resíduos agroindustriais como substrato para a produção de mudas de *Euterpe precatoria*. *Pes. Agropec. Trop.* **2020**, *50*, e58709. [CrossRef]
31. Araújo, J.C. Adubação Nitrogenada e Fosfatada para Produção de Mudas de Açaizeiro Solteiro (Euterpe Precatoria Mart.). Ph.D. Thesis, Universidade Federal do Acre, Rio Branco, Brazil, 2021.
32. Butzke, A.G.; de Brito, R.S.; Neto, R.D.C.A.; Lunz, A.M.P.; da Silva Fiuza, S.; Andrade, R.A. Produção de mudas de Euterpe precatoria Mart. em resposta a diferentes dosagens de nitrogênio e potássio. *Comun. Sci.* **2023**, *14*, e4000. [CrossRef]
33. Pimentel-Gomes, F. *Curso de Estatística Experimental*, 15th ed.; FEALQ: Piracicaba, Brazil, 2009; p. 451.
34. Avalos, G.; Fernández, O.M. Allometry and stilt root structure of the neotropical palm *Euterpe precatoria* (Arecaceae) across sites and successional stages. *Am. J. Bot.* **2010**, *97*, 388–394. [CrossRef] [PubMed]
35. Avalos, G.; Sylvester, O. Allometric estimation of total leaf area in the neotropical palm Euterpe oleracea at La Selva, Costa Rica. *Trees* **2010**, *24*, 969–974. [CrossRef]
36. Brum, H.D.; Souza, A.F. Flood disturbance and shade stress shape the population structure of açaí palm *Euterpe precatoria*, the most abundant Amazon species. *Botany* **2020**, *8*, 147–160. [CrossRef]
37. Clement, C. Growth and Genetic Analysis of Pejibaye (bactris gasipaes Kunth, Palmae) in Hawaii. Ph.D. Thesis, University of Hawaii, Honolulu, HI, USA, 1995.
38. Ramos, A.; Bovi, M.L.A.; Folegatti, M.V.; Diotto, A.V. Leaf area and aboveground biomass estimates in peach palm using allometric relationships. *Hortic. Bras.* **2008**, *26*, 138–143. [CrossRef]
39. Gotelli, N.J.; Ellison, A.M. *A Primer of Ecological Statistic*, 1st ed.; Sinauer Associates: Sunderland, MA, USA, 2011; pp. 277–282.