



Anthropized riparian forests show non-timber forest product potential in an industrial hub of the Eastern Amazon

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Abstract

Understanding the non-timber use potential of riparian forests is essential for advancing the sociobioeconomy in anthropized regions of the Amazon. This study assessed the use potential of species recorded in riparian forests and identified the factors associated with their distribution in an industrial hub in the Brazilian Amazon. Species with the highest importance value index along the region's main rivers and with some conservation status were classified according to their potential uses (food, medicinal, cosmetic, and handicraft). Potential distribution modeling was performed using maximum entropy, considering hydrological, topographic, and land-use variables. A total of 25 species were evaluated, of which only 18 presented at least one use category. The most frequent uses were medicinal, food-related, handicraft, and cosmetic, respectively. The palms *Euterpe oleracea* and *Mauritia flexuosa* stood out for their use potential across all categories, whereas *Byrsonima spicata*, *Eschweilera coriacea*, and *Apuleia leiocarpa* exhibited only a single known use. The most commonly used plant parts were bark (13 species), associated with medicinal purposes; fruits (10 species), mainly for food; and leaves (6 species), primarily used in phytotherapy. However, only three species met the criteria for modeling: *E. coriacea*, *M. flexuosa* and *Symphonia globulifera*. Thus, *E. coriacea* and *S. globulifera* showed negative influence from land use, while *M. flexuosa* exhibited a positive relationship with slope. The functional and use diversity identified highlights the high bioeconomic potential of Amazonian riparian forests; however, the negative influence of land use underscores the importance of integrated conservation strategies and sustainable management of non-timber forest products in anthropized areas.

Keywords Amazon bioeconomy · Urban riparian forests, riparian native species, food use · Cosmetic use · Medicinal use · Handicrafts

Introduction

Riparian forests are key ecosystems in tropical landscapes, acting as interfaces between terrestrial and aquatic environments and performing multiple ecological functions, such as regulating the hydrological cycle, stabilizing riverbanks, retaining sediments and nutrients, and moderating local climatic extremes (Verdonschot and Verdonschot 2023).

They also support biodiversity by providing habitat, food resources, and ecological connectivity for a wide range of species (Salviano et al. 2021). In the Amazon, these forests are particularly important in seasonally flooded environments, such as floodplains (várzeas) and blackwater systems (igapós), where hydrological dynamics strongly influence ecological processes (Nowacki et al. 2019).

Despite their ecological importance, riparian forests are highly vulnerable to land-use and land-cover change (Caldas et al. 2023). Between 1985 and 2023, the Amazon lost approximately 89 million hectares of forest, mainly due to agricultural expansion, logging, and mining (MapBiomass 2024). In the state of Pará, one of the main deforestation frontiers in the Eastern Amazon, about 20% of the original forest cover had been lost by 2023 (PRODES 2024). These interventions have compromised not only the ecological integrity

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of riparian forests but also the ecosystem services they provide to human populations, including water provision, climate regulation, and biodiversity support (Dinca et al. 2025).

In the state of Pará, the municipality of Barcarena exemplifies territorial transformation under the influence of large-scale industrial and port projects. Strategically located in the Eastern Amazon, with direct access to the Atlantic Ocean through its river network, Barcarena hosts one of the largest industrial hubs in northern Brazil (Nahum 2017). The establishment and operation of enterprises linked to mining, steel production, energy, and logistics have substantially altered natural landscapes, particularly along the rivers bordering the territory (Narayanan et al. 2024). Despite these transformations, riparian forest remnants persist in several areas, sustaining significant floristic diversity and harboring species with recognized traditional, pharmaceutical, cosmetic, food, and ornamental uses (Oliveira et al. 2022).

In this context, there is growing interest in approaches that integrate biodiversity conservation with sustainable economic development through a non-timber-based bioeconomy (Araujo et al. 2024). Identifying species with bioeconomic potential, particularly in vulnerable ecosystems such as riparian forests, is essential to support sustainable value chains and conservation strategies (Rosenfeld et al. 2024). In the Amazonian context, such strategies can help reduce pressure on ecosystems while providing nature-based solutions to regional development challenges (Garrett et al. 2024). Identifying native species with bioeconomic potential, especially those associated with riparian ecosystems, is an essential step to support public policies, guide investments, and foster sustainable value chains integrated with ecological restoration programs, territorial development, and climate change adaptation.

Furthermore, understanding the environmental factors that influence species distribution is therefore essential for predicting the dynamics of tree communities in anthropogenic landscapes. In this context, linking species distribution to their potential uses is particularly important to identify areas where species with bioeconomic value are more likely to occur and how they respond to environmental and land-use gradients. Species distribution modeling (SDM) comprises a set of analytical approaches used to relate species occurrence to environmental conditions (Wang et al. 2025). Within this framework, different algorithms can be applied, such as Max-Ent, which is widely used for modeling species distributions based on presence-only data (Ramanan et al. 2025). These approaches have been employed to identify the environmental predictors that determine species occurrence by integrating field data with spatial information on climate, topography, and hydrography (Luo et al. 2025; Njomaba et al. 2025).

This study aimed: (a) to evaluate the potential uses of native tree species occurring in riparian forests associated

with the main rivers of the Barcarena industrial hub; and (b) to assess the environmental factors that influence the distribution of species with potential use in the bioeconomy in riparian forests of the municipality. We hypothesize that native tree species occurring in riparian forests of Barcarena possess diverse bioeconomic uses, and that their spatial distribution is influenced by environmental gradients related to topography, hydrography, and land cover.

Material and methods

Study site

The study was conducted in the municipality of Barcarena, Pará, Eastern Amazon (01°30'21" S; 48°37'33" W; Fig. 1). The climate of the region is classified as tropical humid, according to the Köppen-Geiger system (Alvares et al. 2013). The predominant soil types are Dystrophic Red-Yellow Latosols, Hydromorphic Podzols, and Lateritic Concretionary soils (RADAMBRASIL 1974). The natural vegetation is classified as Dense Ombrophilous Forest (IBGE 2012), although it has been substantially altered by human occupation, particularly due to industrial expansion in the region (MapBiomas 2024). Topography is predominantly flat, with slight variation in upland areas and a subtle elevation gradient in floodplains, ranging from higher várzea near river margins to permanently flooded igapó (Santos et al. 2003).

The definition of the sampled areas was based on the distribution of riparian forest formations along three water bodies located in the municipality of Barcarena, Pará State, Brazil. The classification of impact levels was based on qualitative criteria, including field observations and secondary information by spatial indicators on land use, proximity to urban and industrial areas. Sampling was restricted to riparian forests, and terra firme areas were not included. The selection considered the variation in levels of human intervention, aiming to represent a gradient of socio-environmental impacts and different patterns of land use and anthropogenic pressure. Based on this approach, the study areas were classified into three categories: (a) Murucupi River, (b) Marajó Bay, and (c) Barcarena River. The sites located along the Murucupi and Barcarena rivers are predominantly associated with igapó environments, while Marajó Bay area corresponds, predominantly, to várzea environments.

The Murucupi River represents the category with the highest level of human impact, as it flows through a highly urbanized and industrialized region. In this area, riparian vegetation is heavily altered by land-use changes associated with urban expansion and industrial activities, resulting in reduced vegetation cover, fragmentation, simplified forest

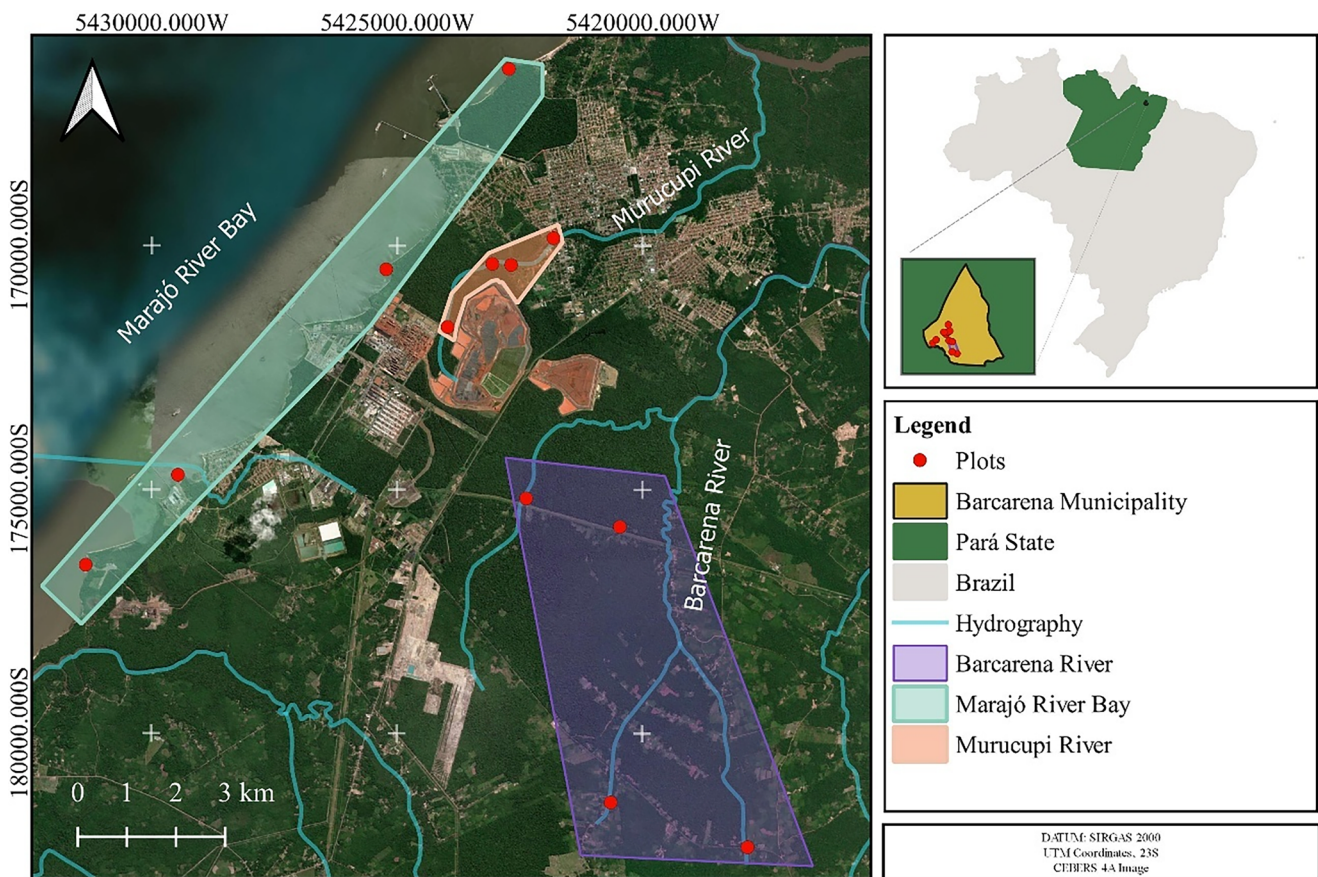


Fig. 1 Sampling points in areas of the industrial hub located in the municipality of Barcarena, Eastern Amazon, Brazil

structure, and a higher dominance of disturbance-tolerant species. These conditions directly affect species composition and limit natural regeneration processes. The Marajó Bay is in a transition zone between urban and estuarine environments and is subject to continuous disturbance. Riparian vegetation in this area is moderately altered, with partial removal of vegetation cover and recurrent human use of riverbanks. These pressures contribute to intermediate levels of structural alteration and shifts in species composition, particularly affecting the recruitment and persistence of less tolerant species. The Barcarena River was characterized as the area with the lowest direct human impact, serving as a reference for less altered conditions. In this region, riparian vegetation is more continuous and better preserved, with greater structural complexity and a higher representation of native species. These conditions support more stable ecological processes and provide a baseline for comparison with more disturbed environments.

Floristic data collect

A total of 12 plots, each measuring 25 m × 100 m, were established, with four plots allocated to each of the three

hydrological influence areas. This plot size (2,500 m²) is commonly adopted in tropical forest inventories and is consistent with the spatial scale of ecological and modeling studies, as tree attributes such as diameter and height are often collected in plots of similar or smaller size (Fleming et al. 2015). Within each plot, a floristic inventory was conducted, including all tree, shrub, and palm individuals with a diameter at breast height (DBH, measured at 1.30 m above the ground surface) ≥ 3.82 cm. This DBH limit was adopted to include the naturally slender palms and other small-diameter individuals typical of riparian forests, which would be underrepresented using more conventional thresholds (e.g., 5–10 cm). In addition to DBH measurement using diameter tapes, total height (Ht) was estimated using the Biltmore stick method. When in situ species identification was not possible, standardized botanical samples were collected and later compared with reference specimens at the Felisberto Camargo Herbarium of the Federal Rural University of the Amazon (UFRA), located in Belém, Pará.

All species were classified according to their conservation status as Vulnerable (VU), Critically Endangered (CR), or Least Concern (LC), following the criteria established by the (IUCN 2024) and (Martinelli and Moraes 2013). This

classification was used to identify species of greater conservation concern and to evaluate whether species with bioeconomic potential are associated with higher levels of threat, thereby supporting priority-setting for conservation and sustainable management in riparian forests. Additionally, the Importance Value Index (IVI) was calculated following the methodology proposed by Müller-Dombois and Ellenberg (1974), as the sum of relative density, relative frequency, and relative dominance, with all components equally weighted.

Bioeconomic potential assessment

The bioeconomic potential was evaluated for two complementary groups of species: (i) the ten species with the highest Importance Value Index (IVI) in the studied areas, representing those with the greatest ecological relevance in terms of dominance, frequency, and abundance; and (ii) species with an assigned conservation status, due to their ecological vulnerability and priority for conservation actions. Species that met both criteria were considered only once in the final list, to avoid duplication. This combined approach allows the identification of species that are both structurally important to ecosystem functioning and/or of conservation concern, thereby supporting strategies that integrate restoration, biodiversity conservation, and sustainable use.

The type of use was assessed using the Useful Tropical Plants database (Fern 2025), which enabled classification into four categories: (a) food use, when related to the direct consumption of fruits, seeds, or other plant parts by humans or animals; (b) medicinal or pharmaceutical use, or species utilized in traditional systems or by the pharmaceutical industry; (c) cosmetic use, for species employed in cosmetic formulations, personal hygiene products, or perfumery; e (d) handicrafts, referring to the use of wood, bark, fibers, or seeds for artisanal production. Additional searches were conducted in the technical and scientific literature to supplement the database information and identify uses for species not listed in the database.

To evaluate the diversity of species uses, an undirected bipartite network was constructed following (Dormann et al. 2009), connecting the ten species with the highest IVI to the identified use categories. Additionally, the overlap between IVI values and the number of use categories was analyzed using a scatter plot, which allowed the determination of species prioritization regarding their bioeconomic potential in each study area. Priority was defined based on the species' position in the plot quadrants: species of highest priority were located in the first quadrant (upper right), whereas lowest-priority species were in the third quadrant (lower left). The remaining quadrants encompassed species considered relevant in only one of the axes (IVI or number of use categories).

Species modeling and distribution

To evaluate the environmental factors influencing the distribution of species with bioeconomic potential, we used environmental predictors related to topography, hydrography, and land cover. For topography, the digital elevation model (DEM) was obtained from the Shuttle Radar Topography Mission (SRTM) with a spatial resolution of 30 m, using the *elevatr* package in R (Hollister 2017). From the DEM, slope and aspect (in degrees) were derived using the *terra* package (Hijmans 2020). The hydrographic network was extracted from OpenStreetMap using the *osmdata* package (Maspons et al. 2017), considering features classified as river, stream, and canal, and the minimum distance to watercourses was calculated for each sampling plot. In addition, land-use and land-cover layers were obtained from MapBiomass (Collection 9) and used as categorical variables in the modeling. The original classes were reclassified to represent the main land-use categories present in the sampled study area, including forest formation, secondary vegetation, urban infrastructure, water bodies, and other anthropogenic uses (agriculture, pasture).

These predictors were selected to represent complementary environmental gradients influencing species distribution in riparian systems. Topographic variables describe terrain structure and drainage conditions, hydrographic distance acts as a proxy for flooding intensity and soil moisture, and land-use classes capture anthropogenic influences on habitat structure. Together, these variables provide an integrated representation of the main factors driving species occurrence in the study area. All raster variables were reprojected to the same geographic coordinate system (WGS84) and clipped to the extent of the municipality of Barcarena using the *crop* and *mask* functions of the *terra* package. For each plot, the mean value of continuous predictors and the predominant class of categorical variables were extracted, generating a matrix of environmental variables associated with each sampling point.

Collinearity among environmental predictors was assessed using the variance inflation factor (VIF), retaining only variables with $VIF < 10$. Subsequently, potential distribution modeling was performed using the maximum entropy algorithm implemented in the *maxnet* package (Phillips 2016). At this stage, only species with at least two presence records after removing missing predictor values were considered, given the limited number of sampling plots ($n = 12$) and the resulting low frequency of occurrence for several species, particularly those with non-timber use potential. Species distribution models were fitted using presence (1) and absence (0) data derived from plot-level observations. Each model was generated automatically using the *maxnet* formula function, including linear, quadratic, and interaction terms to capture relationships between species and predictors.

Model accuracy was assessed using the Area Under the ROC Curve (AUC), calculated directly on the training dataset (Training-AUC). The use of training data for model evaluation was necessary due to the low number of observations ($n=12$) and the limited number of presence records for several species, which prevents both traditional k-fold cross-validation and data partitioning approaches (e.g., 70/30 split), as these would result in an insufficient number of occurrences for model calibration. AUC values were classified according to Metz (1978), as follows: (a) $AUC < 0.7$ = poor performance; (b) $0.7 \leq AUC < 0.8$ = acceptable; (c) $0.8 \leq AUC < 0.9$ = good; and (d) $AUC \geq 0.9$ = excellent. The influence of environmental factors on each species' distribution was determined based on the magnitude and direction (positive or negative) of the coefficients from the maxnet model.

Results

A total of 1,385 individuals were inventoried, distributed across 53 botanical families and 209 species. However, only four species (92 individuals) had assigned conservation status in these databases, representing 1.91% of the total species and 7.55% of the botanical families (Table 1).

The highest IVI value was recorded for *Euterpe oleracea* Mart. along the Barcarena River (5.18%), whereas *Ormosia coutinhoi* Ducke and *Mauritia flexuosa* L.f. were among the ten species with the highest IVI values across all areas. *Tapirira guianensis* Aubl. was the only species not recorded in the Murucupi River. *Taralea oppositifolia* Aubl., *Symphonia globulifera* L.f., and *Virola surinamensis* (Rol. ex Rottb.) Warb. were among the ten species with the highest IVI values in both the Barcarena and Murucupi rivers (Fig. 2).

After removing duplicate occurrences and applying the selection criteria, 25 unique species were identified for the

evaluation of bioeconomic potential. Most species (72%) presented at least one recorded use, while a smaller proportion had no documented uses. Medicinal use was the most frequent category, followed by food-related uses, whereas handicraft and cosmetic applications were less common. A few species exhibited multiple use categories (Fig. 3), with palms such as *Euterpe oleracea* and *Mauritia flexuosa* standing out due to their broad versatility. Plant use was predominantly associated with bark, fruits, and leaves. Bark and leaves were mainly linked to medicinal applications, while fruits were primarily used for food, reflecting a clear functional pattern in resource use (Table 2).

In the Barcarena River area, *Euterpe oleracea* was identified as a species of high bioeconomic priority (Fig. 4a). In contrast, *Parkia* sp., *Taralea oppositifolia*, and *Vochysia maxima* Ducke were classified as low priority, showing low values for both IVI and use categories. In the Murucupi River area, no species were classified as high priority, however, *M. itauba*, *Symphonia globulifera*, and *M. flexuosa* were considered relevant due to the number of use categories (Fig. 4b). *Virola surinamensis* (Rol. ex Rottb.) Warb. and *T. oppositifolia* stood out for their high IVI values but had no recorded uses. In Marajó Bay, *Spondias mombin* L. was identified as high priority (Fig. 4c), whereas *M. flexuosa*, *Simarouba amara*, and *Jacaratia spinosa* were considered relevant due to their high number of use categories.

Only three species (*Eschweilera coriacea*, *Mauritia flexuosa*, and *Symphonia globulifera*) met the minimum presence criterion and, consequently, had valid MaxEnt models generated and analyzed (Table 3), reflecting the low number of species with sufficient occurrence records for modeling. Model performance varied among species. *Eschweilera coriacea* showed high predictive performance ($AUC=0.98$), classified as excellent according to the ROC criteria adopted. In contrast, *Mauritia flexuosa* ($AUC=0.50$) and *Symphonia globulifera* ($AUC=0.67$) presented poor model performance, indicating limited ability to discriminate between presence and absence conditions. The predictor with the greatest weight was slope for *Mauritia flexuosa*, with a positive coefficient, indicating that the occurrence of this species is more strongly associated with areas of higher slope. *Eschweilera coriacea* was influenced by both land use and aspect, whereas *Symphonia globulifera* was influenced by land use (Table 3).

Discussion

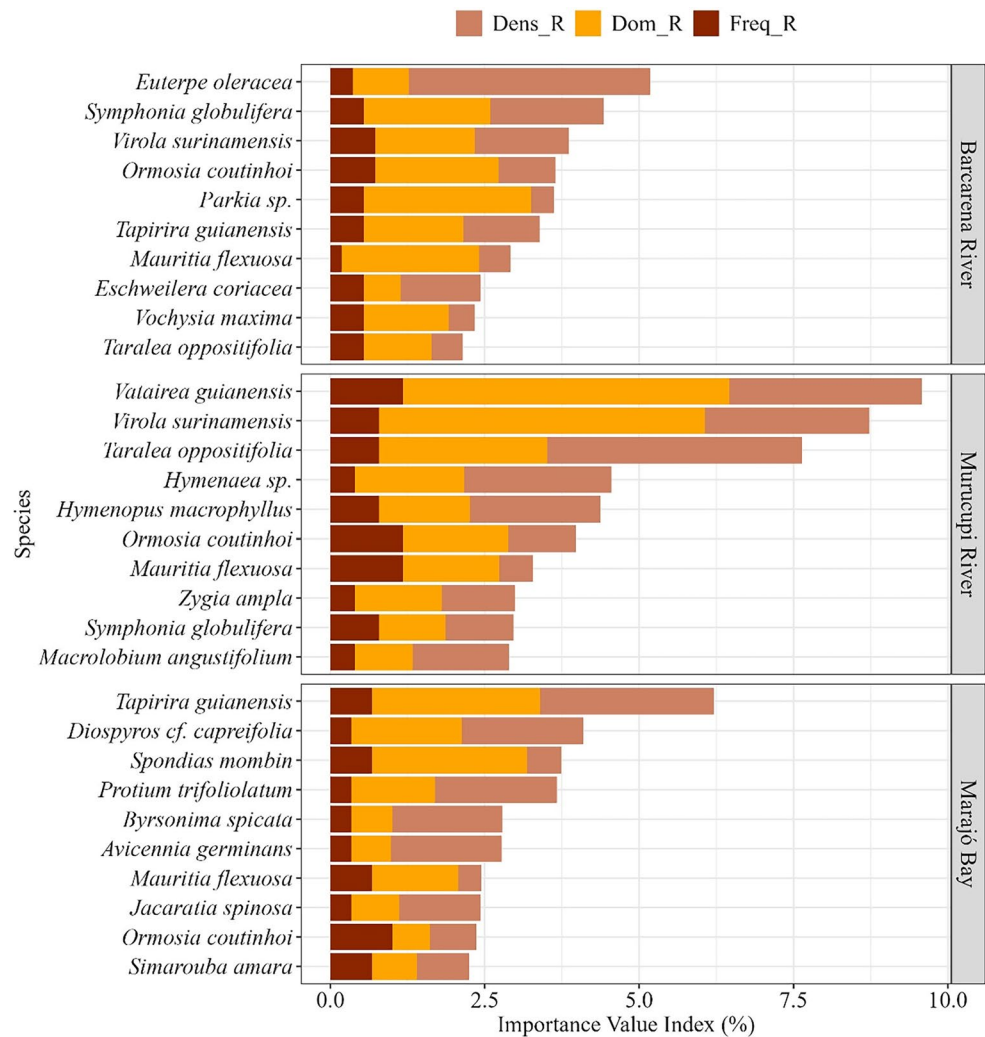
Our results demonstrate that a substantial proportion of the recorded species present non-timber use potential, particularly for medicinal and food purposes, highlighting their relevance for local livelihoods. In addition, this potential

Table 1 Species with a conservation status and number of individuals in riparian forests located in areas influenced by different river systems in the municipality of Barcarena, Eastern Amazon, Brazil

Family	Specie	MMA (2013)	IUCN (2025)	Number of individuals
Fabaceae	<i>Apuleia leiocarpa</i> (Vogel) J.F.Macbr.	VU	-	6
Lauraceae	<i>Mezilaurus itauba</i> (Meisn.) Taub. Ex Mez	VU	VU	1
Myristicaceae	<i>Virola surinamensis</i> (Rol. ex Rottb.) Warb.	VU	EN	80
Sapotaceae	<i>Manilkara elata</i> (Allemão ex Miq.) Monach.	-	EN	2
Total				92

VU Vulnerable, LC Least Concern, EN Endangered

Fig. 2 The ten species with the highest importance value index (IVI) in riparian forests located in areas influenced by different river systems in the municipality of Barcarena, Eastern Amazon, Brazil



is not uniformly distributed across the landscape, as environmental gradients such as topography and proximity to watercourses influence the availability and accessibility of these resources in riparian forests. At the same time, the limited representation of species of conservation concerns and the reduced number of species suitable for modeling reinforce existing constraints for conservation and management. It suggests that management and conservation strategies tend to concentrate on a limited number of well-known species, while neglecting a large portion of the local biodiversity. Therefore, this study is particularly relevant for assessing the non-timber use potential of native species in riparian forests, aiming to identify opportunities for sustainable forest resource use and to contribute to the development of strategies that integrate environmental conservation with social benefits (Oliveira et al. 2024).

The results of this study reveal a paradox between the recognized socio-economic value of certain species and the limited knowledge about the broader floristic community. On the one hand, species such as *Euterpe oleracea*

and *Mauritia flexuosa* stand out for their well-documented economic and cultural importance, being widely used and contributing to local livelihoods. From an ecological perspective, these species are also strongly associated with specific hydrological regimes, which favors their dominance in flood-prone environments and reinforces the role of environmental filtering in shaping species distribution. On the other hand, a considerable number of species recorded in the study area have no documented uses, indicating knowledge gaps that may lead to the underutilization of potentially valuable resources. In practical terms, this suggests that management and conservation efforts tend to focus on a few well-known species, while neglecting others that could also support sustainable use and local economies.

E. oleracea (açai), recognized as a native species of riparian forests and for its economic and ecological importance (Teixeira et al. 2024), was the predominant species in the Barcarena River area (the less anthropized site), corroborating the bioeconomic potential of conserved areas, since this species represents one of the main sources of income for the Amazonian

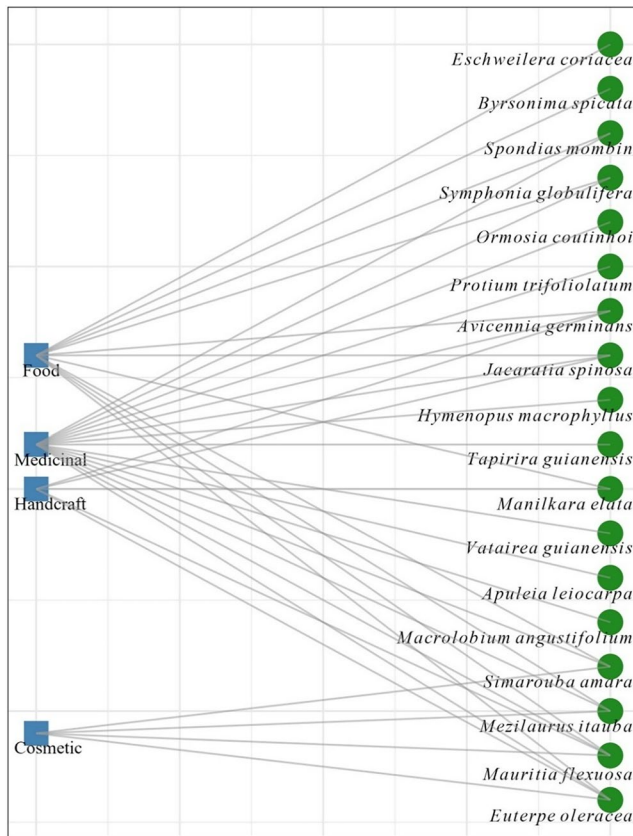


Fig. 3 Undirected bipartite network of the potential uses of the ten species with the highest IVI and a conservation status in riparian forests along the main rivers of the municipality of Barcarena, Eastern Amazon

population (Barbosa and Carvalho Junior 2022). Its distribution is closely linked to areas with higher soil moisture and periodic flooding, indicating that hydrological gradients are key drivers of its spatial occurrence. In addition, the identification of *Mauritia flexuosa* as relevant for multiple use categories suggests that the area has a high potential for the utilization of non-timber forest products (NTFPs), as well as for sustainable management activities. This species provides multiple uses, ranging from craft production using its leaves to the extraction of oils and food from its fruits (Silva et al. 2023b).

In the case of açaí, the growing demand for the species has driven the conversion of natural or mixed-use areas into monocultures, resulting in biodiversity loss within the forest (Freitas et al. 2021). In this context, low-impact management is a relevant strategy, as it integrates practices that reconcile production with conservation without compromising vegetation structure (Silva et al. 2023b). However, the economic viability of such systems depends on market stability, access to infrastructure, and equitable benefit distribution among local communities, which are not always guaranteed. Regarding *Mauritia flexuosa*, its consistent presence among the ten most important species across all analyzed areas,

including zones under higher anthropogenic influence, indicates its capacity for persistence and adaptation in disturbed environments (Kahn et al. 1993; Almeida et al. 2024). The presence of this species can be interpreted as a sign of the ecological resilience of riparian ecosystems, whose floristic structure still maintains characteristics of stability despite landscape transformation. This pattern aligns with the literature, which recognizes the species as tolerant to hydrological and anthropogenic disturbances, with a high regeneration capacity and multiple economic uses (Kahn et al. 1993).

M. flexuosa and *E. oleracea*, in addition to their important ecological roles, offer economic opportunities that can be integrated into sustainable development strategies (Freitas et al. 2024). Nevertheless, the assumption that NTFPs inherently promote sustainability should be treated with caution, as overexploitation, market pressures, and unequal access to resources may lead to outcomes like those observed in timber-based systems. Beyond its bioeconomic importance, the analysis of environmental factors that guide species distribution, such as slope for *M. flexuosa*, is ecologically consistent with the literature. The species is frequently associated with subtle topographic gradients, where higher slopes may indicate efficient soil drainage, reducing water saturation and optimizing water and nutrient supply, especially in riparian transition zones (Kahn et al. 1993; Almeida et al. 2024). However, the interpretation of these relationships should be approached with caution, given the variability in model performance among species. While some models showed high discriminatory ability, others presented low AUC values, indicating limited predictive power.

Regarding tree species, the resin obtained from *Symphonia globulifera* (Lukubye et al. 2023) and the essential oils from *V. surinamensis* (Ferreira et al. 2022) possess medicinal properties and can be used in pharmaceutical and cosmetic production (Table 2). On the other hand, although the results indicate the presence of species important in ecological and economic terms, the unregulated expansion of industrialization, port infrastructure, and urbanization in the municipality of Barcarena poses serious risks to biodiversity, as observed by Ritter et al. (2017) in other Amazonian areas. In this study, the negative influence of land use observed for *Eschweilera coriacea* and *Symphonia globulifera* suggests that the occurrence of these species is significantly reduced or compromised in anthropized land-use classes. Our results reinforce the role of land-use change as a strong environmental filter, capable of overriding natural gradients such as topography and hydrology in highly disturbed landscapes. Therefore, this study indicates the sensitivity of these species to ecosystem disturbance, highlighting that maintaining the integrity of riparian vegetation cover is a crucial factor for their conservation. Specifically, *E.*

Table 2 Use categories assigned to the selected species in riparian forests along the main rivers of the municipality of Barcarena, Eastern Amazon, based on ethnobotanical records

Species	Habit	Use	Part of the plant	Description of use
<i>Avicennia germinans</i> (L.) L.	Tree	Food	Leaves and root	Vegetable salt preparation
		Medicinal	Leaf	Hemorrhoid treatment
			Bark	Treatment of skin problems, tumors, diarrhea, inflammation, and bleeding
			Root	Treatment of intestinal problems
		Handicraft	Bark	Natural reddish dye
<i>Byrsonima spicata</i> (Cav.) DC.	Tree	Food	Fruit	Juices and desserts
<i>Eschweilera coriacea</i> (DC.) S.A.Mori	Tree	Food	Seed	Consumption
<i>Euterpe oleracea</i> Mart.	Palm	Food	Fruit	Juices, smoothies, ice cream, and other food products
			Palm heart	Cooking
		Medicinal	Leaves and Seed	Fever treatment
			Root	Diarrhea treatment
			Fruits	Hygiene and personal care
<i>Jacaratia spinosa</i> (Aubl.) A.DC.	Tree	Handicraft	Leaves, fibers, Seeds	Biojewelry, decorative and household utensils
		Food	Fruit	Fresh or cooked (jams, sweets)
		Medicinal	Fruit	Anti-inflammatory and anti-helminthic
<i>Hymenopus macrophyllus</i> (Benth.) Sothers & Prance	Tree	Medicinal	Fruit	Biojewelry
			Bark	Anthelmintic
<i>Macrobium angustifolium</i> (Benth.) R.S.Cowan	Tree	Medicinal	Bark	Fever treatment
<i>Mauritia flexuosa</i> L.f.	Palm	Food	Fruit	Fresh and cooked (jam, flour, juice, desserts)
			Flor	Sugar and wine production
			Palm heart	Cooking
		Medicinal	Seed	Burn treatment
		Cosmetic	Fruit	Hygiene and personal care
<i>Ormosia coutinhoi</i> Ducke	Tree	Medicinal	Leaves, Fruit and fibers	Biojewelry, toys, decorative and household utensils
			Bark	Induce sweating and treat fever
<i>Protium trifoliolatum</i> Engl.	Tree	Medicinal	-----	-----
<i>Simarouba amara</i> Aubl.	Tree	Food	Seed	Baking oil
		Medicinal	Leaf and Bark	Treatment of malaria, fever, and dysentery
		Cosmetic	Seed	Oil for making soaps, lubricants, and other cosmetics
<i>Spondias mombin</i> L.	Tree	Food	Fruit	Juices, vitamins, ice cream, and other food products
		Medicinal	Bark and flowers	Treatment of digestive tract diseases, back pain, rheumatism, and malarial fever
<i>Symphonia globulifera</i> L.f.	Tree	Food	Fruta	<i>In natura</i>
		Medicinal	Bark	Laxative, treatment of coughs, itching, and ulcers
<i>Tapirira guianensis</i> Aubl.	Tree	Medicinal	Bark	Treatment of childhood candidiasis, cuts, and wounds
<i>Vatairea guianensis</i> Aubl.	Tree	Medicinal	Bark	Ulcer treatment
<i>Apuleia leiocarpa</i> (Vogel) J.F.Macbr.	Tree	Medicinal	Bark	Treatment for syphilis
<i>Mezilaurus itauba</i> (Meisn.) Taub. ex Mez	Tree	Food	Fruit	<i>In natura</i>
		Medicinal	Bark	Abortifacient
		Cosmetic	Bark	Essential oil
<i>Manilkara elata</i> (Allemão ex Miq.) Monach.	Tree	Food	Fruit	<i>In natura</i>
		Handicraft	Latex	Rubber for making chewing gum

Source: prepared by the authors based on data from (Fern 2025)

Fig. 4 Relationship between the importance value index (IVI) and the number of use categories of tree species in the areas influenced by the Barcarena river (a), Murucupi river (b), and Marajó bay (c) in the municipality of Barcarena, Eastern Amazon

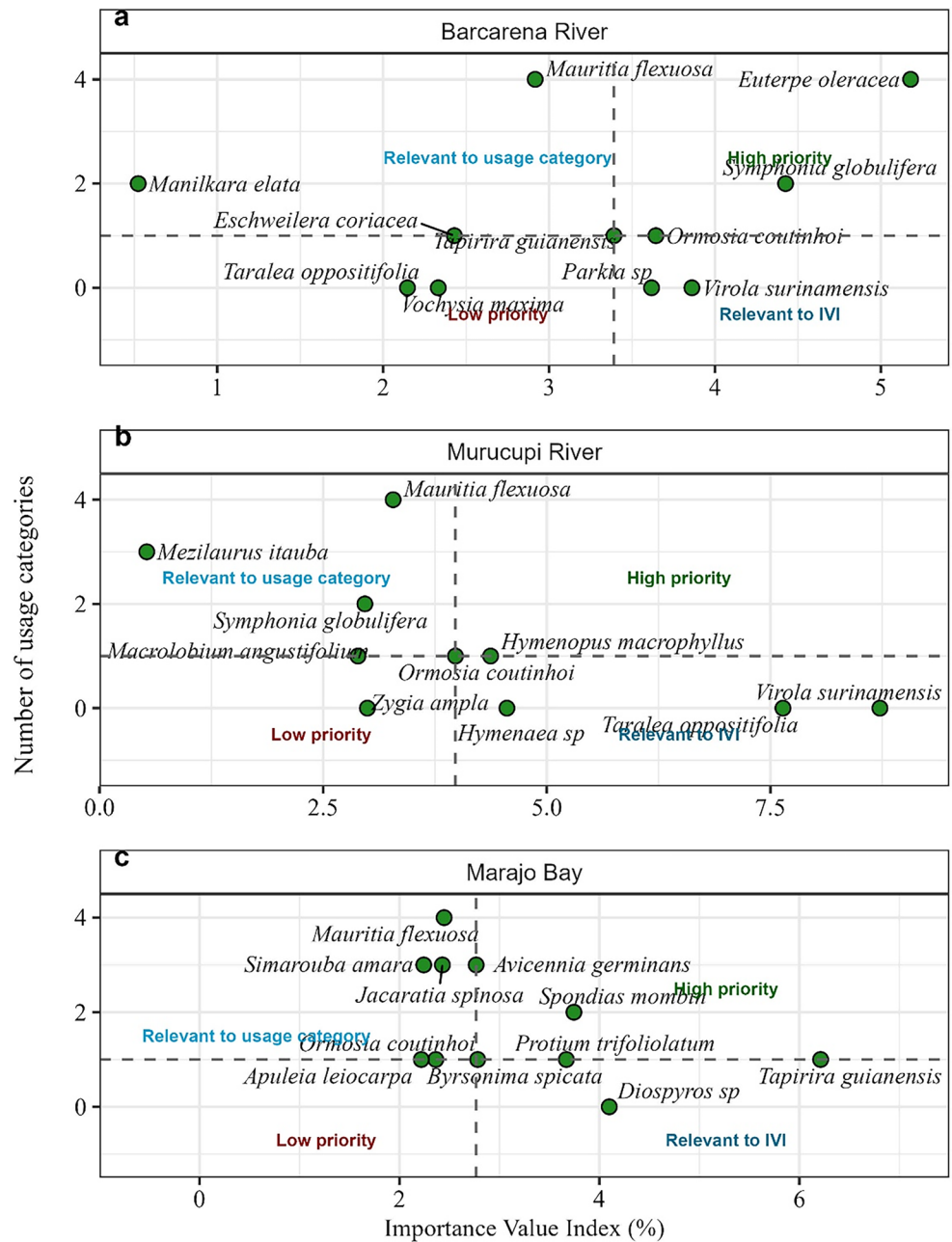


Table 3 Weight and direction (positive or negative) of the influence of environmental predictors in the potential distribution models of the selected species in Barcarena, Pará

Species	Variable	Coefficient	AUC
<i>Eschweilera coriacea</i>	Land Use	-0.117	0.9800
	Aspect (degrees)	-0.006	
<i>Mauritia flexuosa</i>	Slope (m)	0.269	0.5000
<i>Symphonia globulifera</i>	Land Use	-0.102	0.6667

coriacea also showed a slight preference for areas with lower solar exposure or specific topographic gradients (Schmitt et al. 2021), reinforcing the importance of microclimatic topographic factors.

Several species recorded in this study, such as *Diospyros* sp., *Hymenaea* sp., *Parkia* sp., *Taralea oppositifolia*, *V. surinamensis*, *V. maxima*, and *Zygia ampla*, showed no documented uses within the considered categories, indicating potential gaps in knowledge or the possible underutilization of local biodiversity. A relevant example observed in this study was the recording of food, medicinal, and cosmetic uses of *Mezilaurus itauba* (itaúba), a species widely exploited for its highly durable timber, highly valued in civil construction and luxury furniture manufacturing, currently exceeding BRL 4,000 per cubic meter of sawn wood in the market (Pará 2016). Despite

this, the species is classified as vulnerable, and continued timber extraction may compromise its natural regeneration and increase extinction risk. In this context, the identification of alternative non-timber uses highlights opportunities to develop more sustainable value chains that generate income without removing reproductive individuals. In this study, the identification of use categories was based on available ethnobotanical records, but the inclusion of local traditional knowledge could further enhance the understanding of species value. Traditional communities possess fundamental knowledge regarding sustainable management, medicinal uses, and processing of NTFPs (Vieira 2023). Integrating this knowledge with scientific research, while respecting ethical protocols for benefit-sharing established by the Convention on Biological Diversity (Brasil 1994), can strengthen participatory conservation strategies and sustainable development. Furthermore, traditional knowledge is often closely linked to environmental gradients, as resource use practices tend to vary according to flooding regimes, soil conditions, and species availability. This is supported by the predominance of the medicinal use category (Table 2; Fig. 3), consistent with studies conducted in Amazonian communities, where medicinal plants are widely utilized due to limited access to healthcare services and a strong tradition of local ethnobotanical knowledge (Homma 2014).

The food use category, attributed to 11 species (Table 2; Fig. 3), highlights the role of riparian forests in supporting food security for nearby riverine and urban communities. However, the presence of multiple anthropogenic activities in the Barcarena industrial hub significantly increases the risk of environmental contamination, particularly by heavy metals and persistent organic compounds (Matos et al. 2023), which may compromise the use of non-timber forest products (NTFPs) for food purposes. However, this study did not include analyses of contaminants in plant tissues, which represents a limitation when assessing the safety of these resources for food use. Therefore, this study emphasizes the need for detailed chemical analyses, including measurements of heavy metal concentrations in soil, water, and plant tissues, as well as phytotoxicity tests and biomonitoring, to assess potential risks to public health and food safety for the local population.

The species identified as high priority in this study, as well as those with greater potential for distribution as indicated by the MaxEnt models, can be integrated into productive ecological restoration models, in which the recovery of ecological functions is combined with the generation of economic benefits for local populations (Borchardt et al. 2023). The use of adapted native species, those that demonstrated resilience or preference for specific ecological factors, such

as *M. flexuosa* in areas with steeper slopes, can enhance both restoration success and the long-term sustainability of multifunctional riparian landscapes, to reforestation projects in highly disturbed areas, particularly those with high IVI and bioeconomic value, represents a promising strategy to enhance the effectiveness of restoration programs while simultaneously promoting NTFP-based productive activities in the Amazon. Adopting this approach can facilitate community engagement and the financial sustainability of environmental recovery initiatives. Therefore, participatory ethnobotanical studies with local communities are essential to disseminate traditional knowledge not yet documented, strengthening the link between science and sustainable management (Oliveira et al. 2024).

The results of this study suggest opportunities for strengthening NTFP-based value chains, which are often undervalued in industrialized Amazonian contexts. The integration of conservation, sustainable biodiversity use, and ecological restoration is crucial for the future of Amazonian riparian forests, particularly in regions like Barcarena, where socio-environmental challenges are complex. In practice, the findings of this study can support forest management strategies that reconcile economic utilization with the maintenance of ecological integrity. In Pará, the development and implementation of public policies, such as the Pará State Bioeconomy Plan (PlanBio - Pará) and the guidelines of the Pará State Bioeconomy Strategy, provide opportunities to consolidate these integrated use and conservation models (Mascarenhas et al. 2024), provided that production diversification and the strengthening of productive value chains are promoted (Rosenfeld et al. 2024). For this purpose, the linkage between science, public policy, and civil society will be essential to ensure that the bioeconomic potential of riparian forests is fully harnessed, without compromising their ecological function or their role in mitigating Amazonian socio-environmental inequalities.

Conclusion

Riparian forests under anthropogenic influence can still harbor species with high bioeconomic potential, particularly for food, medicinal, and cosmetic uses, reinforcing their relevance for sustainable use and local livelihoods. By integrating ecological importance and use potential, our findings highlighted opportunities to diversify non-timber forest product (NTFP) value chains while supporting conservation in human-impacted landscapes. Although the potential distribution modeling provided insights into the influence of environmental predictors, these results should be interpreted with caution due to the limited number of species modeled,

restricting broader generalizations. Overall, our results suggest that productive restoration strategies in riparian areas can contribute simultaneously to biodiversity conservation and income generation. However, in anthropized regions, the safe use of these resources depends on further assessments of environmental contamination, particularly for species intended for food and medicinal purposes.

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Data availability The available data can be found at <https://doi.org/10.5281/zenodo.18061997>.

Declarations

Competing interests The authors declare no competing interests.

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