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RESEARCH

The problem of conserving an ecosystem that has not been completely delineated and mapped: the case of the Cocais Palm Forest

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Abstract Land cover changes threaten biodiversity and alter the geographic distribution of forests worldwide. Studies on this topic are important to establish conservation strategies and public policies. However, different studies may propose different spatial representations due to differences when identifying, classifying, and/or mapping the same vegetation formation, as observed for the Cocais Forest region. This palm-dominated ecosystem predominates the Brazilian mid-north region in an ecotone region with 3 of the 6 Brazilian biomes. In this study, we conducted a literature review of studies that delineated and mapped the Cocais Forest, aiming to compare different mapped regions and to establish a new distribution map integrating these spatial data. We found seven sources that revealed spatial divergences in identifying the spatial distribution of Cocais Forest, including its characteristics in terms of size and shape, which could affect the conservation, socioeconomic, and cultural policies and studies carried out on this emblematic vegetation formation and influence area. The delineation proposed by de Sousa Nascimento and Lima (Revista de Políticas Públicas 189–192, 2016) encompassed the largest area. In addition, there was a lack of consensus regarding the nomenclature for this ecosystem, and few works offered a detailed description of the mapping process. Despite the different spatial distributions found for the Cocais Forest, we succeeded in establishing a common area by overlapping individual maps, resulting in the identification of a core region exclusive located in the State of Maranhão.

Keywords Cartography · Spatial distribution · Palm trees · Babassu · Forest conservation · Maranhão

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Introduction

Climate change, land use and land cover change, the irrational use of natural resources, and biodiversity loss are major contemporary global crises. These factors act synergistically to increase the vulnerability of the environment, endanger ecosystem balance and human life, and modify the global distribution of ecosystems (Allen et al., 2010; Arroyo-Rodríguez et al., 2020; Jain et al., 2021; Luintel et al., 2018; Ma et al., 2019; Newbold et al., 2015; Silvério et al., 2019). Conservation and restoration of forest ecosystems are essential approaches in addressing biodiversity loss and enhancing their capacity as carbon sinks. Disturbances in forest dynamics are highly variable based on factors such as forest type and location, resilience, and disturbance type and intensity, which require the analysis of a set of spatial–temporal data (Díaz-Yáñez et al., 2016; Ojha et al., 2020).

Knowledge regarding the nature and territorial delimitation of ecosystems is essential for the effective management and conservation of biodiversity (Marques et al., 2019). The ecological security of a landscape requires an adequate planning and design to optimize the spatial representation of its heterogeneity and diversity (Wang et al., 2019). Thus, information on the biodiversity of an environment, characterization of its occurrence patterns in the landscape, and mapping of vegetation extent and land cover are the main prerequisites for ecology and conservation biology studies, as well as for the formulation of public policies aimed at conservation, environmental zoning, and land use management (Frederico et al., 2021; Marques et al., 2019).

Avoiding divergences in land cover delineation could contribute to provide the good-quality spatial information required to support environmental conservation strategies. To increase the success of these strategies, it is necessary to prevent the discrepancy between the spatial scale of environmental management and ecological processes that often hamper environmental conservation goals (Nguyen et al., 2022).

Tropical forests have been highlighted as priority management areas owing to their high ecological complexity, diversity of species and hotspots, and for being the largest carbon sinks in terrestrial environments (LeFevre et al., 2020; Pan et al., 2011; Phillips et al., 1998). Transition zones between large tropical biomes, also known as ecotones, are rich in complexity and community interactions. Thus, these ecotones require more complex and in-depth research for the adoption of appropriate biodiversity conservation strategies (Torello-Raventos et al., 2013; Marques et al., 2019). Among the various forest formations in central-northern Brazil, the Cocais Forest or Cocal Zone (also known locally as Mata de Cocais or Zona dos Cocais) is a palm-dominated transition zone between the humid Amazon forests in the north, the Cerrado Savannas in the south and east, and the semi-arid Caatinga regions in the northeast. These transition regions are hotspots of diversity and could serve as refuge for endemic species from the surrounding biomes (Argibay et al., 2020; Saraiva et al., 2020). This region occurs across tropical, equatorial, and semi-arid climates (Nunes et al., 2012), and is also known as babassu forest because of the predominance of the emblematic palm tree species *Attalea* spp. (locally known as babassu palms). This palm tree is primarily found in tropical countries such as Mexico, Bolivia, Colombia, and Suriname (Reis et al., 2018; Santos-Filho et al., 2013; Silva et al., 2013; Teixeira, 2008).

Several studies have presented results on Brazilian land cover at various scales (IBGE, 2012; Batistella et al., 2013; LAPIG, 2019; Alencar et al., 2020; Project MapBiomas, 2021). However, there are several differences concerning the nomenclature, classes, and its spatial extensions, which are important criteria in boundary delimitation and spatial distribution. Although palm tree formations are included in global classifications such as the global ecoregion maps (Olson et al., 2001) or the European Space Agency Climate Change Initiative land cover product, there are currently no official maps for the distribution of Cocais Forest. This region has been scientifically neglected or misunderstood in the context of large-scale floristic characterization or mapping (Batistella et al., 2013), despite its great importance for local traditional people and communities, such as the babassu breakers, who depend on the sustainable extraction of the babassu coconut (de Oliveira et al., 2022; Mitja et al., 2019; Porro & Porro, 2015; Porro et al., 2011).

Because of the great significance of coconut babassu extraction for local communities and regional economies, as well as the need to conserve the remnants of Cocais Forest, here we performed a literature review aiming to analyze divergences on its spatial delineation from different sources, and to propose an official map that will serve as reference to improve conservation policies, ecological studies, and socioeconomic planification in the mid-north region of Brazil.

Methods

Study region

The Cocais Forest region has great landscape heterogeneity and is considered a type of secondary vegetation with tree clusters that form dense forests or more open regions with the presence of palm trees, such as in pasture or savannah areas (Barreto et al., 2019; Santos-Filho et al., 2013). It is estimated that this region comprises approximately 500 plant species. Palm trees such as *Attalea speciosa* Mart. ex Spreng, *Bactris setosa* Mart., *Copernicia prunifera* (Mill.) H. E. Moore, *Euterpe edulis* Mart., and *Mauritia flexuosa* L. F. are predominant and have a great socioeconomic value to local communities that depend on sustainable extraction activities (Campos et al., 2015; Pinheiro, 2011). Despite initiatives to detect palm tree formations through remote sensing approach, there are still uncertainties about the real extent of these formations and its conservation status (Vieira et al., 2017).

Systematic bibliographic research

In this study, we performed a literature review to gather spatial information on the distribution and delineation of the Cocais Forest by comparing several cartographic delineations. First, we conducted a systematic bibliographic research on different databases such as SciELO, Scopus, Web of Science (WoS), and Wiley Online Library (WOL). The search was performed considering studies involving the Cocais Forest with no defined date range. Based on the different nomenclatures observed in English and Portuguese, we searched for the terms “Mata dos Cocais” OR “Cocal Forest” OR “Floresta de Babaçu” OR “Babassu Forest,” limiting the search to titles, abstracts, and keywords in the Scopus database, and to any field category in the other databases. In addition, we searched for other gray literature in online and print formats to supplement the data from the systematic bibliographic research. We considered all studies that included a map of the Cocais Forest; additional information is given in the PRISMA flow diagram in Online Resource 1.

Shapefiles with State and municipal boundary data were obtained from IBGE (2020b).

Geoprocessing procedures

For each study selected from the systematic review, we extracted the following information: mapping and publishing year; the nomenclature used by the authors to classify the Cocais Forest region (e.g., biome, ecoregion, and phytoregion); the spatial range and references used for mapping; the number of municipalities within the region attributed to Cocais Forest per State considering all municipalities that cross the shapefiles; and the size of the mapped region in square kilometers (km^2).

We gathered these data from shapefiles whenever available, and for studies that had no spatial information in shapefile format, we georeferenced the maps using QGis software version 3.18 Zurich® and the Georeferencer tool in a SIRGAS 2000 projection-based coordinate system. Next, using the georeferenced maps, we manually delineated the polygon defined for this vegetation formation from the figure map presented in each analyzed source, at a scale of 1:4,000,000, with the vertices corrected for a scale of 1:2,000,000, generating the respective vector (shapefile) of its boundaries.

We calculated the total area and other features based on the number of municipalities included and their areas inside each Cocais Forest boundaries. In addition, we overlapped the shapefile layers derived from the different maps to create a single boundary map for this vegetation formation based on all the collated sources. Then, vector files were rasterized with a 1-km spatial resolution to ensure compatibility with the spatial resolution of other climate and environmental products derived from remote sensing (e.g., 1 km for precipitation data derived from CHIRPS, 500 m to 1 km for MODIS derived products) and to facilitate the processing and evaluation of future analyses. We used the raster calculator to sum the individual layers created by each study using map algebra functions. Based on the overlapped map, we determined the following information: the total region attributed to the Cocais Forest by combining the areas of all maps, and a core region defined by the intersection between all maps.

Results and discussion

Systematic bibliographic research

The systematic review on databases returned a total of 116 papers, being 16 from SciELO, 54 from Scopus, 46 from WoS, and none from WOL (Online Resource 1). However, none of studies presented explicit figures or maps of the Cocais Forest extent; for this reason, we could not use them to accomplish our goal. Thus, we searched for the gray literature which yielded seven maps of the Cocais Forest extent that served as cartographic data for this study (Table 1): World Wildlife Fund for Nature Brazil (WWF Brasil, 2004), Rocha et al. (2011), Santos-Filho et al. (2013), de Sousa Nascimento and Lima (2016), Barreto et al. (2019), Deforestation Polygon Assessment Tool (DEPAT) of the Image Processing and Geoprocessing Laboratory (LAPIG) of the Federal University of Goiás (UFG) (LAPIG, 2019), and Maranhense Institute of Socioeconomic and Cartographic Studies (IMESC) (2021).

Cartographic surveys of Cocais Forest and its implications for nature conservation

Maps from the identified studies revealed spatial divergences of the Cocais Forest region (Fig. 1a to g). Each map depicted a unique representation of the spatial delimitation of the Cocais Forest, both in terms of its size and shape, as well as the Brazilian States encompassed. Considering the analyzed sources (Fig. 1), Cocais Forest was identified in five of the 27 Brazilian States: Ceará (CE), Maranhão (MA), Pará (PA), Piauí (PI), and Tocantins (TO), most located in the northeastern region of Brazil. The absence of a cartographic consensus among the references may have a direct impact on studies that guide the landscape characterization process and the implementation of public policies aimed at managing and conserving this plant formation (Colten, 2018; de Almeida et al., 2019; Barreal & Jannes, 2020). Anything that has not been rightly delimited or identified cannot be protected or conserved properly, as has

Table 1 Compilation of the cartographic data extracted from the selected sources

Reference	Year of publication	Mapping year(s)	Mapping reference(s)	Spatial range used for mapping	Nomenclature used to define Cocais Forest	Number of municipalities incorporated, by State	Cocais Forest area (km^2)
WWF Brazil	2004	*i.n.f*	IBGE (1993); Olson et al. (2001)	Global	Ecoregion	CE: 12; MA: 125; PI: 57	141,628.98
Rocha et al	2011	*i.n.f*	*i.n.f*	Northeast	Type of vegetation	MA: 129; PI: 74; TO: 17	219,219.49
Santos-Filho et al	2013	2006	WWF and IBGE	Maranhão and Piauí	Zone	MA: 126; PI: 54	149,361.81
De Sousa Nascimento; Lima	2016	*i.n.f*	Several authors	Ceará, Maranhão, Pará, Piauí, and Tocantins	Babassu ecological region	CE:1; MA: 168; PA: 12; PI: 86; TO: 33	260,039.07
Barreto et al	2019	2015	IBGE (2012)	Maranhão, Piauí, and Tocantins	Landscape	MA: 108; PI: 53; TO: 25	164,994.67
LAPIG	2019	*i.n.f*	Sano et al. (2019)	Cerrado Biome	Ecoregion	MA: 87; PI: 21	74,129.07
IMESC	2021	*i.n.f*	ZEE/MA (2021)	Maranhão	Zone	MA: 14	27,905.24

i.n.f information not found, *CE* Ceará State, *MA* Maranhão State, *PA* Pará State, *PI* Piauí State, *TO* Tocantins State

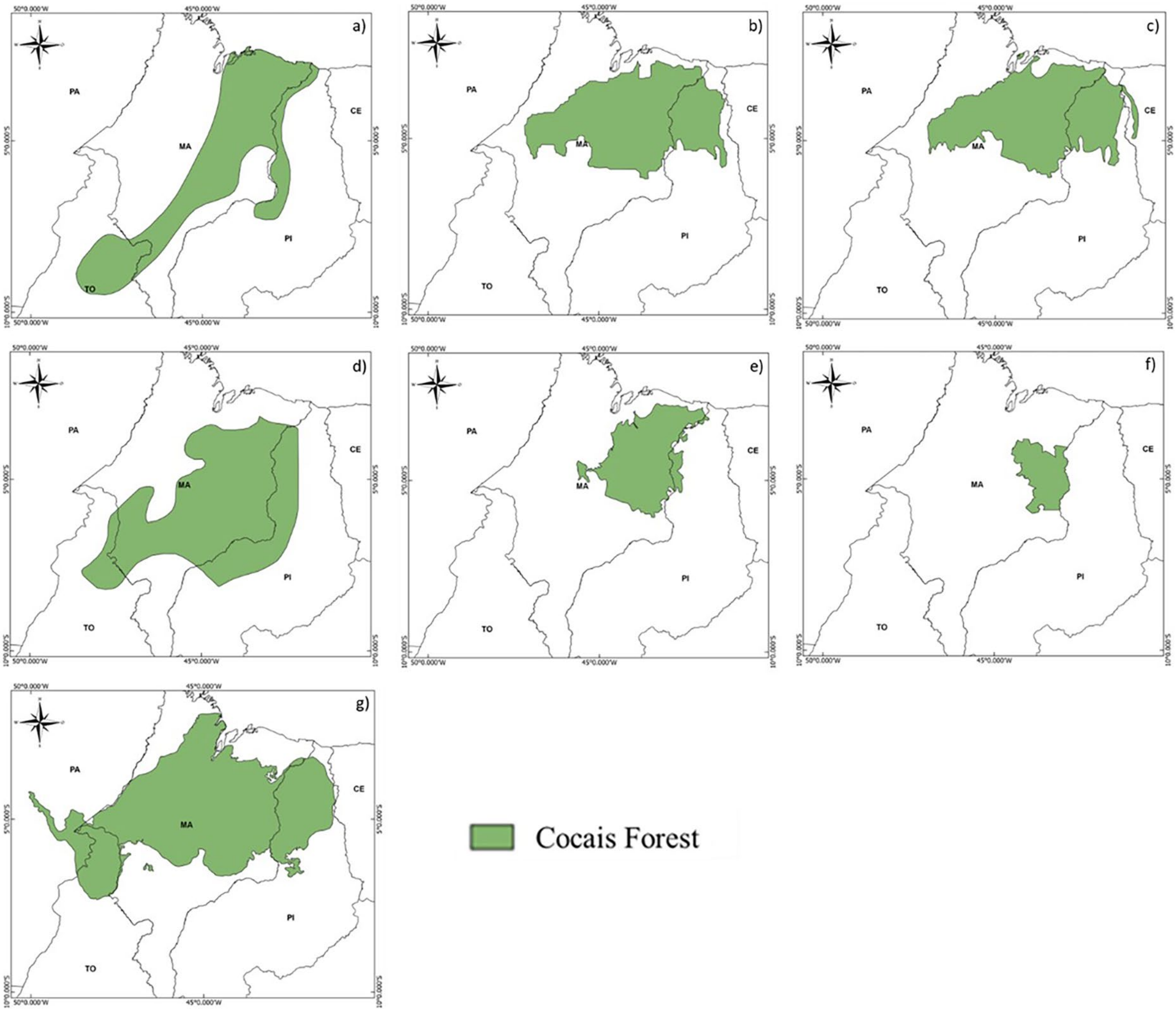

Fig. 1 The main spatial delimitations of Cocais Forest. Maps were adapted from the Cocais Forest distributions reported by **a** WWF Brasil (2004), **b** Rocha et al. (2011), **c** Santos-Filho et al. (2013), **d** de Sousa Nascimento and Lima (2016), **e** Barreto et al. (2019), **f** LAPIG (2019), and **g** IMESC (2021)

been the case for other ecosystems such as the Asian savannas, which have been misclassified in global and local research, resulting in controversies over conservation efforts (Ratnam et al., 2016). In the case of the Cocais Forest in Brazil, misclassification or inaccurate definitions of its spatial distribution could affect related research. For example, the extent and correct delineations of land cover are important to determine the effects of fire regime changes and how that affect the flammable and fire-adapted ecosystems (e.g., Cerrado savannas) and the more fire-sensitive forest ecosystems (e.g., gallery forest, amazon forest) where fire could cause forest fragmentation or degradation (Silva-Junior et al., 2022). Accurate spatial information serves as a cartographic basis for burned area analyses (Alves & Alvarado, 2019; Argibay et al., 2020; Silva et al., 2021; Syphard & Keeley, 2020), particularly in these transition zones as the Cocais Forest region characterized by a mosaic of patches of palm forest into a matrix of anthropic areas and savannas.

The spatial information obtained from mapping a region is essential for establishing and applying spatial indices and landscape metrics for structural quantification, forest landscape management, and diagnosing and measuring spatial changes in landscape composition and configuration (Herold et al., 2003; Feng et al., 2018; Dadashpoor et al., 2019; Jia et al., 2019; Mandal & Chatterjee, 2021). These metrics require different types of land-mapping data for their equations and algorithms, such as area and perimeter data (Kupfer, 2012). Thus, maps with distinct spatial delimitations produce divergent geometric information and location vectors, implying that different results are produced for aspects associated with landscape changes at various scales. In addition, research on landscape metrics has demonstrated a correlation between landscape metrics and ecosystem services (Duarte et al., 2018; Hou et al., 2020; Wang et al., 2019; Zhang et al., 2011), making it important to properly and accurately delineate vegetation formations.

In areas with a high degree of anthropization, such as the Cocais Forest region (Santos-Filho et al., 2013), landscape metrics are essential for predicting habitat restrictions when considering the movement and potential for species dispersion and other aspects associated with population dynamics (Jackson & Fahrig, 2015; Rezende et al., 2020; Santos et al., 2020), and population genetics (Wan et al., 2018). The forest cover of a landscape is inextricably linked to the availability of natural resources and consequently to the richness, abundance, perpetuation, and population density of species (Fahrig, 2003; Godefroid & Koedam, 2003; Gignac & Dale, 2007; Fahrig, 2013; Jackson & Fahrig, 2015; Uroy et al., 2019). The number of studies analyzing the influence of landscape connectivity on biodiversity has increased considerably since the early part of the twenty-first century (Ayram et al., 2015). Thus, as biodiversity patterns vary widely (Bridgewater et al., 2004; Milliken et al., 2010; Soares et al., 2020), forest managers require highly accurate forest cover information (Unger et al., 2014).

Regarding the States encompassed in each single map (Fig. 1), the area established by de Sousa Nascimento and Lima (2016) (Fig. 1d) contained the greatest number of Brazilian States (Ceará, Maranhão, Pará, Piauí, and Tocantins), whereas the region defined by the IMESC (2021) was the most limited and restricted exclusively to the State of Maranhão. Highly restrictive classifications might prevent the spatial characterization of areas on official maps by disregarding or inadequately identifying its actual characteristics. A map that underestimates the extent of a landscape may not encompass all its economic and ecological heterogeneity and multifunctionality. For example, landscape heterogeneity has the potential to mitigate the detrimental effects of habitat fragmentation (Tscharntke et al., 2012; Uroy et al., 2019) and is essential for the perpetuation of biological diversity, provision of ecosystem services, and conservation of endangered species (Dorresteijn et al., 2015; László et al., 2018).

The differences in spatial delimitation observed in the analyzed maps (Fig. 1a to g) have a substantial impact on the quality of the sustainability assessment of the Cocais Forest ecosystem, which has great social, economic, scientific, and ecological interest (de Oliveira et al., 2022; Mitja et al., 2019; Porro & Porro, 2015), and has historically been impacted by anthropogenic activities (Santos-Filho et al., 2013), needing strategic plans for ecological protection and recovery. By estimating the spatial delimitation of the Brazilian Caatinga biome, Antongiovanni et al. (2018) quantified its spatial structure and assessed the extent to which the remaining areas were susceptible to anthropogenic disturbances. Thus, mapping properly an area makes it possible to understand the complexity of mosaic landscape dynamics, including its composition, changes, and the intensity and potential effects of human disturbances that can influence ecological processes and conservation strategies (Marques et al., 2019; Souza-Filho et al., 2019; Yang et al., 2019; Wang et al., 2019). Marques et al. (2019) obtained different values for estimated deforested areas in the Caatinga biome compared to the mapping performed by IBGE, demonstrating one of the effects associated with different spatial delimitations for the same region.

Another associated issue is the inconsistency between maps in terms of its distribution and quantification of potential forest biomass along forest landscapes. For example, spatial differences influence the estimation of the above-ground biomass and its potential carbon sequestration of the region, causing under- or overestimations of these values (Wang et al., 2019). This scenario makes it difficult to develop and implement a green (low-carbon) economy and adopt strategies targeted at efficient natural resource management, green investment, technological innovation, and poverty eradication (Brand, 2012). Furthermore, it prevents the acquisition of economic incentives for the land organization and management, and landscape-scale conservation efforts such as payments for ecosystem services (Hartig & Drechsler, 2009; Muradian et al., 2010; Ruggiero et al., 2019; Nguyen & Liou, 2019; Nguyen et al., 2022).

Implications of the criteria and methods used to delimit the Cocais Forest region

Assessment of the identified maps in the analyzed studies revealed that the mapping year was the most unreported information since it was only reported by Santos-Filho et al. (2013) and Barreto et al. (2019). The absence of a temporal record affects the evaluation of spatial and temporal dynamics in the short and long term and the analysis of land cover change dynamics (Turner & Gardner, 2015). It is the baseline to know the current status, reconstruct the past history, quantify the degradation level, or predict the future trajectory of Cocais Forest vegetation. In addition, to achieve an accurate interpretation of the landscape, it is important that the temporal and spatial scales are well-defined, allowing for the separation between the effects associated with landscape connectivity from other factors, such as dispersal mode (Uroy et al., 2019).

It is important to emphasize the lack of information about the mapping process or methodological approaches used in all analyzed studies, such as the descriptive information on the primary sources (e.g., satellite images, other sources of bibliographic references, and field data) and variables (e.g., vegetation reflectance, topography, rainfall, and temperature) used by these authors to map the Cocais Forest region. This prevented us from discussing the key variables in the biogeographic delimitation of this formation. In general, the recurring absence of information throughout our literature review indicated the need to better characterize the methodological procedures used in the studies on Cocais Forest to clarify the criteria and variables used to delimit this region, which can serve as a foundation for future research on this plant formation.

The problem involved with the definition of the Cocais Forest is not exclusive to this region. In the Brazilian Caatinga biome and its phytophysiognomies, a similar discrepancy between the information from multiple maps is observed, particularly regarding the semiotic choices made during the preparation of the map classification system (Bontempo et al., 2020). The absence or inadequacy of this information exacerbated the issue raised by Sousa-Baena et al. (2014), who analyzed primary data on angiosperm biodiversity in Brazil. The authors identified knowledge gaps regarding this primary data and reported that most biodiversity data is not available in digital format and not georeferenced or is limited to the extent that makes them unusable. In the context of conservation-oriented public policies, this directly affects their implementation because the available digital knowledge employed is limited, biased, or insufficient. According to Frederico et al. (2021), primary data are required to develop knowledge that can be applied more diligently. The limited methodological information restricts the use of these cartographic materials to develop biogeographical research and, consequently, to establish environmental conservation strategies or to explain landscape dynamics.

Another controversial issue is the various nomenclatures used by authors to refer to the Cocais Forest formation. Some publications used similar terms, such as WWF Brasil (2004) and LAPIG (2019), which referred to Cocais Forest as an “ecoregion,” whereas Santos-Filho et al. (2013) and IMESC (2021) used “zone.” The remaining studies applied different nomenclatures (landscape, type of vegetation, and babassu ecological region). However, even among references employing similar terminology, distinct cartographic delimitations were observed (Fig. 1c, e, and b, f). Regarding the conceptual aspects of landscape ecology, the various terms used to represent the spectrum of approaches used by the authors, ranging from a geographic approach that focuses on the anthropogenic effects on geographic areas to an ecological approach that emphasizes the relationship between the area and its ecological processes (Pickett & Cadenasso, 1995; Turner & Gardner, 2015). This confirms the lack of consistency about the nomenclature used, even among studies employing the same methodological approach (geographical or ecological). Using terminology better suited to characterize the Cocais Forest is essential for the development of studies in this field, especially in terms of formulating public policies aimed at the specificities of this research to reinforce the core objectives of environmental standards. More concrete notions can guide decision-makers in developing initiatives with a more integrated perspective, thereby facilitating the adaptation of the normative framework and management of available resources (Sposati, 2016).

Among the references analyzed in this study, only Barreto et al. (2019) used the term “landscape” to refer to the Cocais Forest. Given the notion underlying this term, as described by Wu and Qi (2000) and Siqueira et al. (2013), who considered a landscape as a dynamic product of physical, biological, and anthropogenic factors, this nomenclature appears more biogeographical than the other afore mentioned terms. Landscapes are identified as areas exhibiting considerable spatial differences, which are sometimes expressed in the form of mosaics of patches with distinct shapes, sizes, histories, and compositions, and the Cocais Forest fits this definition. Although this region comprises naturally dense areas, it also has fragmented anthropogenic areas across States in the Brazilian mid-north region (Santos-Filho et al., 2013).

Regarding the spatial range utilized for mapping, different scales have been used in previous studies. WWF Brazil used the widest scale, with global-scale vegetation mapping based on studies by IBGE (1993) and Olson et al. (2001), whereas the IMESC (2021) used the smallest scale, performing mapping at the State level only for State of Maranhão using the Maranhão Ecological-Economic Zoning database process (2021), which represents a political bias. Establishing a suitable scale for landscape analyses is highly relevant for accomplishing biogeographic delimitations and ecological analyses because living organisms respond to environmental gradients rather than political boundaries. The differences observed in this information may result in spatial data with distinct spatial arrangement patterns and precision, and most important, excluding regions where this formation is present. The scale used could compromise the characterization of environment, such as the heterogeneity of its systems, owing to changes in how its varying nature is perceived (Wu & Qi, 2000). Interestingly, the map presented by LAPIG (2019) (Fig. 1e), based on the study by Sano et al. (2019), was developed exclusively for the Cerrado ecoregions. Thus, according to the criteria of these authors, it is believed that the Cocais Forest area could have been larger than it appeared on the map if the same information had been available for the Amazon biome.

Sousa Nascimento and Lima (2016) reported the largest area (260,039.07 km^2) including the largest number of municipalities ($n = 300$, 56% of which were in State of Maranhão). The study of Rocha et al. (2011) reported the second largest area with 219,219.49 km^2, which contained the second-highest number of municipalities ($n = 220$, with 58.6% of these located in State of Maranhão). In contrast, the IMESC study (2021) restricted to a single State (Maranhão), presenting the smallest area with 27,905.24 km^2 and consequently the smallest number of municipalities ($n = 14$). The IMESC data (2021) (Fig. 1f) resulted from a local sociopolitical approach, from the technical work carried out by the State of Maranhão government to define zones for management and territorial planning (Maranhão Ecological-Economic Zoning – ZEE project), limiting the extent of the studied area to the geographical State boundaries rather than following the natural distribution of Cocais Forest formation (Barros, 2020; SEATI, 2020). This approach has been criticized by several researchers who affirm that it favors the socioeconomic interests over the environmental interests on the conservation of the forest remnants in the State (Celentano et al., 2017; Silva-Junior et al., 2020, 2021).

Restringing the studies to a geographical boundary may also have contributed to a more limited spatial definition by excluding areas in other States or other palm formation regions, such as those occupied by carnauba palms (known as *carnaubais* in Portuguese) in Piauí State (Santos-Filho et al., 2013). Piauí is divided into 12 so-called Development Areas (*Territórios de Desenvolvimento* in Portuguese), one of which is referred to as the Cocais Development Area, comprising 22 municipalities in the north of the State, and a second one referred as the Carnaubais Development Area encompassing 16 municipalities in the mid-north of the State (SEPLAN-PI, 2019). Although the geographic boundaries of the States were the primary criteria for limiting the mapping area in these studies, the Cocais Forest was delineated in each one using different classification criteria.

The new proposed Cocais Forest area delimitation

The sum of the raster layers of the single analyzed maps (Fig. 1a to g) indicated that the total area allocated to Cocais Forest encompassed 425,529.30 km^2 and comprised five Brazilian States (Ceará, Maranhão, Pará, Piauí, and Tocantins) (Fig. 2). In terms of total area, the largest portion (270,591.13 km^2)

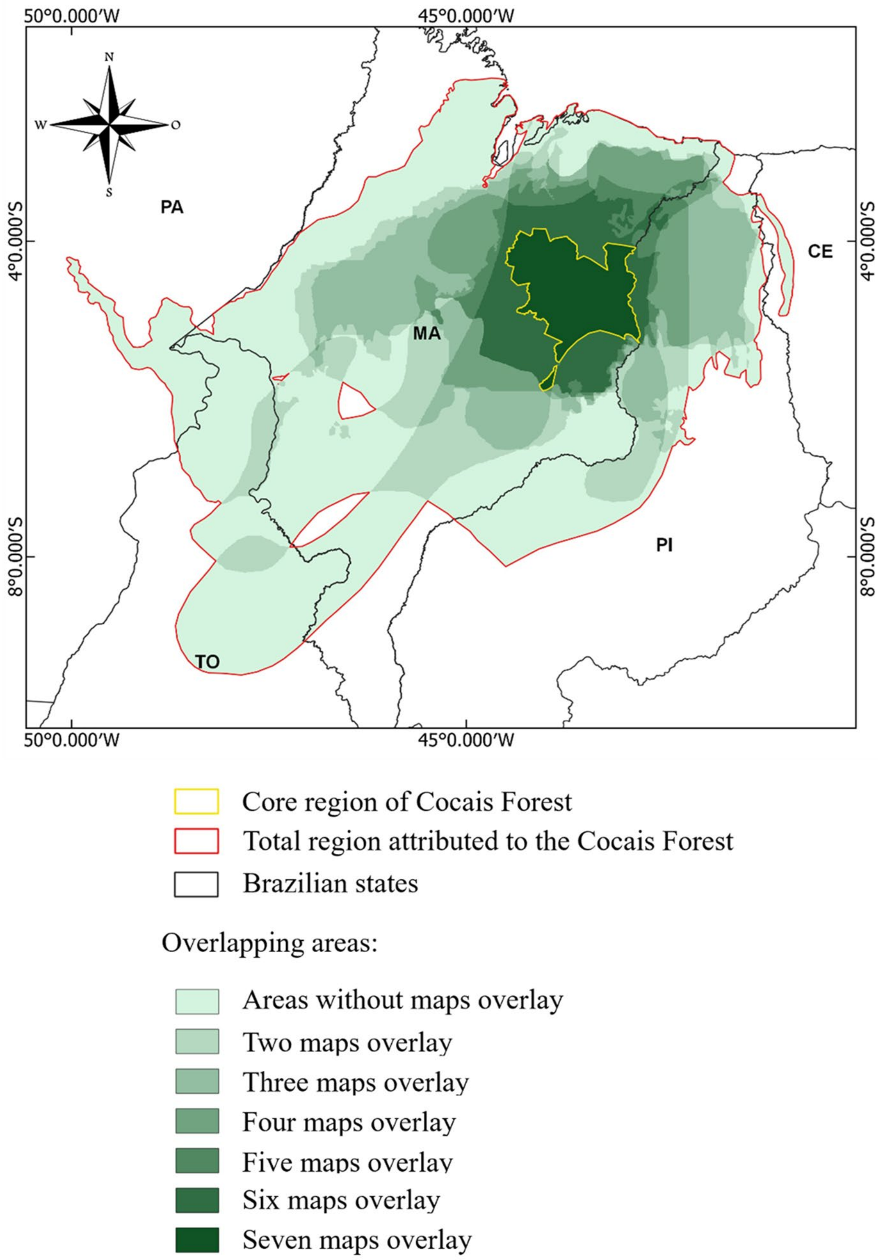

Fig. 2 Overlay map of the areas attributed to Cocais Forest in the reviewed studies, highlighting the total area and core region

was in Maranhão State, accounting for 63.59% of the total area and 82% of the State (Table 2). The Cocais Forest region included a total of 392 municipalities, 51.28% of which were in Maranhão, which also corresponded to the most representative State in the new proposed Cocais Forest delimitation, with 92.63% of its municipalities (201 from 217) included in this formation. In contrast, Ceará State had the smallest percentage of municipalities (6.52%). All studies indicated that the largest area of occurrence designated as Cocais Forest were in Maranhão State (Fig. 1a to g), corroborating the findings of Batistella et al. (2013), who characterized this forest formation as a typical landscape of Maranhão.

The overlapping of different layers made it possible to determine the intersection between the 7 analyzed maps, resulting in a core region that proved to be exclusively within Maranhão State and

Table 2 Geographic aspects of the States included in the total area attributed to Cocais Forest. The values in parentheses represent the proportions of municipalities within the total region that are attributed to Cocais Forest relative to the total number of municipalities in that State

Brazilian State	Area of the State (km^2)	Area of the State within the total Cocais Forest region (km^2)	Percentage area of the State within the total Cocais Forest region (%)	Percentage area of the State in relation to the total region attributed to Cocais Forest (%)	Number of municipalities incorporated
Maranhão	329,651.56	270,591.13	82.08	63.59	201 (92.63%)
Piauí	1,245,870.28	79,166.09	6.35	18.60	108 (48.21%)
Tocantins	277,423.57	60,169.46	21.69	14.14	59 (42.25%)
Pará	251,755.48	13,321.82	5.29	3.13	12 (8.33%)
Ceará	148,894.44	2,280.80	1.53	0.54	12 (6.52%)
Total	2,253,595.33	425,529.30	-	-	392 (43.17%)

predominantly in the eastern region. This core region contained 14 Maranhão municipalities and occupied an area of 20,643.94 km^2 where 95.5% (4975.85 km^2) of the Caxias municipality belongs to this core area and the other nine municipalities are entirely situated within the core (Online Resource 2). In terms of environmental aspects, based on information from the IBGE database (2012; 2020a), the entire core region was in the Cerrado biome, and a considerable portion of this area was situated in the Brazilian semiarid region (Caatinga biome), in areas where seasonal deciduous and semi-deciduous forests occurred.

Considering the consensus between the cartographic data analyzed, and reinforced by the presence of a region whose plants are indicative of Cocais Forest, the IMESC (2018) defined a Development Area denominated “Cocais” in Maranhão State based on a socioeconomic classification. This reinforced the close relationship between the local communities in the region and these palm trees that constitute this forest formation and that contribute to its domination in the landscape, particularly babassu tree palm (de Oliveira et al., 2022; Mitja et al., 2019; Porro & Porro, 2015; Porro et al., 2011).

Based on the identified studies, the overlay map of the locations attributed to Cocais Forest could be regarded as a new proposed area for its occurrence. Thus, it could be inferred that the larger the number of overlay maps, the greater the possibility of a region being classified as a Cocais Forest region. However, studies about the potential species distribution and niche distribution modeling are strongly recommended to perform a robust analysis based on field occurrence data of the dominant tree palms.

Regarding environmental conservation strategies, mapping that underestimates the breadth of a landscape similarly affected the definition of priority areas for conservation (Rezende et al., 2020). Based on this interpretation and utilizing this new proposed map as a cartographic reference, the vulnerabilities that permeate this environment can be studied more assertively (Wang et al., 2019). Consequently, the initial areas for management and conservation plans for their communities and sustainability can be identified.

Conclusions

The analyzed data confirmed the existence of spatial and nomenclatural divergence in the Cocais Forest region, as evidenced by the various spatial delimitations from the selected studies, which highlighted the necessity to better characterize and report the methodological procedures employed to perform these classifications. The lack of consensus regarding cartographic boundaries could impact the characterization of geographic areas and biogeographical analyses necessary for the implementation of public policies to manage and conserve the Cocais Forest region.

Considering the challenges in characterization and nomenclature, a fundamental issue in biogeographical studies, ecologists bear a considerable amount of responsibility for appropriately defining this type of ecosystem. In addition, a highly anthropized environment requires interdisciplinary action to integrate aspects intrinsic to landscape ecology and geography in an approach that encompasses physical and biotic components as well as anthropogenic and social factors.

Combining the different maps resulted in a new proposed occurrence delimitation for Cocais Forest, which included 392 Brazilian municipalities across five States and could be regarded as a potential delimitation area. Although, more studies are needed to better understand the potential species distribution of the dominant and emblematic tree palms and its niche distribution. Despite the various spatial delimitations of Cocais Forest, a common area was established by overlapping the single selected maps, resulting in the identification of a core zone located on Maranhão State, which may be used as a priority area to focus conservation efforts.

This study offered key insights for researchers, policymakers, and practitioners. Future studies based on field work and remote sensing techniques are required to provide scientifically robust data and assess the practical impacts of these divergences on this ecosystem, as a basis for multidisciplinary researchers in the conservation of this relevant landscape.

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Author contribution Santos, D.P., was responsible for surveying the database and formatting the figures and tables. All authors participated in writing and revising the manuscript.

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Data availability The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval All authors have read and understood and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors. The authors approved the manuscript, and there are no ethical issues to declare.

Consent to participate The authors have agreed on the manuscript, and there are no issues to disclose.

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