



Full Length Article



Measuring the natural capital of Amazonian forests: A case study of the National Forest of Carajás, Brazil

Tereza Cristina Giannini^{a,b,*}, Caroline Oliveira Andrino^{a,c},
 Rafael Gomes Barbosa-Silva^{a,d}, José A. Bitencourt^a, Rafael C. Borges^a, Renata R. Brito^b,
 Rosane Cavalcante^a, Claudia P.W. Costa^a, Sidnei Dantas^a, Markus Gastauer^a, Vitor F. Gomes^a,
 Ulysses M. Maia^a, Felipe Martello^{a,e}, Leonardo Miranda^{a,f}, Sâmia Nunes^a,
 Guilherme Oliveira^a, Amanda Paracampo^b, Paulo R. Pontes^a, Silvio Ramos^a,
 José E. Santos Jr^g, Orlando T. Silveira^d, Renata Tedeschi^a, Rafael B. Valadares^a,
 Pedro Viana^d, Jacobus Biesmeijer^h

^a Instituto Tecnológico Vale. Rua Boaventura da Silva, 955. Belém, Pará, Brazil

^b Programa de Pós-Graduação em Zoologia. Instituto de Ciências Biológicas. Universidade Federal do Pará. Belém, Pará, Brazil

^c Departamento de Botânica. Universidade de Brasília. Brasília, DF, Brazil

^d Museu Paraense Emílio Goeldi. Belém, Pará, Brazil

^e School of Geography and Environment. University of Oxford. Oxford, UK

^f Lancaster Environment Centre, Lancaster University, Lancaster, UK

^g Departamento de Genética, Ecologia e Evolução. Instituto de Ciências Biológicas. Universidade Federal de Minas Gerais. Belo Horizonte, Minas Gerais, Brazil

^h Naturalis Biodiversity Center. Leiden, the Netherlands

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ABSTRACT

We propose an innovative approach that links nature and people to assess the natural capital of tropical forests in the Amazon. Our study location is a protected area inside Eastern Amazon forest, where we defined 14 sampling points and analyzed ten components, which encompass the maintenance of standing forests (nature to itself) and the provision of ecosystem services (nature to people). Five components were used to assess ecosystem functions and five components were used to assess ecosystem services. As for ecosystem functions, we registered 467 species of animals (122 bees, 53 butterflies, 292 birds) and 418 plant species, and a mean interaction diversity of 2.8 (from 480 bee-plant interactions). Based on functional traits, we found that at least 83 % of species must be preserved to guarantee resilience, and that functional diversity relies on 60 % of non-replaceable species. Eleven per cent of birds and 9 % of plants are endangered. As for ecosystem services, carbon storage in soil and vegetation is 41.6 and 173 MgC/ha (on average), respectively. One to four uses by Amazonian traditional communities were reported on 42 % of plants. In the vicinities of the protected area, we found that 66 % of crops (13 from 20 crop species) depend on pollinating bees, and the value of annual crop pollination service is US \$4.5Mi. Regarding water protection and local climate regulation, data modelling has shown that the presence of protected forests leads to a 21 % increase in evapotranspiration and a decrease in temperature of 0.4 °C. Our framework showed a clear link between the megadiversity found in Amazonian tropical forest and the robust benefits provided to human welfare, highlighting forest conservation as a key element for sustainable development. Advances in understanding the value of forests stimulate significant new opportunities to improve the effectiveness and efficiency of forest conservation and management policies and decision-making.

1. Introduction

The need for recognizing the social-economic dependency on the

biosphere has grown with the urgency of addressing biodiversity and climate crises (Dasgupta, 2021), and incorporating nature into decision-making strategies, improving data collection, expanding accounting

* Corresponding author.

E-mail address: tereza.giannini@itv.org (T.C. Giannini).

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concepts, and bringing non-market assets into the balance sheet can help achieve this goal (Nordhaus and Kokkelenberg, 1999). Natural capital is defined as the stock of natural resources, which includes biodiversity itself and the abiotic features that support it (Bateman and Mace, 2020). Estimating this stock is not a trivial task (Edens and Hein, 2013, Fleming et al., 2022) and, traditionally, scientists have focused less on ways to measure the Earth's natural assets and more on ways to measure the benefits people obtain from them (Schaefer et al., 2015). Meanwhile, biodiversity loss and global temperature rise are depleting global natural capital. There is an urgent need to balance conservation efforts and the sustainable use of natural capital, while safeguarding other forms of capital, to ensure sustainable possibilities for the future (Díaz et al., 2019, Vardon and Bass, 2020).

While natural capital encompasses the inherent characteristics and processes within ecosystems, it is crucial to acknowledge the interconnectedness with other forms of capital, such as built and human capital, which are embedded in society, and in turn are embedded in nature (Costanza, 2020). The availability of detailed data to describe ecosystems and their economic uses and benefits is important in natural capital approaches, influencing the valuation of ecosystems (UN et al., 2024). The balance between these forms of capital is a crucial element underlying the strong sustainability concept, which recognizes that not always the natural capital can be replaced by other forms of capital (Barbier, 2019, Cohen et al., 2019). Thus, understanding the critical natural capital components (*sensu* Mace, 2019) is a pressing need. Additionally, accounting for biodiversity (broadly defined as the variety of life on earth) is an even harder task due to its complexity, evolutionary history and the interactions between its components and human societies (Pascual et al., 2021). In this way, biodiversity and natural capital emerge as key concepts that can be used to promote the cooperation of scientists, communities, and public and private sectors while informing decisions and fostering sustainable development (Guerry et al., 2015).

Ecosystems were defined by Convention on Biological Diversity (CDB) as “a dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit” (CDB, 2011, p. 4), which makes clear the relationship between biodiversity and the abiotic environment in the stock of natural resources. Ecosystem functions and ecosystem services are two key elements in natural capital assessments (Mace, 2019), showing intermingled linkages with biodiversity (Harrison et al., 2014, Smith et al., 2017). The ecosystem functions point to the intrinsic characteristics of the ecosystem, which represent the set of ecological processes through which the ecosystem maintains its integrity (Spangenberg et al., 2014). These functions are responsible for maintaining the performance and organization of complex natural systems and give rise to the flow of goods and services (Bateman and Mace, 2020). Many of the characteristics that can be seen as ecosystem functions can also be seen as descriptors of compositional (e.g., species abundance), structural (e.g., plant biomass), or abiotic (e.g., surface albedo) states (UN et al., 2024). Ecosystem services refer to the processes of nature that sustain and maintain human life (Daily, 1997), and were also defined more recently as the contributions of ecosystems to the benefits that are used in economic and other human activity (UN et al., 2024). Their flow is derived from the integrity of the stock of natural resources (La Notte et al., 2017). This distinction is fundamental in the assessment of natural capital, because, despite the emphasis on ecosystem services, it is necessary to understand which aspects are key to maintaining the adequate performance of the ecosystem under analysis, thus safeguarding the delivery of services. The values underlying these concepts are not easily translated into monetary terms (Spangenberg and Settele, 2010), given the nature and complexity of the interconnections between ecosystem elements and human societies, but when the methods and data are available such information is of great importance (e.g. Costanza et al., 2014). However, to achieve sustainability, decision-making should systematically integrate these concepts (Farrell et al., 2022) and consider the critical role of current generations on protecting the

natural environment to benefit future generations and their access to natural capital assets.

Components to evaluate natural capital should encompass multiple facets of forest ecosystems, also targeting the critical natural capital that cannot be replaced (UN et al., 2024). Some components were already targeted by previous works. Examples include species that participate in interspecific interactions (Mougi and Kondoh, 2012), pollinators and seed dispersers (Groot et al., 2002), and plants used by animals to collect floral and seed resources (Norton et al., 2018). Analysis of functional redundancy (Bellwood et al., 2003), species richness assessments (Baskin, 1997, Smith et al., 2017), representative and/or distinct species (Gollier, 2019), and threatened or declining species (English Nature, 1995) were also considered. Regarding ecosystem services, those identified as important for natural capital assessment include climate regulation, nutrition, water availability, and livelihood support (Farrell et al., 2022). Crop provisioning services (food and fiber production, fodder), soil quality, water flow and flood control, pollination services, carbon retention and sequestration were also highlighted (UN et al., 2024). Wild species, soil, water, carbon and wild foods were also previously emphasized (Natural Capital Committee - NCC, 2013). Cultural services such as recreation and aesthetic landscapes have also been evaluated (Smith et al., 2017). However, few works have proposed indicators to address natural capital in tropical forests. Some of these studies analyzed only ecosystem services (Teoh et al., 2019, Zheng et al., 2019, Ruiz-Agudelo et al., 2022) or only one service (Cram et al., 2015). However, to our knowledge, there is no work for tropical forests that analyzes a significant set of components associated with ecosystem services and functions to address natural capital and based on empirical data from field surveys. Such an initiative would strengthen the practical and theoretical understanding of natural capital in megadiverse habitats such as tropical forests, and contribute to public policies and decision-making on conservation, restoration and management of natural capital assets found in these biomes. Furthermore, the inclusion of metrics to assess ecosystem services is essential to deepen the understanding of the link between people and nature, since nature delivers benefits for human well-being, and its protection is necessary to safeguard future generations.

In evaluation of natural capital, it is essential to consider specific features that characterize the biomes, as they constitute a unique set of biodiversity components and ecosystem functions and services. Tropical rainforests are of particular interest to the economics of biodiversity, as they contain an estimated 50 % of Earth's biodiversity (Dasgupta, 2021). Moreover, tropical forests globally are home to traditional human communities, which are highly dependent on the ecosystem services provided by the natural habitats where they live (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services - IPBES, 2019, Ellwanger et al., 2023). Thus, the survival of these communities is closely intertwined with forest resources that support their livelihoods, such as food and water resources, and other aspects related to their culture and sense of place (Pascual et al., 2017, 2021).

The Amazon forest biome is home to a remarkable known biodiversity, including 18 % of all vascular plant species, 14 % of birds, 9 % of mammals, 8 % of amphibians, and 18 % of fishes in the Tropics (Science Panel for the Amazon, 2021). Endemism rates are high in the Amazonian lowlands (below 250 m), with around 34 % of mammals and 20 % of birds not found elsewhere. The biome has been inhabited for at least 12,000 years, currently occupied by a diversity of people with multiple livelihood strategies, housing 47 million people, including Indigenous people (nearly 2.2 million) (Science Panel for the Amazon, 2021). In the eastern Amazon, a region historically highly impacted by deforestation (Souza-Filho et al., 2016) and climate change (Nobre et al., 2016), a protected area stands out as being relatively well conserved, the National Forest of Carajás. It is located in three municipalities that are home to nearly 635 thousand inhabitants (Instituto Brasileiro de Geografia e Estatística - IBGE 2022). The importance of ecosystem services has already been assessed in neighboring rural communities, mapping

the perception of people about them, and showing that people are aware of the role of forests in providing and protecting food, livelihoods, and quality of life, giving high importance to all assessed services (Brito et al., 2020).

Our main objective is to propose a method to link ecological perspectives and assess the natural capital of tropical forests in the Amazon, addressing both ecosystem functions and services. For this, we defined ten biophysical components, including those related to the maintenance of standing forest (ecosystem functions; nature to itself) and those related to ecosystem services provision (ecosystem services; nature to people). Each component was then evaluated through massive assessments conducted in the National Forest of Carajás, one of the largest areas of protected pristine forest in the eastern Amazon.

2. Material and methods

Methodological Framework: components.

We divided the components of our framework into two major categories, Nature to Itself and Nature to People (Fig. 1). Our framework is based on the cascade diagram proposed by La Notte et al., (2017), in which the components of an ecosystem (the biophysical structure itself) interact with dynamic biophysical processes (which are considered as ecosystem functions) to produce ecosystem services and their benefits on which people depend. Thus, functions are more associated with environmental elements (ecological sphere) while services are at the interface of this sphere with the socioeconomic one (La Notte et al., 2017). Nature to Itself encompasses the ecosystem functions, which are the intrinsic characteristics of the ecosystem and represent the set of ecological processes through which the ecosystem maintains its integrity (Spangenberg et al., 2014). The ecosystem functions were used to aggregate the processes that we considered as associated with nature's

ability to persist as a standing forest ("nature to itself" in Fig. 1) (sensu Mace, 2019) and sustain the flows of matter and energy in the long term. Nature to People encompasses the ecosystem services provision from nature to people (Daily, 1997) ("nature to people" in Fig. 1). Five components were used to assess ecosystem functions: species richness, bee-plant interactions, resilience, insubstitutability and threatened species. Other five components were used to assess ecosystem services: water protection, carbon storage (soil and vegetation), local climate regulation, tree uses for people and crop pollination. For ecosystem services, we used some of the categories proposed by Díaz et al., (2018), and added "uses of trees by traditional people" which will be defined below. Another point worth noting is that, although Díaz et al., (2018) considered carbon storage as an aspect of the climate regulation service, we analyzed these two components separately. In fact, carbon storage measurements can provide robust information for decision-making aimed at maintaining carbon stocks in the biosphere. Combined with measurements of carbon transport capacity and land-use history, carbon storage can be used to inform other aspects of carbon emissions resulting from the conversion of natural ecosystems to other land uses, such as restoring biological carbon stocks through reforestation, identifying land uses that result in carbon removal or sequestration, and elucidating trade-offs in ecosystem services, biodiversity, food, fiber, and timber production (UN et al., 2024). Details of each component used in this study are summarized in Table 1.

The influence of ideas originating from economics and conservation on the concept of natural capital dates back a long time (Missemmer, 2018), which makes clear the complexity of the value of nature's concept, which is perceived in different ways by different cultures and peoples. As previously stated, we based our framework on ecosystem functions and services (La Notte et al., 2017), also considering the critical components of natural capital (Mace, 2019), which are

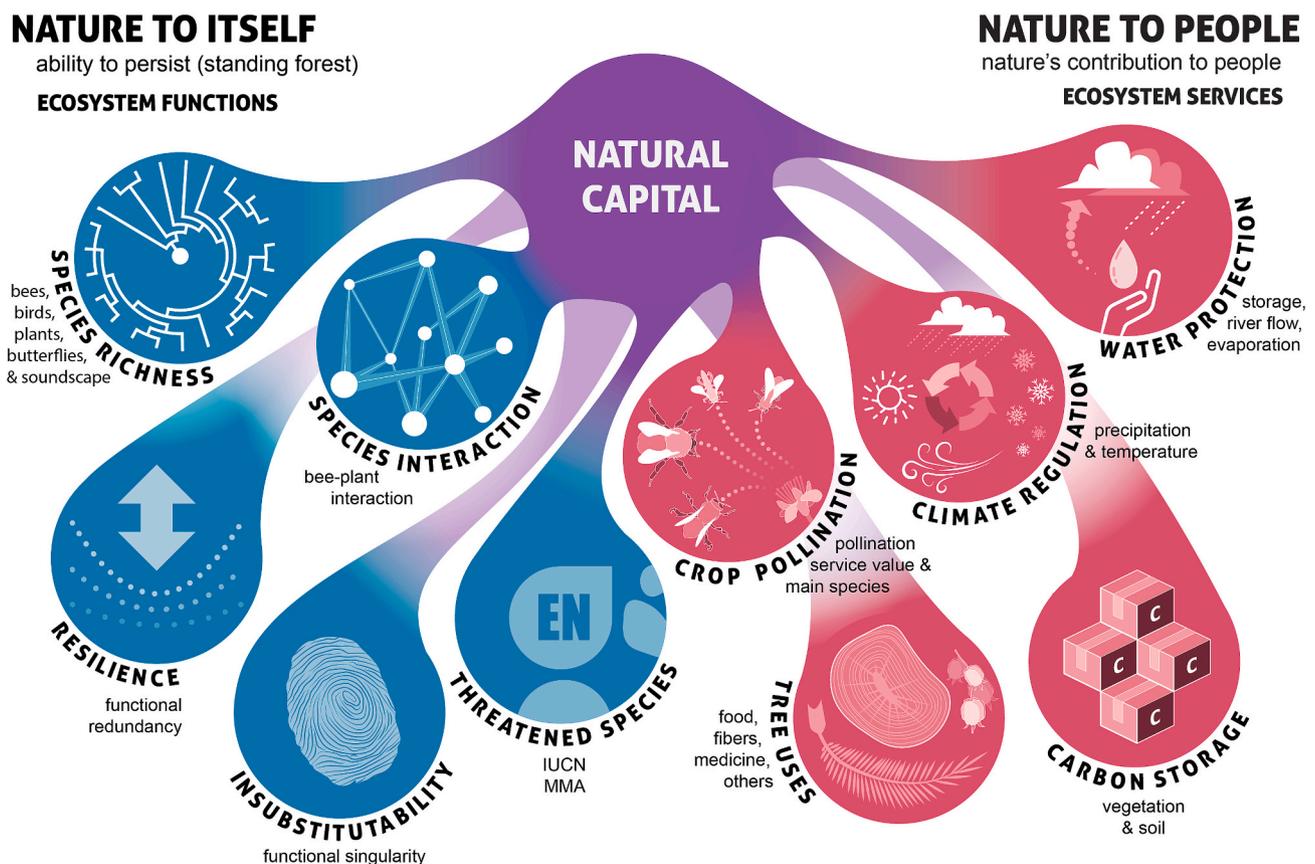


Fig. 1. Overview of the two major components (nature to itself and nature to people) and the ten components used to assess Natural Capital in the Amazon forest in this study (designed by Marcelo Kubo).

Table 1

The ten components used for assessing Natural Capital in the Amazon forest. Blue icons are Nature to Itself components and red icons are Nature to People components.

	Species richness: number of collected/recorded species of birds, butterflies, bees at 14 sampling points. Woody plants were collected on 6 sampling points.
	Bee-plant interactions: diversity of interactions in interaction networks formed by floral visitors (bees) in search of food resources in plants present in the sampling points.
	Resilience: it evaluates the impact of local species loss, based on the concept of functional redundancy, that is, the redundancy of specific characteristics that determine also specific roles of the species in nature.
	Insubstitutability: it evaluates the impact of species loss, based on the concept of functional uniqueness, meaning specific unique characteristics in the species that cannot be replaced if they are lost.
	Threatened species: number of species collected in the sampling points that are considered threatened.
	Local climate regulation: the role of the forest in local climate regulation was evaluated through simulations with local climate data modeling, considering changes in temperatures and precipitation.
	Water protection: the role of the forest in water protection was evaluated through simulations with hydrological data modeling, considering changes in evapotranspiration.
	Carbon storage: Soil carbon storage was evaluated considering soil samples from the 14 sampling points. Carbon in vegetation was evaluated at 6 of these points.
	Uses of trees by traditional people: the list of plant species sampled in the sampling points was evaluated considering fifteen uses by traditional communities.
	Crop pollinators: it focuses on crop pollinator species sampling in the sampling points, and the value of the pollination service for crop production in the vicinities of the protected area.

intermingled with biodiversity itself (Harrison et al., 2014, Smith et al., 2017). We measured general characteristics of biodiversity (species richness and their interactions) as ecosystem functions, which also are related to the delivery of most of ecosystem services. As critical assets of natural capital, based on the idea of the habitat's capacity to persist, we measured, also as functions, the resilience, insubstitutability and threatened species. Related mostly to biodiversity (species richness and their interactions), as mentioned above, we considered the ecosystem services as being water protection, climate regulation, carbon storage, crop pollination and uses of trees by local people. Finally, the components were chosen considering also the feasibility of measuring them in fieldwork and if they could characterize megadiverse tropical forests.

3. Study case

3.1. Study area

The National Forest of Carajás (hereafter, Carajás) is a protected area located inside the Amazon Tropical Forest biome, encompassing three municipalities in Pará state, Brazil (Parauapebas, Canaã dos Carajás, and Água Azul no Norte). This protected area is mostly covered by open rainforest and is contiguous to other protected areas (Souza-Filho et al., 2016). The area of Carajás is equal to 3927 Km². We sampled 14 sites of pristine forest (Fig. 2; for raw data, see Supplementary Material 1) using different, but standardized sampling methods (see below). Each sampling point was at least 2 Km apart (except 01–02 and 13–14, respectively at 1.69 Km and 1.49 Km).

3.2. Species richness and interactions

For surveying birds, we recorded the soundscape of the forest using automatic digital recorders (Audiomoth 1.0.0; Hill et al., 2018) placed in each sampling point in the understory of the forest at about 1.5 m from the ground. Recorders captured one-minute within a ten-minute interval for seven consecutive days (repeated 3 times, 21 days recorded from

each sampling point), with a sampling frequency of 48 kHz and medium amplitude gain. We used the records to identify the birds with the help of a specialist on bird species vocalization (SD).

We collected frugivorous butterflies using a bait trap, adapted from the Van Someren-Rydon model, baited with a mixture of banana and beer, fermented for at least 48 h (adapted from Uehara-Prado et al., 2005). Traps were exposed for 6 consecutive days in each point (18 days in total). Revisions and bait refills occurred every 48 h from the first day of setting up the traps.

We sampled wild bees with three methods, aromatic traps, honey traps and flower visitors. Aromatic traps were used to collect orchid bees, being widely used and designed for attracting males of the Euglossini tribe (Krug and Alves-dos-Santos, 2008). These scent traps were made from PET (polyethylene terephthalate) bottles with two openings and a bait containing an artificial essence. They were distributed in the same way as butterfly traps, and remained at each sampling point for 48 h. Four different artificial scents were used: eucalyptol, vanillin, eugenol and methyl salicylate. To attract wild bee foragers, we used a 1:1 mixture of honey and water that was sprayed on approximately one square meter in the vegetation at 1.5 m high. We waited for one hour and captured all bees that arrived during 10 min, using an entomological net. A second 10 min of sampling was performed after two hours (adapted from Wille, 1962). In each sampling point we repeated this process 3 times, in non-consecutive days, totaling 60 min of sampling per site. We also collected floral visitor bees as described below.

To characterize the bee-plant interaction networks in each of the 14 sites, we sampled the visiting bees on flowers using an entomological net. Each flower was observed for 5 min, and all the visitors were collected. Plants with several open flowers or inflorescences were observed long enough to observe all flowers; when possible, multiple flowers were observed at the same time (adapted from Sakagami et al., 1967). We started each day by searching for plants with open flowers, and collected all the flower visitors for two nonconsecutive hours between 7:30 and 11:30 am. To characterize the interaction diversity of networks, we used the interaction diversity index defined as the weighted diversity of interactions across a network, calculated based on the Shannon diversity, which considers the equity between species richness and abundance (Dormann, 2011). Higher homogeneity of interaction frequencies (i.e. higher interaction diversity) is related to greater ecosystem functional robustness (Kaiser-Bunbury and Blüthgen, 2015). We calculated this index for each area using the bipartite package (Dormann et al., 2024) from R (R Core Team, 2021) and after this, we calculated the average for all surveyed areas.

For surveying the flora, we used six of the 14 above mentioned sampling points (points 2, 3, 5, 6, 10, 11 at Fig. 2), delimiting six plots of 20x100m. We identified all woody plants species and measured the circumference at breast height (CBH) of all individuals larger than 10 cm using a tape measure and the height (m) through visual estimation.

All specimens were deposited at the entomological collection and the herbarium of Museu Paraense Emilio Goeldi (MG), located in the municipality of Belém (Pará, Brazil).

3.3. Resilience and insubstitutability

To quantify the resilience and insubstitutability, we first aggregated samples from all sampled sites, representing integrated communities for each taxonomic group (Supplementary Material 1). For each of these taxonomic groups, we calculated a functional diversity index: Functional Richness (FRic), which is based on a set of functional traits that infer the ecosystem services and functions provided by these groups. FRic measures the total hypervolume of functional space occupied by a community based on species traits, reflecting its range of ecological functions (Villéger et al., 2008). The FRic was first calculated for the integrated communities of each group (considering all species) and then for communities where we simulated different levels of species loss. The

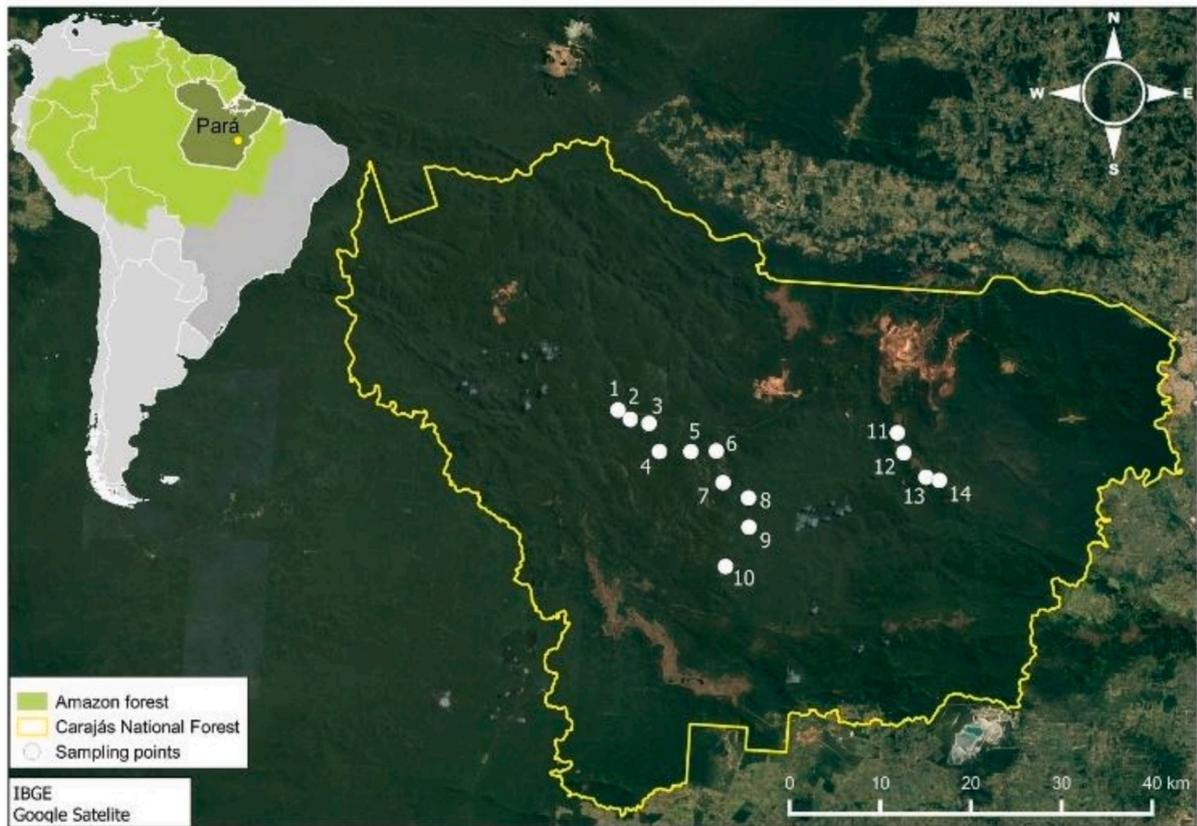


Fig. 2. Above. Fourteen sampling points surveyed in the National Forest of Carajás (Pará, Brazil). Below. Panoramic view of the Carajás National Forest landscape (photo taken between sampling points 12–13 by Miguel Aun).

number of species loss levels corresponds to all possible species loss scenarios, ranging from the loss of a single species to a minimum of three remaining species, as functional diversity indices cannot be calculated with fewer than three species.

To assess resilience, we performed random simulations of species loss and defined resilience as the percentage of species richness at which 95 % of simulated communities exhibited functional diversity index values equal to or greater than 95 % of the indices calculated for intact communities. To assess insubstitutability, we performed non-random species loss simulations, prioritizing the removal of species from communities with the lowest functional diversity values. For each level of species loss, we calculated the FRic value for all possible communities and selected the one with the lowest FRic value, representing the worst-case scenario of functional diversity loss at a given species loss level. We then excluded the species removed from this community in subsequent simulations. Next, we calculated the area under the curve (AUC; [Supplementary Material 2](#)) of the relationship between the FRic values of these communities (expressed as a percentage of the FRic of integrated communities) and the percentage of total species richness. Finally, we defined insubstitutability as the difference between the AUC of simulated species and the hypothetical AUC of the same relationship in communities where each species contributes equally to maintaining functional diversity—i.e., where the loss of any species reduces FRic equally. Since FRic values and species loss were converted into percentages, this hypothetical AUC represents an isosceles right triangle with an area of 0.5. Therefore, the insubstitutability was calculated as twice the AUC of the relationship between the FRic values of these communities and species loss in these communities.

3.4. Threatened species

All surveyed species were checked related to their threat status on two repositories: International Union for Conservation of Nature (IUCN) Red List and the Brazilian Minister of the Environment (MMA, Portuguese acronym) Red List.

3.5. Local climate regulation

For this analysis, we used the Carajás' Complex of protected areas, which is a mosaic of contiguous forest including Carajás and other protected areas ([Souza-Filho et al., 2016](#)). To estimate the role of the protected areas in Carajás to the local climate, we conducted an experiment using climate modeling. First, we addressed climate variables (temperature and precipitation) using a current scenario, which refers to the maintenance of the current forest cover in the region without modifications. Secondly, we simulated a partial replacement (Carajás only) by pasture/forest mosaic. Finally, a total replacement of forest cover (all protected areas) by pasture/forest mosaic was simulated. The experiments were conducted with the RegCM4 climate model, which is the fourth generation of the local climate modeling system ([Giorgi et al., 2012](#)) developed by the International Center for Theoretical Physics (ICTP). For this purpose, changes were made to the surface scheme (Biosphere-Atmosphere Transfer Scheme – BATS) ([Dickinson et al., 1993](#)) of RegCM4, so that they represent the different land covers of the analyzed area. Our modeling considered the climate data from 1994 to 2018.

3.6. Water protection

To understand the role of the Carajás in water resources, we used a hydrological model to estimate how the forested areas may influence evapotranspiration and streamflow compared with surrounding deforested areas ([Pontes et al., 2019](#)). The experiment follows the steps: 1) Calibration of the model using in-situ daily streamflow data (from 1998 to 2007) to guarantee a good representation of the natural system (water cycle in the watershed) ([Pontes et al., 2019](#)); 2) estimation of

evapotranspiration (soil evaporation, plant transpiration, and evaporation of water intercepted in the canopy of trees) and streamflow in forested and deforested areas.

3.7. Carbon storage

Soil: Using all the 14 sampling points, we estimated the soil carbon stock using a 0–20 cm soil layer (following [Briedis et al., 2012](#)). Since soil bulk density was not determined directly in the field, we estimated it using the pedotransfer function ([Benites et al., 2007](#)).

Vegetation: Using the six plots above-mentioned for flora sampling (points 2, 3, 5, 6, 10, 11 at [Fig. 2](#)), all trees, bamboos, lianas and palm trees with circumference at breast height (CBH; CBH > 10 cm) equal to or greater than 10 cm were identified and measured. Their respective total height was estimated visually. The choice of equations to estimate aboveground biomass was made considering the type of vegetation and the habit of individuals, based on height and diameter data. For Seasonal Deciduous Forest we used the allometric equation defined by [Scolforo \(2008\)](#), and for the Open Rainforest we used [Chave et al., \(2014\)](#) equation and wood density from the Global Wood Database ([Chave et al., 2014](#), [Zanne et al., 2009](#)). To convert the value of biomass into carbon, we used the coefficient equal to 0.47 recommended by the Intergovernmental Panel on Climate Change (IPCC) for tropical forests ([IPCC 2003](#)).

3.8. Tree uses

Considering the plant species found at the surveyed sampling points, we identified those that were quoted on a large dataset about trees used by traditional communities ([Salomão et al., 2007](#)), according to fifteen different forms of uses. They are food for wildlife (fruit); food for people; white wood with commercial value; hardwood with commercial value; medicinal; ornamental; charcoal/firewood production; cellulose production; dye production; production of aromatic essence; fiber production; latex production; production of essential oils; resin production and; production of poisonous substance.

3.9. Crop pollinators

We compared the bee species collected during the fieldwork to those already quoted as crop pollinators for Brazil ([Giannini et al., 2020](#)) to estimate how many species can represent a stock of pollinators to crop pollination service. Moreover, we analyzed the crops produced in the municipalities where Carajás is located, relying on a Brazilian database about annual crop production ([Instituto Brasileiro de Geografia e Estatística - IBGE, 2021](#)) to determine which ones depend on pollination service. Municipalities distant up to 30 km from the edges of the protected area were analyzed. This limit was used because it is the maximum foraging distance of the collected bees (based on the largest bee, *Xylocopa frontalis* Olivier, 1789; see [Supplementary Material 1](#)). Thus, the municipalities of Marabá, Parauapebas, Canaã dos Carajás, Água Azul do Norte and Curionópolis were included. Crops' dependence was already determined elsewhere ([Giannini et al., 2015](#)). Finally, we calculated the value of pollination services for the year 2021, which is the annual production of each crop multiplied by its dependence rate on pollinators (following [Gallai and Vaissiere 2009](#)). Methods used here were applied previously to Brazil ([Giannini et al., 2015](#)) and Pará state ([Borges et al., 2020a](#)), where more details can be found. However, it is important to consider that the final value obtained is probably underestimated as not all crops have their production measured by the Brazilian Institute of Geography and Statistics (IBGE), and in some cases, fruits and seeds resulted from animal pollination are obtained directly from the forest through extractivism ([Paz et al., 2021](#)).

4. Results

Results are summarized in Fig. 3. We found a total species richness of 122 bees (1581 specimens), 292 birds (on 7000 min of recording), 53 frugivorous butterflies (176 specimens) and 418 woody plant taxa (290 species identified; 2278 specimens) (Supplementary Material 1). A new species occurrence was detected, the butterfly *Amphidecta calliomma* Felder 1862, whose known occurrence record further east was almost 700 km away from Carajás (Paracampo et al., 2023). We also detected 480 bee-plant interactions in the 14 interaction networks, with 57 bee species interacting with 73 plants (Supplementary Material 1). The average diversity of interactions was 2.8 (ranging from 1.9 to 3.6). Regarding resilience, our evaluation showed that at least 83 % of the species are responsible for maintaining functional diversity in the forest (functional redundancy) and that 60 % of this diversity is supported by non-substitutable species (functional singularity). As for threatened species, 9 % of plant and 11 % of bird species were reported as presenting some degree of threat (Supplementary Material 1).

The simulation of forest removal resulted in an increase in temperature (up to 0.4 °C) across the basin where the Carajás is located, in both experiments (partial or complete forest removal). Changes in precipitation (increase of up to 2 mm/day) are also observed, with the most intense changes being observed in the rainy season. Considering water protection, the amount of water that returns to the atmosphere through evapotranspiration is 1277 mm/year (72 % of annual precipitation) within forested areas (Pontes et al., 2019), exceeding 272 mm/year the evapotranspiration in deforested area (1005 mm/year). About 5 km³ of water is transferred to the atmosphere annually through

evapotranspiration in the Carajás National Forest. The forested area also has an essential role in streamflow regulation. The surface runoff varies from 325 mm/year (in the forests) to 1,100 mm/year (deforested areas), reinforcing that deforestation may increase flooding issues in deforested areas.

As for carbon storage, the estimation for soil ranged from 18.04 to 95.36 MgC ha⁻¹ (equivalent of 66.1 to 349.7 MgCO₂.ha⁻¹), with an average stock of 41.6 MgC ha⁻¹ (152.5 MgCO₂.ha⁻¹) per sampling plot. Regarding the carbon stock in the trees, the average value obtained was 173 MgC ha⁻¹ (634.3 MgCO₂.ha⁻¹) for each sampling plot, considering only the aboveground biomass. The species with the highest carbon stock estimated were *Erisma uncinatum* Warm., *Marlinoimia psilostachya* (DC.) L.P. Queiroz & Marc.F. Simon and *Bertholletia excelsa* Bonpl.

Considering the use of trees by traditional people, we found that, of the 266 plant species completely identified (including palm and bamboo and excluding vines), 42 % had at least one type of use quoted (Supplementary Material 1). Species with the highest number of uses (4 types) were *Bertholletia excelsa* Bonpl. and *Lecythis lurida* (Miers) S.A. Mori. As for crop pollination, among the 122 identified bee species, 28 species were cited as pollinators of agricultural crops in studies in Brazil (Giannini et al., 2015) (Supplementary Material 1). Among these, the majority (16 species) belong to the Meliponini tribe (stingless bees). In the analyzed municipalities, 20 crops are cultivated, of which 13 depend on animal pollinators. Three crops (cocoa, passion fruit and watermelon) have an essential degree of pollinator-dependence, meaning that around 95 % of production depends on the pollination service. Two crops (açai and tomato) have a high degree of dependence (65 %). Four crops have modest dependence (25 %) and three crops (beans, papaya

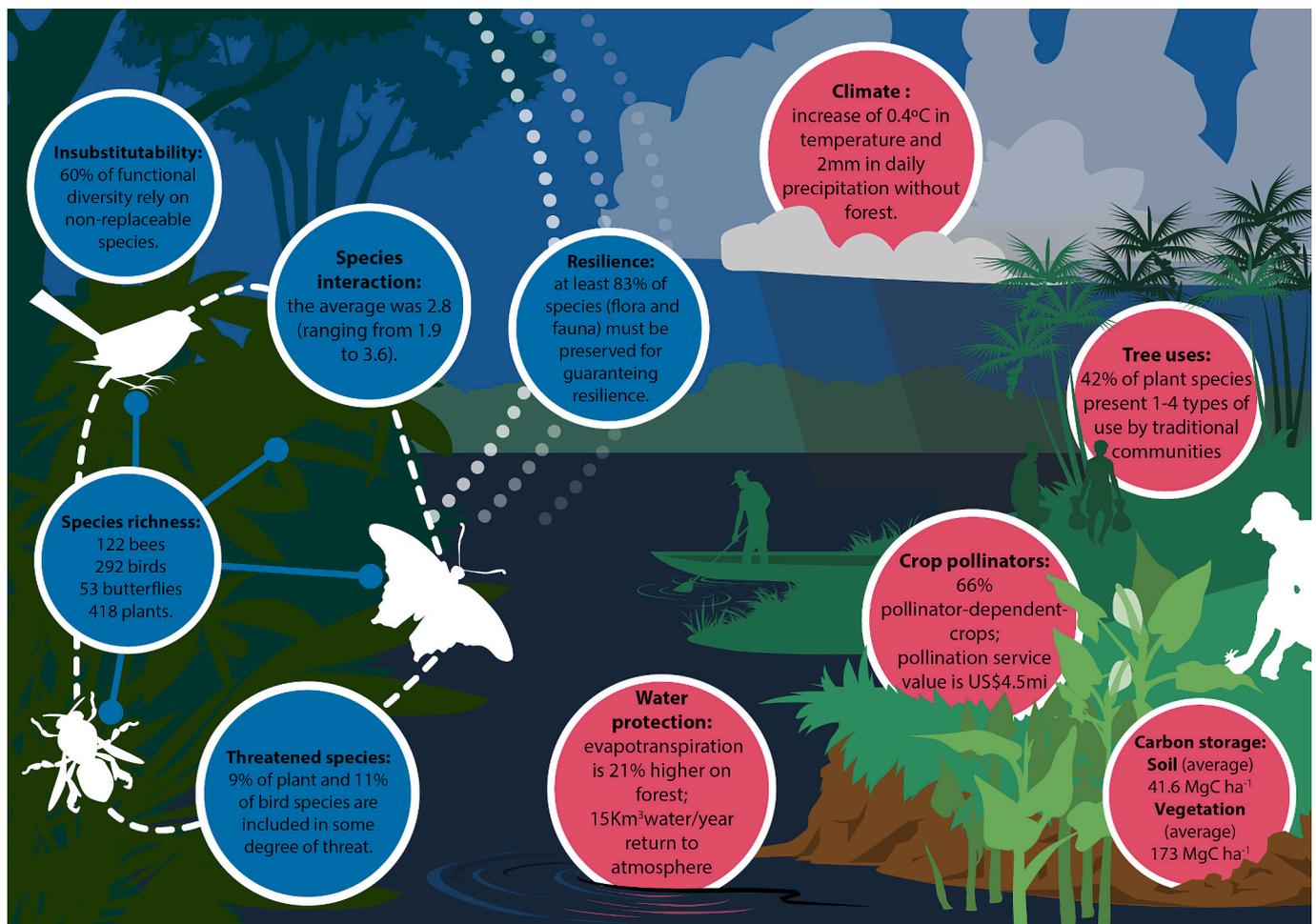


Fig. 3. Ten analyzed components of Natural Capital in the National Forest of Carajás (designed by Marcelo Kubo).

and tangerine) have small dependence (5 %). In 2021, the animal pollination service corresponded to approximately US\$4.5 million in these municipalities, considering the market values of crops in the Eastern Amazon.

5. Discussion

We propose here a method to evaluate natural capital relying on empirical data surveyed in the eastern Amazon tropical forest. We addressed ten components in order to shed light on some key functions underlying a standing forest, as well as their benefits delivered to people. With the method proposed here, different aspects of the natural capital, feasible to be addressed through fieldwork, data analysis and modeling were presented and can be adapted and applied to other tropical forests.

The components used here have direct links with human well-being. Regarding the ecosystem functions analyzed, as previously presented, they are essential for the maintenance of the standing forest and for the provision of ecosystem services, which, in turn, are translated into benefits for humankind. Climate regulation, water provision and carbon sequestration and storage are essential to reduce the increasing effects of climate change, ensuring agricultural production, thermal comfort, reducing the risks of extreme weather events, poverty and food insecurity, and contributing to people's health, reducing the risk of diseases especially affecting the most vulnerable people. The provision of water itself is an important benefit for people with regard to their daily individual needs, but also for agriculture and industry. Crop pollinators, with their fundamental importance for the production of fruits and seeds, are associated with food security and also with income for farmers who produce pollinator-dependent crops. Finally, trees that have different uses are important both for food and for the culture and livelihoods of the local people. All of them are directly related to United Nations' Sustainable Development Goals (SDG) (United Nations - UN 2015), addressing SDG1 (poverty), 2 (food), 3 (health), 6 (water) and 13 (climate). Our resonance is also aligned to Goal B (prosper with nature) of the Kunming-Montreal Global Biodiversity Framework (CDB, 2022) that aims to the valuation and sustainability of biodiversity, including ecosystem functions and services, to support the achievement of sustainable development for the benefit of present and future generations.

Biodiversity data is a limitation to evaluate natural capital, especially due to the complexity of variables used that, broadly speaking, can include biotic and abiotic factors (Leach et al., 2019). Our methodological framework relies heavily on fieldwork data. To fill the knowledge gaps about biodiversity, a common concern for tropical forest, we collected standardized data in our study area (Collen et al., 2008, Beaudrot et al., 2016). Despite the existence of some historical biodiversity data collected on Carajás forest (e.g. Brown 1997, Bonaldo et al., 2006), few standardized surveys on forest, with the same effort, had been conducted, which hindered previous data comparison. In addition to field surveys, data-modeling using well-established methodologies was conducted to assess some of the ecosystem services evaluated here. The multidisciplinary approach was crucial for the successful development of our study case, as already pointed out (Kumar et al., 2013). Complex and mega-diverse environments such as the Amazon tropical forests can benefit from such a broader approach. Monitoring natural capital through standardized data was also suggested as being important to understand natural capital conditions (UN et al., 2024) and potential risks that could undermine it (NCC 2013), as well to help policy-makers on defining effective decision-making strategies (Ruijs et al., 2019). Better decision making is a central justification for natural capital assessment, enabling broad, cross-sector evaluation, monitoring natural resource stocks and services flows, which are regularly omitted, and defining the sustainability of the economy and business (Miteva, 2019, Bagstad et al., 2021).

Another striking feature of the framework used here is its broader scope, which analyzes not only the services but also the ecosystem

functions that support the maintenance of the forest itself, thus ensuring the continuous delivery of services. The framework and the ten components can be used to other tropical forest, since they are based on empirical data. Due to all these listed features, our framework can clarify the various components of natural capital and offer a well-founded support to forest conservation and management considering sustainable development. Our framework can also be easily applied and is standardized, with comprehensive well-defined metrics, which is a crucial step to a broader application. Accounts of natural capital can be produced with existing data, if available, and expertise can be mobilized to generate specific assessments (Vardon and Bass, 2020), such as on water, soil, climate, and carbon accounts. The use of common classifications, access to data, appropriate valuation techniques and spatial boundaries for aggregate the information are important strategies, as well enhancing the comprehension of them in the broader community (Vardon and Bass 2020). This last aspect is key to generate public participatory involvement and effective results related to natural capital evaluation aiming at a more sustaining society (Hinson et al., 2022).

The Amazon forests have been reported as having a rich biodiversity, whose species have complex forms of interaction with each other and with the environment, in addition to high rates of endemism (Science Panel for the Amazon, 2021), but it is highly threatened (Flores et al., 2024). There is a global recognition of their importance as ecosystem services providers, especially their role on climate regulation with high rates of carbon sequestration and storage, and housing an impressive freshwater flow (Davidson et al., 2012). Carajás' species richness, listed in the data allocated in biodiversity museums and collections, show higher figures when compared to those obtained through our surveys. For example, 620 species of birds have been recorded previously (Miranda et al., 2019) and 222 species of bees (Borges et al., 2020b). The role of Carajás' forest, demonstrated here, in protecting water resources and regulating the climate locally are relevant, especially considering the population density of neighboring cities. Other measurements, for example, evaluated the richness of birds in the Tucuruí Hydroelectric dam influence area showing 479 species (Henriques et al., 2021) and at the Paragominas with 440 species (Lees et al., 2012), both in the state of Pará (Eastern Amazon). Another work was conducted at the Tapajós National Forest (area 527,319 ha), resulting in a list with 761 angiosperm species (Giacomin et al., 2022).

Assessing the value of natural capital present on these components is a challenge, and caution is necessary when applying economic methods (Spangenberg and Settele, 2010). People communities present different perceptions about the importance of the forest (Barton et al., 2018). They benefit from nature in many ways (Lienhoop and Schröter-Schlaack, 2018). Examples are: using raw materials to generate labor and to producing art and other culture expressions; consuming water and different wild foods; experiencing health and leisure; enjoying the aesthetical aspect of natural areas; developing a sense of place; among other forms of nature's benefits. Many of these benefits have intangible values (Mace et al., 2012), and trying to monetize them does not always lead to the expected goals of sustainability or protection of natural resources. Therefore, acknowledging the importance of ecosystem services and their socioeconomic value is urgently needed, as well, improving the knowledge base to support decision-making on the topic (Spangenberg and Settele, 2010).

Fieldwork is a challenge on tropical forests, which are characterized by dense vegetation with a high canopy and remote access. Our survey was carried out mainly near the few roads that exist within the protected area, as they were the only accessible points. Automation in biodiversity data collection is of great help in these cases, but even when using, for example, soundscape recorders, they need to be placed manually, which also reduces the choice of sampling points. In addition, species identification of different biological groups is still a challenge on megadiverse biomes, as several taxonomists need to be involved, which demands resources, time and effort. The use of molecular methods is a crucial step, but there is still some gap on molecular sequences deposited in

open access libraries, which makes it difficult to obtain a more precise identity about the species surveyed. This fact hinders cross information concerning, for example, the use of plant species by traditional communities, or the role of crop pollinator for bee species. Thus, technological innovation applied to biodiversity monitoring, and the promotion of research in systematics and genomics should be continuously encouraged. Long-term monitoring and baseline data are generally scarce, but are fundamental strategies for understanding natural capital changes over time.

Finally, our study is located in a common scenario found in other tropical forests in emerging countries, where a thriving forest is house for traditional people and also, meets urban areas with different local actors, many of whom are in poverty (Bradshaw et al., 2009). Next steps should include the voices of local people in the valuation of natural capital, to map their understanding and needs regarding the themes discussed and presented here. Local conditions define very particular processes that are context-specific, and so are the solutions (Pascual et al., 2021). The availability of information influences the valuation method to be used, but, currently, methodologies have not yet reached maturity to integrate peoples' values, behaviors and the impact on biophysical indicators, and it is urgently needed to balance market-based values with those specific values to local people to achieve more just and sustainable futures (Pascual et al., 2023). Most of those values are not fully replaceable (IPBES, 2019) or are non-substitutable and need to be fully recognized and protected.

6. Conclusion

Assessing natural capital of forest biomes is an important exercise to build a sustaining view that recognizes the indissoluble bond between people and nature. The definition of natural capital clarifies the notion that the ecosystem services provided by natural assets contribute directly to generating goods and products. Therefore, the lack of clear estimates of these assets hinders the measurement of the impacts caused by the loss of natural areas and how the management of these areas should be, based on measurable sustainable actions. Strategies for forest conservation, restoration, and management are most successful when based on well-founded data, and decision-making benefits from science-based initiatives. Thus, our study clarifies the importance of forests for human well-being, solidifying the clear relationship between people and nature, and offers a set of metrics that can be standardized and whose data can be obtained through fieldwork. Instead of achieving a final figure that represents natural capital value, the aim here was to promote a broad view of components to capture the main elements whose measurements are feasible to help in decision-making and enhancing public awareness. Ecosystem functions and services with their various types of benefits to humankind can be easily understood by the public and decision makers, and protecting them is a political decision, not necessarily in need of an economic justification. However, if the data for such a measure is available, it would reinforce the need to protect the asset. If the asset is irreplaceable, the need to protect it is even greater and more easily justifiable. When facing biodiversity crisis and climate change, it is crucial to substantiate decision-making on nature conservancy, guaranteeing the delivery of nature's benefits and ensuring human welfare and sustainable development. We recommend including components of nature by itself to account for the maintenance, resilience and uniqueness of the ecosystem that, ultimately, keep the flows of matter and energy and deliver the nature's contributions to people.

CRedit authorship contribution statement

Tereza Cristina Giannini: Writing – original draft, Project administration, Funding acquisition, Data curation, Conceptualization. **Caroline Oliveira Andriano:** Formal analysis, Data curation. **Rafael Gomes Barbosa-Silva:** Formal analysis, Data curation. **José A. Bitencourt:** Methodology, Investigation, Formal analysis, Data curation. **Rafael C.**

Borges: Formal analysis, Data curation. **Renata R. Brito:** Formal analysis, Data curation. **Rosane Cavalcante:** Methodology, Investigation, Formal analysis, Data curation. **Claudia P.W. Costa:** Methodology, Investigation, Formal analysis, Data curation. **Sidnei Dantas:** Data curation. **Markus Gastauer:** Methodology, Investigation, Formal analysis. **Vitor F. Gomes:** Methodology, Formal analysis. **Ulysses M. Maia:** Formal analysis, Data curation. **Felipe Martello:** Methodology, Formal analysis. **Leonardo Miranda:** Methodology, Investigation, Formal analysis, Data curation. **Sâmia Nunes:** Methodology, Investigation, Formal analysis. **Guilherme Oliveira:** Methodology, Investigation. **Amanda Paracampo:** Formal analysis, Data curation. **Paulo R. Pontes:** Methodology, Investigation, Formal analysis, Data curation. **Silvio Ramos:** Methodology, Investigation, Formal analysis, Data curation. **José E. Santos:** Data curation. **Orlando T. Silveira:** Methodology, Investigation, Data curation. **Renata Tedeschi:** Methodology, Investigation, Formal analysis. **Rafael B. Valadares:** Methodology, Investigation, Formal analysis. **Pedro Viana:** Methodology, Investigation, Formal analysis, Data curation. **Jacobus Biesmeijer:** Methodology, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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