Natural Capital of the Carajás Forests

Tereza Cristina Giannini
ORGANIZATION

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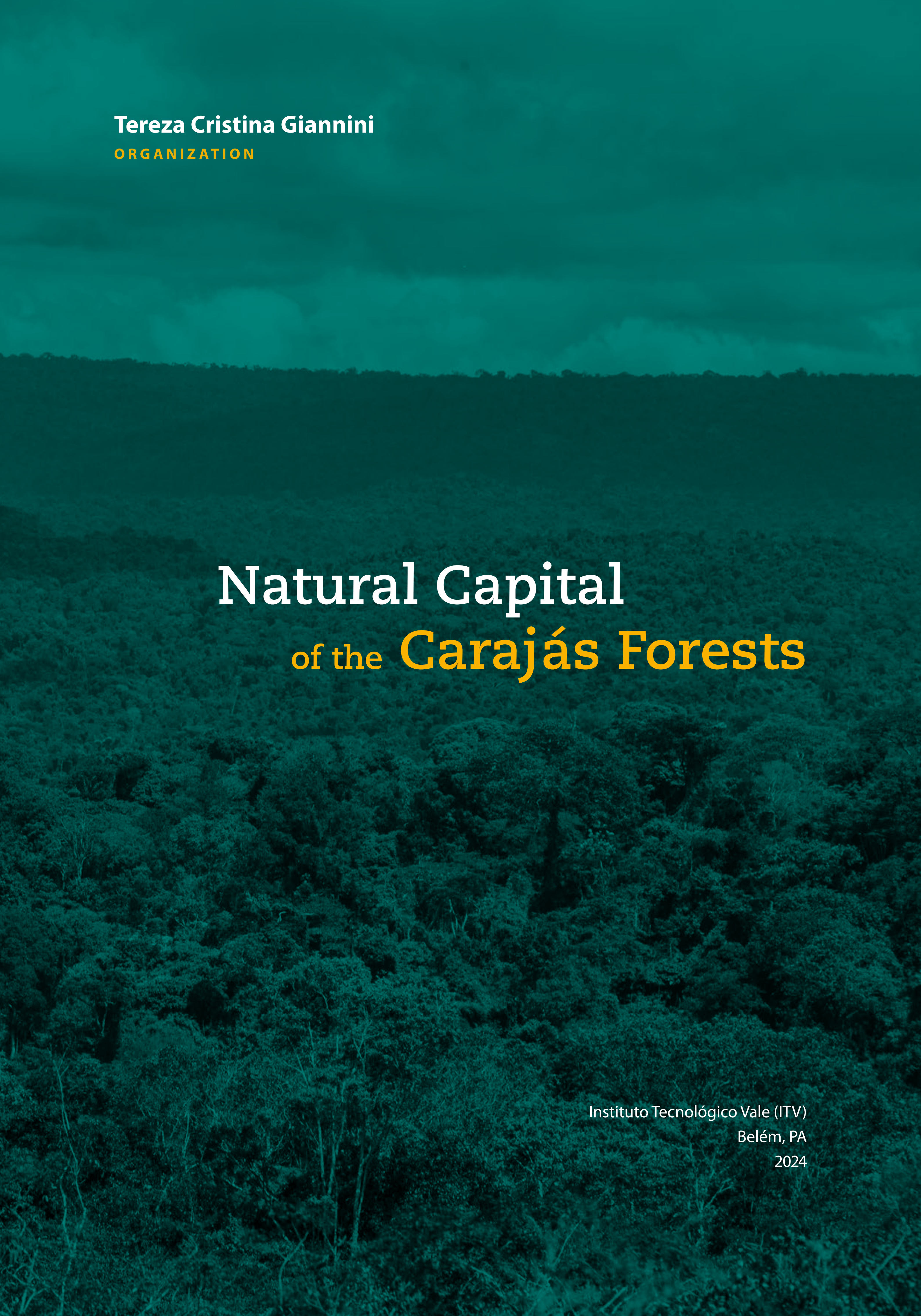

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Instituto Tecnológico Vale (ITV)
Belém, PA
2024

Summary

Ecological functions that maintain the forest

Benefits of the forest for human well-being

Contributions to conservation and mitigation of the global changes

The importance of the scientific collections as evidence of biodiversity

Presentation

Guilherme Oliveira

Valuing the stock of natural resources, or natural capital, has become increasingly more relevant in discussions about the preservation of nature. The integration of environmental and socioeconomic data strengthens a more comprehensive and multifunctional view of the interrelationships between stocks of environmental assets and the direct and indirect benefits they bring to humanity. The notion of strong sustainability assumes that the human well-being depends on the benefits provided by certain forms of natural capital stored in nature, so that the use and management of this capital must be conducted without exceeding its renewal rates.

The concern about not exceeding planetary limits is global, especially in a scenario of quick change, such as that arising from the climate crisis. At the 2022 United Nations (UN) Biodiversity Conference in Montreal (COP15), one of the objectives was to strengthen the commitment to stop the biodiversity loss by 2030 and institute a new global plan to distribute resources for nature conservation and the restoration. Already in 2023, at the UN Climate Conference (COP26) in Glasgow, a joint statement for nature, people and the planet was signed, in which multilateral development banks committed to expanding the positive investments for nature, i.e., the investments whose gains in terms of biodiversity protection and restoration are strengthened, in addition to supporting their client countries in achieving their biodiversity targets. A central commitment of this joint statement was to create institutional strategies to integrate nature and biodiversity in the investments, operations and consulting services in the private and public sectors. However, to comprehend this stock of environmental resources and their relationship with benefits is still a challenge which has to be addressed so that such resources can be valued objectively.

This book brings the fruits of the project "**Natural capital of the Carajás forests**", which was born at ITV trying to understand the multiple aspects of the stock of natural resources that make up a standing forest. Furthermore, it is also known that tropical forests produce a series of benefits for people, such as, for example, the regulation of the local climate and the protection of the water resources, among others. So, the project aimed to answer two classes of questions: what would be the fundamental elements to characterize a tropical forest in the Amazon biome? Which of these elements deliver benefits to people, and how to value these benefits?

Thus, based on this dual approach, a broad field survey was started, which lasted for almost five years. The idea was to have results based on data collected locally, as there are still important knowledge gaps about the forests. The data collection is a fundamental pillar in the scientific research, because results based on empirical data build solid and reliable knowledge. On the other hand, the field work is also a challenge. For example, it is very difficult to access forests, and most of the days are rainy or foggy, which the work unfeasible. However, the work in the field holds many surprises which, when discovered, make all the effort worthwhile.

The book you now hold in your hands seeks to describe the process of assessment of the natural capital stored in the Carajás forests. It describes the path followed within the project, from the development of the key questions that guided the project at the beginning, to the consolidation of the results, conclusions and main findings. The presented texts do not intend to have the last word about the subject, but, as it is common in science, they aim to present some answers and raise other questions which will inspire new works seeking deeper knowledge about the tropical forests.

As a central benefit, by reading the text and observing the photos presented throughout the pages, you will be provided with a glimpse of the complexity of the research within a forest environment in the Amazon biome. Furthermore, along the reading, it will be possible to realize the incredible diversity of nature and how difficult it is to map this diversity, especially when the environment complexity represents a key environmental feature. And finally, it enables comprehending how nature and human well-being are inseparable. The benefits of nature for people are multiple, and bring the perception that the value of the natural capital stored in standing forests cannot always be measured using conventional methods. On the contrary, this value must also reflect the value of the very existence of both nature and the people who depend on it. Therefore, this book aims to be a good companion for anyone dedicated to deepening their knowledge about the relationship between people and nature, comprehending the points of connection and the complexity behind them.

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Natural Capital concepts and metrics

Tereza Cristina Giannini

Definition of Natural Capital

In its broadest definition, capital refers to the stock (or assets) of resources or wealth which can be used to generate income or produce goods and services. For example, economic capital is the most tangible form of capital, because it refers to money or other assets which can be used to invest in businesses or other enterprises. On the other hand, human capital, for example, can be considered less tangible because it refers to the set of existing knowledge and skills which also generate values. Within this context, natural capital is defined as the stock of resources (in this case, natural) which support different ecosystem functions, responsible to maintain the performance and the organization of the complex natural systems, giving rise to a flow of goods and services (Bateman & Mace, 2020). The relationships and the values underlying this concept are not easily translated into financial terms, given the nature and the complexity of the interconnections between the ecosystem elements. However, this concept must be systematically integrated in decision-making (Farrell et al., 2022). Natural capital approaches make the underlying values of nature clear, and such concept is supported by a cross-disciplinary vision, making the cooperation between scientists and decision makers in rural communities, governments and the private sector easier.

As highlighted above, ecosystem functions and services are two key concepts in the assessment of natural capital (Mace, 2019). The functions point to the intrinsic characteristics of the ecosystem, which represent the set of ecological processes by means of which the ecosystem keeps its integrity (Spangenberg et al., 2014). On the other hand, the services refer to the benefits nature provides for people (Daily, 1997), the flow of which is derived from the functions, which, finally, derive from the degree of integrity of the stock of resources (La Notte et al., 2017). This distinction is fundamental in the assessment of natural capital, because despite the emphasis on the ecosystem services, it is necessary to understand which aspects are key to maintaining the adequate performance of the analyzed ecosystem; thus, guaranteeing the provision of these services.

The distinction between natural capital and ecosystem services is well defined. As stated above, natural capital is more directly related to the idea of stock and refers to the elements that describe the state of an ecosystem, and the services that are made available by this stock over time (La Notte et al., 2017). However, many assessments consider natural capital as equivalent to services, once the provision of benefits for people is the main way to understand the value of natural capital. However, it may be a mistake to confuse the stock (capital) with the flow of services, as there is no direct linear relationship between the two. In other words, the services are provided and made available by the combination of functions that support and are derived from this stock; therefore, a restricted focus on the services does not guarantee the assessment of all involved elements (Mace, 2019).

Biodiversity, Sustainability and Natural Capital

Biodiversity is the basis of natural capital and is inextricably associated with sustainability in such a way that the loss of biodiversity breaks the association between environment, society and economy, in addition to leading to risk to sustainability (Barbier, 2019). This derives from the central role of biodiversity, which is directly associated with the stability of the ecosystems; these are the direct sources of resources (natural capital) and the flow of which generates ecosystem services (Mace et al., 2015). Probably the most important contribution of assessing biodiversity from the point of view of natural capital consists in re-dimensioning the relationships between people and nature, an essential step towards building a sustainable future for humanity (Dasgupta, 2021).

The needs of human societies have been met by using natural capital as it has the potential to generate wealth and well-being through the transformation of its assets into human and/or economic capital. However, if the natural capital assets are not maintained, the flow of services may be depleted, leading to a non-sustainability situation. This gives rise to the idea of critical natural capital, which defines the assets that cannot be replaced and the loss of which, is irreversible and irremediable. In this context, their protection becomes essential to guarantee sustainability (Ekins et al., 2003). Therefore, sustainability directly depends on the maintenance of the natural capital stock, and an excessive decline in this stock must be avoided. Within this context, when the provision of human well-being over time is achieved by replacing natural capital (e.g., ecosystems) with human and/or economic capital (e.g., infrastructure, technology), without robust analyses of the critical limits associated with the irreversible degradation of the natural resources, sustainability is considered weak (Barbier, 2019). On the other hand, strong sustainability is related to the perception that there are limits for natural capital to be replaced by other forms of capital, and that certain (critical) stocks have to be maintained to support the provision of human well-being. Global analyses involving the industrial sector and agriculture have revealed that the degree of substitutability of natural capital by other forms of capital may be lower than expected, which requires more robust decisions in public policies aimed at its protection (Cohen et al., 2019).

Metrics

Natural capital has been assessed since the 1990s, analyzing different aspects of the ecosystems (Mason et al., 2022). The metrics have included biotic and abiotic factors, and should preferably also focus on functions and processes involved in the ability of nature to persist (Mace, 2019). Therefore, to assess natural capital based on biodiversity data of preserved areas is not a trivial task.

There is no standardized protocol to enable practical application of the concept of natural capital, or which enables data-based assessment that considers the complexity of biodiversity (Fleming et al., 2022), especially for mega-diverse tropical forests and in countries with important knowledge gaps about biodiversity, like Brazil. However, such assessment is a fundamental subsidy for several private sectors, as well as the Federal Prosecution Office, and other actors involved in impact mitigation. Furthermore, such assessment, as above mentioned, is a direct part of the concept of sustainability, an important target for private sector companies and governmental institutions. Finally, to incorporate the notion of natural capital can guide decision-making processes towards innovation, new markets and partnerships, and result in important opportunities for the sustainability of natural areas (Ruijs & Egmond, 2017).

To address this challenge, a methodology was developed and applied to the Carajás National Forest (Pará), mainly based on the collection of empirical data in 14 sampling points (Figure 1).

The metrics used were divided into two categories: functions and services (Figure 2). The ecosystem functions were used to aggregate the processes associated with the ability of nature to persist as a living forest (“nature for itself” in Figure 2). The ecosystem services are related to the benefits of nature for human well-being (“nature for people” in Figure 2).

Five metrics were used to analyze the functions: species richness, species interaction, resilience, irreplaceability and threatened species (Table 1). Five metrics were also used to assess the services: crop pollination, climate regulation, water protection, uses of trees by traditional communities and carbon stock (soil and vegetation).

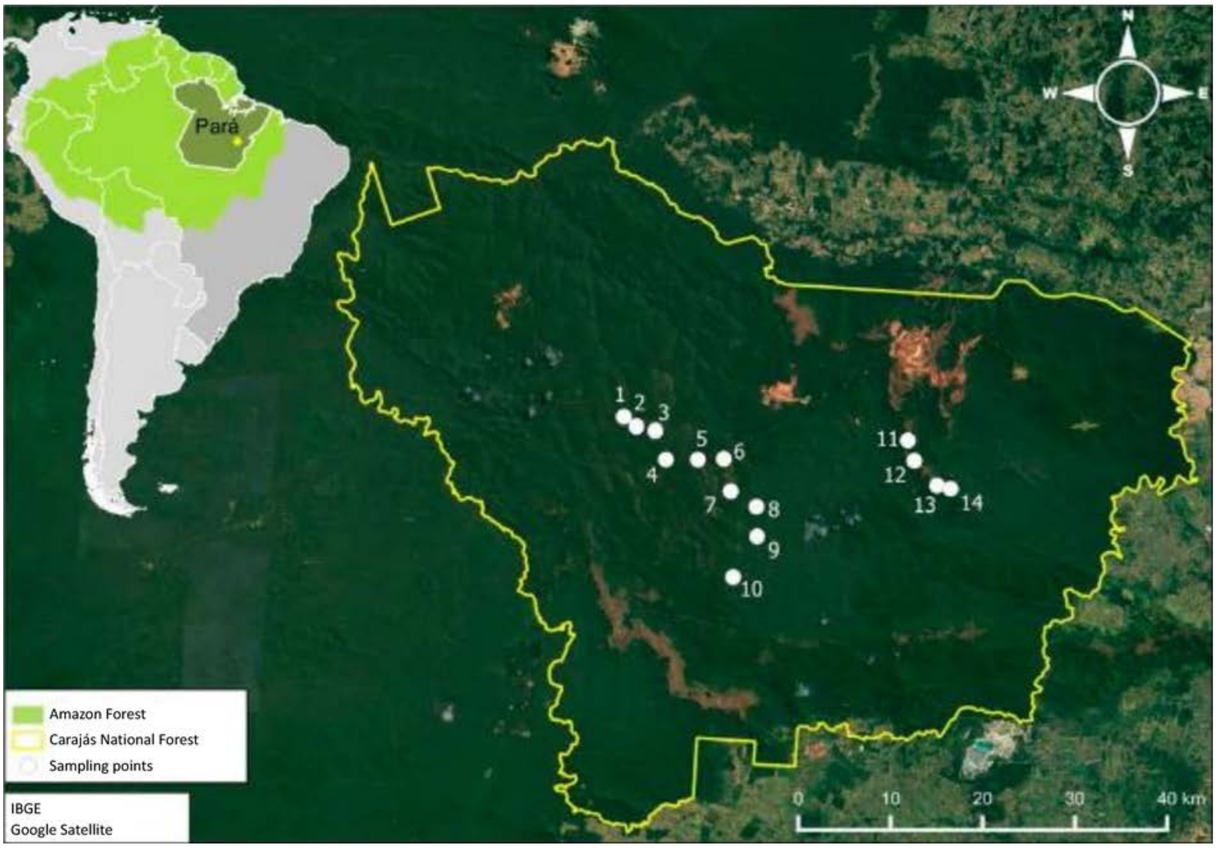

Figure 1. Sampling points in the Carajás National Forest (Pará).

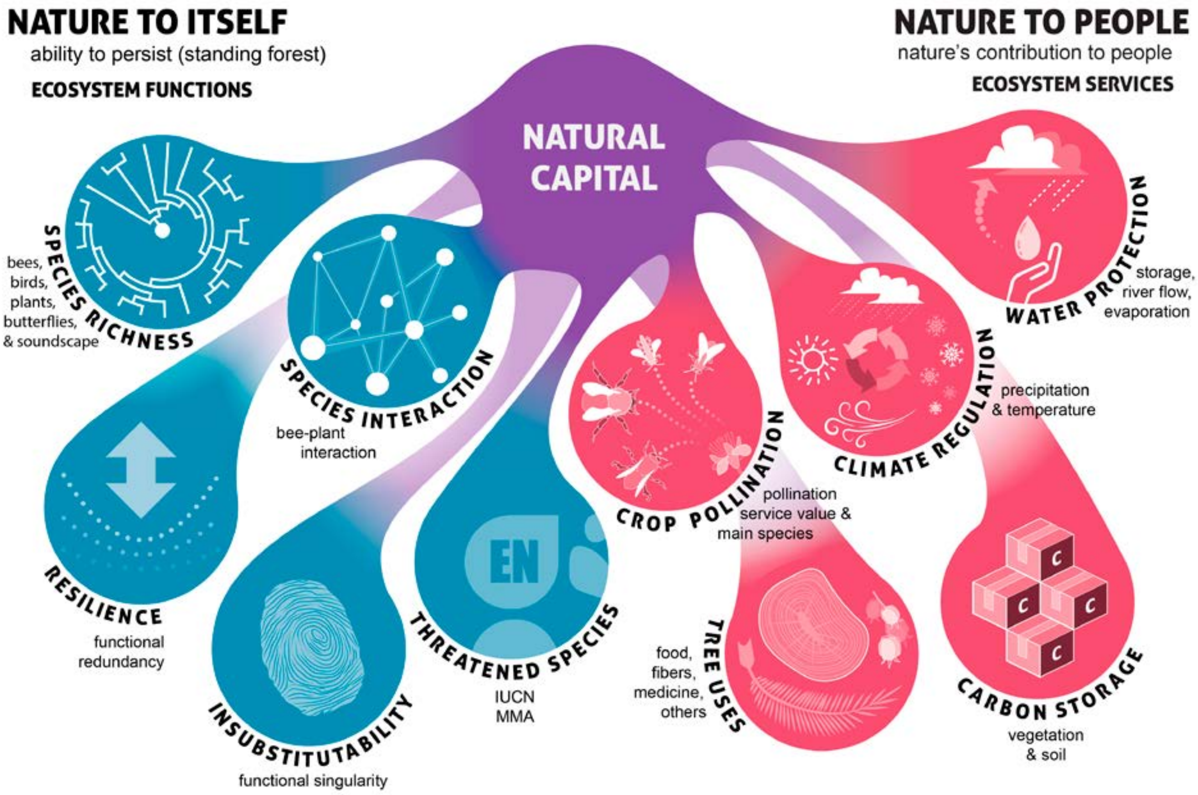

Figure 2. Representation chart of the analyzed metrics.

Table 1. Metrics used to assess the natural capital of the Carajás National Forest, considering the ecosystem functions (blue) and services (pink).

🔵	*Species richness:* number of collected/recorded species of birds, butterflies, bees and plants at the sampling sites. The birds were identified using recorders and by recognition of their songs by specialists.
🔵	*Interaction between species:* number of interacting species (diversity of interactions) in interaction networks, formed by floral visitors (bees) looking for food resources in plants in the sampled areas.
🔵	*Resilience:* metric that assesses the impact of the loss of species, based on the concept of functional redundancy, i.e., the redundancy of specific characteristics that determine specific roles of the species in nature.
🔵	*Insubstitutability:* metric that assesses the impact of the loss of species, based on the concept of functional uniqueness, i.e., based on specific unique characteristics of the species that cannot be replaced if they are lost.
🔵 EN	*Threatened species:* number of species collected in the sampling areas which are considered threatened and the loss of which is irreversible. The lists of the International Union for Conservation of Nature (IUCN) and the Ministry of the Environment (MMA) were consulted.
🔴	*Agricultural pollination:* focus on species of agricultural pollinators that help in the production of fruits and/or seeds used as food in the surroundings of Carajás and the valuation of the pollination service for agriculture.
🔴	*Climate regulation:* the role of the forest in local climate regulation was assessed through simulations with climate data modeling, considering the changes in the temperatures and the rainfall in scenarios of total and partial forest loss.
🔴	*Water protection:* the role of the forest in the water protection was assessed through simulations with hydrological data modeling, considering changes in evapotranspiration and comparing with nearby deforested areas.
🔴	*Uses of trees by traditional communities:* the list of plant species sampled during the project was assessed considering their uses by traditional communities. Twelve uses were considered.
🔴 C	*Carbon stock:* the carbon storage in the soil was assessed considering soil samples from the 14 sampling points. Carbon in the vegetation was assessed in six of these points, considering the identification of plant species and height and width of the individuals.

The model described above and its metrics were developed throughout the "Carajás Forests Natural Capital" project (Figure 3) carried out at Instituto Tecnológico Vale from 2019 to 2023. The results will be presented in the next chapters. Other initiatives were born and developed throughout the project, aiming to present and discuss the natural capital of the forests, and were also included here to illustrate the inter-disciplinarity of visions and perspectives of the proposal.

Figure 3. Panoramic view of the Carajás National Forest.

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Ecological functions that maintain the forest

2

Plants of the Carajás National Forest and their functions

Caroline Oliveira Andrino, Rafael Gomes Barbosa-Silva, Pedro Lage Viana, Daniela C. Zappi, Tereza Cristina Giannini

Studies of the flora of the Carajás National Forest

The Carajás National Forest is part of one of the largest and most complex tropical ecosystems in the world. It is located in the Brazilian Amazon biome, in the eastern part, situated in the context of one of the largest mosaics of protected areas in the Amazon, which shelters big diversity of plants (Mota et al., 2018). The region is famous worldwide for its iron deposits, found in the open vegetation ecosystems of ferruginous outcrops, or cangas, as these vegetations are also called. The cangas are well documented from the point of view of knowledge about their flora, following the success of the Carajás Canga Flora project. From 2015 to 2018, a partnership established between Instituto Tecnológico Vale and Museu Paraense Emílio Goeldi (MPEG), listed, described and illustrated more than a thousand species of terrestrial plants in the rupestrian canga fields (Oliveira-da-Silva & Ilkiu-Borges, 2018; Mota et al., 2018; Salino et al., 2018). However, the composition of the Carajás National Forest is mostly forest, and there was little information available about this forest vegetation until the completion of the Carajás Canga Flora project. The knowledge of the floristic composition of these forest areas is fundamental, as they are important elements in the delivery of ecosystem services that help maintain global biodiversity, such as shelter and food for a wide variety of species, retention and storage of carbon, regulation of the soil processes, such as fertility and erosion, supply of fresh water, fiber and medicinal resources, as well as regulation of the climate and the quality of air. The forest also shelters a variety of species with economic and cultural importance, from wood used in industrial applications to traditional resources used for the subsistence of the local communities. Considering that the plants contribute differently from each other considering these factors, and that their abundance and rarity in the ecosystem also influence their role, it is necessary to know this composition in order to understand these contributions.

In this context, new efforts have been concentrated in the last years to understand the forest composition of Carajás, increasing the collection in the forest areas and documenting all records from the region deposited in herbaria. In addition to random collections, important for documentation of rare species, six permanent plots were delimited in different types of vegetation, totaling 1.2 hectares of forest, where data were collected from all individuals with circumference at breast height (DBH). above ten centimeters. All individuals were marked with stainless steel tags containing QR codes (or QRCode), and data was collected about height, DBH, georeferenced location, samples for botanical identification, samples for DNA extraction for genetic and population studies, as well as functional traits of each species.

Richness of woody plants

In each type of forest vegetation, there are species considered more dominant, while others are more rare. The records in the areas of permanent plots revealed 348 species (2,278 specimens) of woody plants. The cataloging of herbs, trees and shrubs in the Carajás National Forest comprises more than a thousand species in the forest areas alone. Among the most abundant and rich woody plants in the permanent plots, there are the Rutaceae, Fabaceae, Burseraceae, Sapotaceae and Myrtaceae families, which total more than a thousand individuals and 130 species. Considering all the forest formations in Carajás, the dominant species in the forest are *Esenbeckia grandiflora* Mart. (Rutaceae), *Rinorea riana* Kuntze (Violaceae), *Combretum laxum* Jacq. (Combretaceaae) and *Metrodorea flavida* K.Krause (Rutaceae). Most of these dominant species are in the forest understory, where there is also the greatest richness of woody plants, with 70% of the species recorded, unlike the canopy stratum, with smaller richness of species. Thirty percent of the 348 species found in the 1.2 hectares sampled in Carajás are represented by just one individual each, i.e., many species have sparser distribution in Carajás, becoming rarer locally, half of them are endemic to the Amazon (Flora and Funga do Brasil, 2023). Considering the use by traditional communities mentioned by Salomão et al. (2007), for 42% of the species identified in the inventoried plots, there is some kind of use.

The woody plants in the Carajás forest formations form true networks of interactions with animals which are fundamental both for the forest maintenance and for the environmental services and functions the forest offers us. Among these services, pollination and seed dispersal stand out, examples of ecological interactions that both guarantee the reproduction of the plant species and offer different resources to animals in this interaction. Among the forest species, around 94% are pollinated by insects, almost half of which are pollinated by bees. Other prominent pollinating insects, after the bees are moths and butterflies, and finally, beetles. Pollination by bats and birds is also recorded, less frequently, as well as pollination by wind. To what refers to seed dispersal, the biggest dispersers of the Carajás flora are the mammals, which disperse around 30% of the species, followed by birds, the second biggest seed disperser. Autochory and anemochory dispersal, i.e., carried out by the individual himself or by the wind, are also recorded.

Forest vegetation of the Carajás National Forest

As the Amazon shelters different types of forest (and non-forest) vegetation, in Carajás, the forests are also diversified. One of the main types is the open rainforest (Figure 1), characterized by large trees, plants with evergreen leaves, understory predominantly composed of lianas, palm trees, *Phenakospermum* and/or bamboo. These species contribute to a discontinuous canopy, which enables high incidence of light. These characteristics mean that, when you look more closely at most of the forest, it is possible to see areas with many sparse trees covered by large cluster of lianas.

Another important forest formation is the seasonal semi-deciduous forest, characterized by medium and (few) large trees, not widely spaced, dense understory, composed of many lianas (Figures 2 and 3), and well-distinct vegetation according to the climate season, as the plants lose their leaves in the dry season.

Figure 1. Aerial view of the canopy of an open rainforest area.

Open rain forest

The open rainforest is the predominant forest formation in the Carajás National Forest, which ranges from the lowest areas to seven hundred meters of altitude. Most of the regions sampled in the forest belong to this phytophysiognomy.

The individuals from the tallest trees and with the largest circumferences at breast height are found in the open rainforests. The individuals of emerging trees with the largest circumferences found in these forests at altitudes ranging up to 450 meters were those of *Bertholletia excelsa* Bonpl., the Amazonian Brazil nut tree, ranging from 370 to 440 centimeters DBH. In the highest regions of Carajás, the species with the largest recorded circumferences corresponds to individuals of *Erisma uncinatum* Warm, which ranged from 100 to 630 centimeters DBH. The tallest trees are of the species *Marlimorimia psilostachya* (DC.) L.P. Queiroz & Marc.F. Simon and *Virola michelii* Heckel 40 meters high, *Bertholletia excelsa Bonpl*. and *Enterolobium schomburgkii* (Benth.) Benth, 38 meters high and *Aniba canelilla* (Kunth) Mez 36 meters high.

In these forests, we also found the largest number of threatened species, with two species classified as Endangered (EN) and four in the Vulnerable category (VU)

Figure 2. Open rainforest with lianas dominating the understory towards the canopy.

Figure 3. Example of liana in the Carajás forest.

Figure 4. Open rainforest with bamboos of genus *Merostachys* (Poaceae).

according to the International Union for Conservation of Nature (IUCN, 2023) and/or CNCFlora (Martinelli and Moraes 2013). These species are the Brazil nut tree *Bertholletia excelsa* Bonpl. (VU), yellow ipe *Handroanthus serratifolius* (Vahl) S.Grose (EN), courbaril *Hymenaea parvifolia* Huber (VU), *Pachira tocantina* (Ducke) Fern. Alonso (EN), *Pilocarpus carajaensis* Skorupa (EN) and *Pradosia granulosa* Pires & T.D.Penn (VU).

Open rainforest with bamboo

The open rainforest with bamboos has the understory predominantly made up of arborescent bamboos, which leads to reduction in other species in this stratum, and the trees are even more spaced and the canopy discontinuous. Among the tree species, the most common recorded in this vegetation are *Esenbeckia grandiflora* Mart., *Aparisthmium cordatum* (A.Juss.) Baill., *Metrodorea flavida* K.Krause and *Anaxagorea brevipes* Benth. The most common lianas of this vegetation are of genera *Tynanthus* Miers and *Coccoloba* P.Browne (Bignoniaceae and Polygonaceae). The bamboos that form these forests belong to genus *Merostachys* and are

composed of two new species, i.e., not yet described (Figure 4). These bamboos can also be found in other forest formations in canga, although of lesser abundance. In Carajás, there are bamboo forests mainly in higher altitude regions, such as on the roads on the way to the mine of the Alemão/Igarapé Bahia Project and mainly in the forests between Cangas da Serra Norte (N5, N6 and N7). A new species of bamboo (known as taboca) was recently described for this region (genus *Guadua*) (Afonso et al. 2023).

Figure 5. Forest area of the Carajás National Forest with a patch of seasonal semi-deciduous forest. Above: photo taken during the rainy season, and Below: photo in the dry period, showing the deciduousness of the leaves.

Figure 6. *Lindackeria paludosa* flower, a tree in the understory of the Carajás National Forest.

The plants with the largest circumferences and height of this vegetation are the same as those found in areas of open rainforest without bamboo, *Erisma uncinatum* Warm. and *Marlimorimia psilostachya* (DC.) L.P. Queiroz & Marc.F. Simon, respectively.

In the bamboo forests, the following species were registered *Handroanthus serratifolius* (Vahl) S.Grose (EN), *Pouteria krukovii* (A.C.Sm.) Baehni (VU), *Pradosia granulosa* Pires & T.D.Penn. (VU), all endangered according to the International Union for Conservation of Nature (IUCN, 2023) and/or CNCFlora (Martinelli and Moraes 2013).

Seasonal semi-deciduous forest

The seasonal semi-deciduous forests (Figure 5) are frequent vegetation in the southwest of Carajás, mainly on the road towards Serra Sul. These are forests that range from 350 to 620 meters of altitude. From July to October, dry months, it is possible to notice the high loss of leaves in many plant species.

In these forests, there is higher frequency of individuals of *Casearia ulmifolia* Vahl ex Vent., *Margaritaria nobilis* L.f., and *Bauhinia piresii* Vaz & G.P. Lewis, in addition to liana *Combretum laxum* Jacq. and genus *Fridericia* Mart. emend L.G. Lohmann (Bignoniaceae). Among these most abundant species, *Bauhinia piresii* deserves highlight, a tree species described in 2015 for the region of the Environmental

Figure 7. Big tree (*Virola michelli*) inside the Carajás forest.

Protection Area of Igarapé Gelado, outside the limits of the Carajás National Forest, and which was found within this forest in large populations during our recent collections. The presence of *Lindackeria paludosa* (Benth.) Gilg also stands out in the understory (Figure 6).

There are few trees that stand out with great circumferences and heights in these forests, one of them is *Senegalia polyphylla* (DC.) Britton & Rose, one of the few plants with greater circumference. One of the tallest in the semi-deciduous forest of Carajás is *Anadenanthera colubrina* (Vell.) Brenan.

In the semi-deciduous forests of Carajás, some threatened species are found, such as *Dalbergia spruceana* Benth. (VU), *Cedrela fissilis* Vell. (VU), *Sorocea guilleminiana* Gaudich. (VU), *Pilocarpus carajaensis* Skorupa (EN), *Pachira tocantina* (Ducke) Fern. Alonso (EN), *Handroanthus serratifolius* (Vahl) S.Grose (EN). Thus, the importance of the protected forest areas to safeguard these species and protect the natural capital assets stands out (Figure 7).

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3

Fauna and its functions

Rafael Cabral Borges, Ulysses Madureira Maia, José Eustáquio dos Santos Júnior,
Amanda Paracampo, Sidnei Dantas, Leonardo de Sousa Miranda, Tereza Cristina Giannini

The animals have an intrinsic relationship with human beings. From childhood to adulthood, they occasionally attract the attention of people, who stop to observe, interact or even care for animals, appreciating their colors, shapes and varieties. However, it is not always recognized that many animals have crucial functions and roles within nature, also contributing to different ecosystem services.

The sampling of the Natural Capital project was carried out at 14 points (see Figure 1, Chapter 1) in the Carajás National Forest (Flona) and aimed to assess the fauna (birds, bees, wasps and butterflies) and the ecosystem functions performed by them. This chapter provides a summary of the results achieved in the project.

Species of the sampled fauna

Birds – sounds of the forest

The birds are striking animals that attract the attention of most people due to their colors, their size, their movements, and especially, their sounds. It is no surprise that this is one of the most well-known and studied groups of animals on the entire planet. Bird watching is a common practice, used as a scientific tool, leisure activity and environmental education tool. Among the benefits of this hobby, there are the improvement of the observers' mental health and the environmental education of the people in the surrounding area, as the birds draw attention to the relevance of the natural environments. The birds perform important functions in nature, as they participate in several ecological processes, which cover parts of the reproductive cycle of plants, through pollination and seed dispersal, pest control and nutrient cycling.

The birds of the Carajás forest are well known (see Chapter 4), considering that this is one of the best studied areas in the Amazon. In this project, recorders were

Figure 1. Curica-uruba (*Pyrilia vulturina* Kuhl, 1820).

used to capture the sounds of the forest (see Chapter 5), which enabled the identification of 292 bird species. This is an effective methodology that assures obtaining large sets of standardized and simultaneous data, in addition to reducing the risk and the effort for the involved researchers. Some illustrious presence can be found, such as screaming piha (*Lipaugus vociferans* Wied, 1820), a species that indicates environmental quality; white bellbird (*Procnias albus* Hermann, 1783) considered the loudest vocalizing bird in the world (Podos and Cohn-Haft, 2019); vulturine parrot (*Pyrilia vulturina* Kuhl, 1820) (Figure 1), which is classified as vulnerable on the list of endangered birds in Brazil; and the harpy eagle (*Harpia harpyja* Linnaeus, 1758), the largest bird of prey in South America.

Bees and wasps – the visitors of the flowers

Bees (Figure 2) and wasps (Figure 3) constitute the main groups of floral visitors. When visiting flowers, the bees collect their food resources (pollen and nectar) and in most cases, pollinate the plants (Ollerton, 2017), as it will be detailed below. Although people usually think of these animals as insects that form large, densely populated nests, globally, most species of bees and wasps have a solitary life habit, i.e., the female founder of the nest has no contact with its adult offspring. Field sampling was carried out using three capture methods: a) scent trap; b) use of honey diluted in water and sprinkled on vegetation (honey trap) and c) active collection with entomological nets on flowers (floral visitors).

More than 1,800 individuals of 122 species of bees and 47 species of wasps were recorded totally. Among the bees, 34 species are called orchid bees (Euglossini tribe), as the males visit orchid flowers searching aromatic essences used to attract the females. In the tropical region, a group of bees also deserves attention because they have an atrophied sting, i.e., they do not sting; That is why they are called stingless bees (they belong to the Meliponini tribe). Their colonies are managed intensively by people and are used to produce honey and other products. Among the identified species, 59 are stingless bees. These bees are social, with perennial

Figure 2. A stingless bee flying, approaching to visit a flower of *Mimosa* sp. in the Carajás National Forest.

nests and need to store food in the colony to survive the intense rainy season in the Amazon region.

Figure 3. Social wasp (*Polybia micans* Ducke, 1904) on a flower *of Heliconia* sp. in the National Forest of Carajás.

More than 60% of the total number of bee species recorded depend on cavities to build their nests, generally found in forests (for example, species of genus *Melipona*). Their size also varies, from as small as a grain of rice (about 2.5 millimeters, mosquito bees, genus *Trigonisca* Moure, 1950), to species about 4 centimeters long (bumble bees, *Xylocopa frontalis* Olivier, 1789). The body size is an indication of the flight capacity of the bee species, which can vary from just 50 meters to around 30 kilometers, visiting areas around Flona de Carajás).

Butterflies – Colors of the forest

Butterflies (Figures 4 and 5) are among the most colorful animals in the world, and the different patterns and colors on the wings of these animals attract the attention of observers and predators. Among the invertebrates, it is the most studied group and best represented in collections around the world (Pinkert et al., 2022). They have great cultural and social relevance, present in historical representations from Egypt and Greece to nowadays (Shirey et al., 2022). Furthermore, the high color diversity of the butterflies in a given area is a strong indicator of local environmental quality (Spaniol et al., 2020). Adult butterflies can eat nectar, rotting fruits, decomposing animals, sap, fungi and the minerals in mud and urine. The caterpillars eat mainly leaves.

To discover the diversity of frugivore butterflies (family Nymphalidae) in Carajás, traps with banana bait were installed at different heights of the vegetation, in the understory (approximately 1.5 meters from the ground) and in the canopy, close to the tree canopy (approximately 30 meters). This approach is necessary, as there is a niche partition of the butterfly community between the forest strata (DeVries, 2012), i.e., some species prefer the canopy, while others prefer the understory. This occurs due to the difference in environmental micro-conditions, such as small variations in temperature and incidence of light. In total, 174 individuals were recorded, belonging to 53 species. In the canopy, 25 species were recorded, and in the understory, 36. As for size, these species ranged from about 1.5 centimeters wide (*Hermeuptychia hermes* Fabricius 1775) to about 10 centimeters (*Morpho menelaus* Linnaeus 1758). Especially, we can highlight the collection of butterflies of genus *Morpho*, which attract attention due to their size and sparkling metallic color with shades of blue, which can vary between violet and green, depending on the way the light falls on their wings and our angle of vision.

Although this is well-studied area, Carajás can still reveal a lot of unknown diversity, for example, the species *Amphidecta calliomma* Felder 1862, which was recorded for the first time in Carajás during the collections for this project and constitutes the utmost east record ever made for this species in the Amazon (Paracampo et al., 2023).

Examples of functions of the registered fauna

Figure 4. Butterfly collected in Carajás of the species *Dryas iulia* (Fabricius, 1775).

Many ecological processes and ecosystem functions occur thanks to different forms of interaction. Such interactions can occur between organisms of different species or between organisms of the same species, they help to shape and maintain the complexity in the biodiversity of the ecosystems (Berlow et al., 2009).

Networks of interactions between bees and plants

In the context of the Natural Capital project, the interaction between flowers and their visitors (bees) was recorded. All flowers which were open during the sampling period were observed, and bees were collected with an entomological net. 480 interactions were recorded, which occurred between 57 species of bees and 73 species of plants. An interaction network metric was used to understand the diversity of interactions between plants and bees in each of the sampled areas. Interaction networks help in the analysis of networks formed by multiple partners, in which connections are established between those who interact with each other (Kaiser-Bunburry and Blüthgen, 2015). The diversity of interactions is a common metric that indicates the number of connections, i.e., the higher the index, the more different partners the network presents. The average diversity of interactions calculated, considering the 14 sampling points, was 2.8 (ranging from 1.9 to 3.6), and no significant differences were found among the points, showing the stability of the diversity of interactions.

Figure 5. Butterfly collected in Carajás of the species *Eryphanis automedon* (Cramer, 1775).

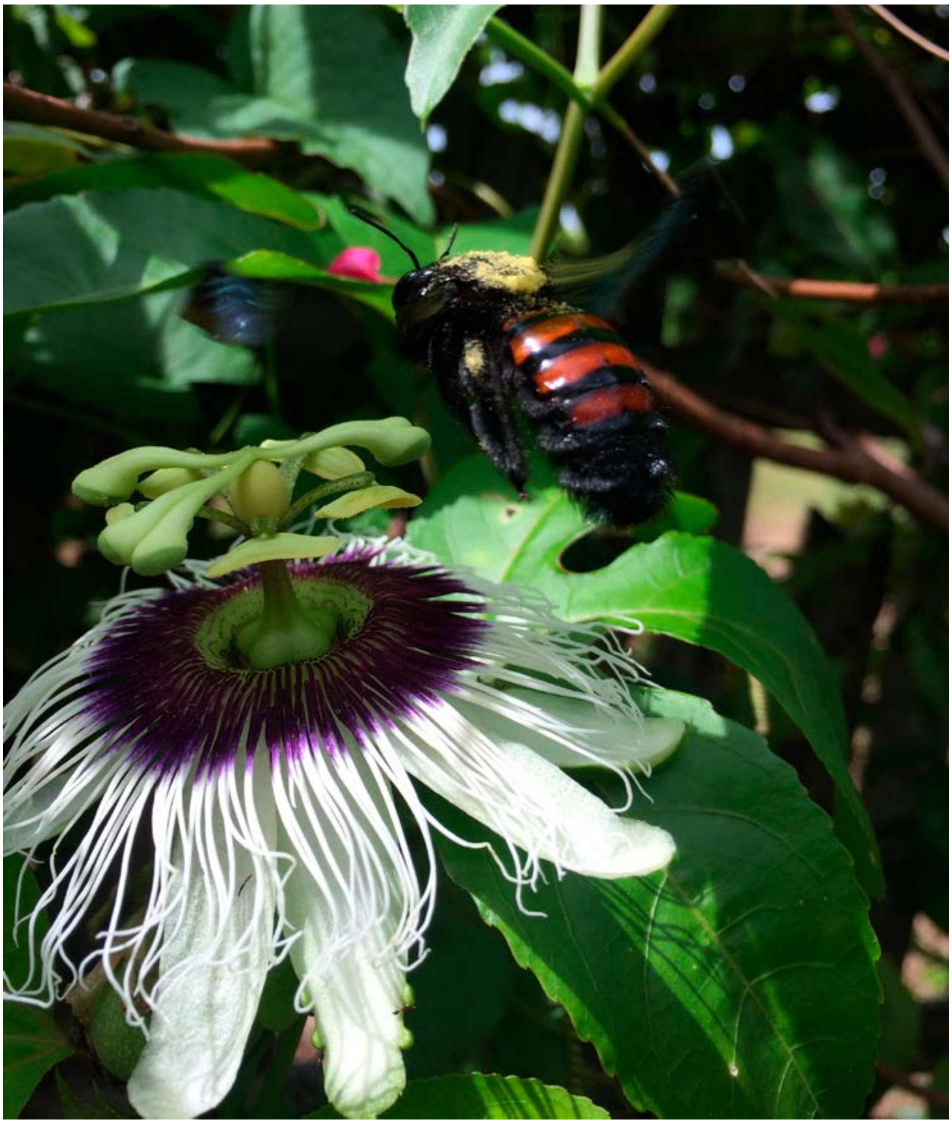

Figure 6. Bumble bee (*Xylocopa frontalis*) visiting passion fruit flower.

Pollination

Animal pollination is an important ecosystem function, because it is necessary to assure the reproductive success and genetic variability of about 80% of the flowering plants (Ollerton, 2017). In pollination, the plants need a vector to transfer male gametes to female gametes; very often, this vector that moves between the flowers is an animal. Animals, in turn, are attracted by important resources, such as nectar, pollen, essences or oil. In Flona de Carajás, important groups of pollinators were recorded, including 117 species of bees and 10 species of birds. Pollination is particularly important for food production, with great emphasis on the role of the bees in the productivity of the agricultural crops (Figures 6 and 7). See also Chapter 13, where this topic will be detailed.

Figure 7. Stingless bees in açaí flowers.

Seed dispersal

Seed dispersal is a fundamental function for the maintenance of the plant species. The plants can disperse and occupy the forest habitats through the transport of the seeds. The birds are one of the most relevant groups of animals responsible for the seed dispersal. When feeding on fruits, they end up ingesting plant seeds, which are not always completely digested, and are then transported and expelled in a new location, which may be favorable for their growth and development. Among the birds identified in this project, 36 species are fruit consumers, and therefore, potentially responsible for the maintenance of the dispersal of seeds in the forest.

Predation – invertivore – herbivore

In the Natural Capital project, we found birds, butterflies and wasps involved in these three functions. Most birds (70%) are invertivore, i.e., they are predators whose diet is based on invertebrates. Wasps are also predators of other small invertebrates (Figure 8), such as spiders and termites. All butterfly species collected are responsible for herbivore activities, once their caterpillars eat living leaves.

Figure 8. Nest of *Apoica pallens* (Fabricius, 1804), a wasp popularly called the marimbondo-chapéu.

Nutrient cycling and soil fertilization

Nutrient cycling occurs by transferring energy and matter from dead (or decomposing) organisms to the environment, and is also important for the maintenance of the ecosystem. In forest areas, many organisms are involved in the cycling of nutrients, which may be of plant and animal origin or may be mineral components of the soil. Among the animals recorded, a species of stingless bee (*Trigona hypogea* Silvestri 1902), seven species of wasps and two species of birds have scavenging habits, i.e., they eat dead animals as a source of protein and contribute to the nutrient cycling. The caterpillars of all collected butterflies eat tree leaves, and the adults eat fruits, thus contributing to the nutrient cycling and the soil fertilization.

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4

Birds of the Carajás National Forest and the surroundings

Sidnei de Melo Dantas, Alexandre Aleixo

Currently, Flona de Carajás can be considered one of the best-known conservation units in the Amazon regarding its bird fauna (Pacheco et al., 2007). Over more than three decades of systematized inventories and sporadic observations, a total of 646 species of birds have been recorded in and around Flona de Carajás. This number is greater than that recorded in the last exhaustive compilation on the bird fauna of the Carajás region (593 species; Aleixo et al., 2012) and reflects an additional set of species recorded in different contexts.

The continuous records of new bird species in and around the region of Flona de Carajás may be due to three main factors: 1) deforestation, with consequent availability of open habitats previously very rare or not present in the area, leading to the colonization of new species; 2) increase of the sampling effort of the local bird community, leading to the registration of species which are very rare locally and difficult to detect, as well as constant refinement of the degree of reliability of the list; and 3) description or recognition of new bird species based on integrative taxonomic studies (those that combine analyses of genetic, morphological and vocal characters) (Ribas et al., 2012, Batista et al., 2013, Portes et al., 2013, Dantas et al., 2021). The importance of the so-called Citizen Science should be highlighted to consolidate the current list, with more than 30 species recorded exclusively by bird observers participating on the platform wikiaves.com.br.

The expansion of the deforestation around Flona de Carajás, as well as the continuation of the local bird fauna monitoring inventory projects, will certainly lead to the registration of new bird species for the area. However, it should be noted that some species highlighted in the checked lists are very far from their areas of documented occurrence, such as Myiodynastes luteiventris, Lophotriccus galeatus and Odontorchilus cinereus, which may be real extensions of occurrence or identification errors. As there is a lack of document data (photos, recordings or core specimens) for these species within the Carajás mosaic of conservation units, currently, it is not possible to distinguish between these two possibilities.

Conservation, threats and perspectives

The total number of bird species recorded for Flona de Carajás and its surroundings to date (646) already makes the area the richest in birds in Brazil and one of the most diverse in the world (Pacheco et al., 2007, Aleixo et al ., 2012, Miranda et al., 2019) (https://tinyurl.com/bdhpbk4n). This results from a combination of factors, such as a high diversity of species and environments, combined with a relatively high concentration of ornithological studies. Most species recorded are predominantly associated with forest environments (around 58% or 376 species), mainly terrestrial forests. The second most important contingent of species is formed by those associated with natural open environments (28% or 184 species). Finally, the remaining 86 species (around 13%) occur predominantly in flooded and/or altered environments.

Regarding the geographic distribution, most species (463 or 72%) are widely distributed (in South America, the Neotropical region or worldwide). However, the set of species endemic to the Amazon in Flona de Carajás and surrounding areas is quite significant (183 or 28%), including four species endemic to a sector of the Brazilian Amazon, the Xingu Center of Endemism (Silva et al., 2002, 2005): *Psophia interjecta* (Psophiidae), *Campylorhamphus multostriatus*, *Xiphocolaptes carajaensis* and *Dendrocolaptes retentus* (Dendrocolaptidae).

Several factors contribute together to the registration of a high number of species with the most varied ecological profiles in Carajás. The vegetation cover is composed of varied mosaics of different types of vegetation, and the location at one end of the ecotone or transition between the Amazon and Cerrado biomes stands out. Furthermore, Carajás is entirely surrounded by a highly anthropized landscape, which includes pastures, cultivated fields, altered forest fragments and urban areas.

However, the elevated species richness of species does not necessarily imply high conservation value. This happens because, in general, species with wide distribution are less vulnerable than those with more restricted distribution, as for the endemic to the Amazon and the Xingu-Tocantins interfluve, where Flona de Carajás is located. Therefore, in addition to sheltering an extremely rich set of species, Flona de Carajás and its surroundings shelter a high number of species of special interest for conservation.

Thirty-two nationally and/or globally endangered species (MMA, 2022, IUCN, 2022) can be found in the Carajás Flona and the surrounding areas, adding another six subspecies listed as nationally endangered by MMA (2022): *Hylexetastes uniformis brigidai* (VU), *Oxyruncus cristatus tocantinsi* (VU) (Figura 1), *Lepidothrix iris iris* (EN), *Procnias albus wallacei* (VU), *Thamnophilus nigrocinereus huberi* (VU) and

Figure 1. *Oxyruncus cristatus* (sharpbill).

Figure 2. *Harpia harpyja* (harpy eagle).

Figure 3. *Hemitriccus margaritaceiventer* (pearly-vented tody-tyrant).

Phlegopsis nigromaculata confinis (VU). This number of species and subspecies of threatened birds recorded for Flona de Carajás and the surrounding areas represents a 700% increase about the previous compilation for the area, in which only four species were considered globally or nationally threatened (Aleixo et al., 2012). This happened as a direct result of the update of the List of threatened species in Brazil, which underwent two review processes in the interstice between 2012 and 2022 (ICMBIO/MMA, 2018, MMA, 2022). These revisions resulted in the inclusion of a very significant number of species and subspecies endemic or with distributions restricted to the region of the so-called "arc of deforestation", in the south and southeast of the Amazon, where Flona de Carajás and the surrounding areas are located (ICMBIO/MMA, 2018, MMA, 2022). The loss of forest habitat in the region of the "arc of deforestation" between the review periods of the List of threatened species in Brazil (ICMBIO/MMA, 2018, MMA, 2022) contrasts with the high degree of integrity of the forest ecosystem in Flona de Carajás and the surrounding areas, which represents a key area for the conservation of these species and subspecies currently considered threatened. Eastern Amazonian endemic, such as *Penelope pileata*, *Hypocnemis striata* and *Dendrocolaptes retentus* can be

Figure 4. *Hirundinea ferruginea* (cliff flycatcher).

Figure 5. *Cacicus cela* (yellow-rumped cacique).

Figure 6. *Pseudastur albicollis* (white hawk).

found relatively frequently in the area, while several other species of interest for conservation occur in naturally low densities throughout their respective distribution areas (such as *Campylorhamphus multostriatus*, *Harpia harpyja* (Figure 2) and *Xiphocolaptes carajaensis*). In addition to threatened species, Flona de Carajás also shelters populations of species with restricted distribution and local occurrence, such as *Antrostomus sericocaudatus* (Caprimulgidae), *Taeniotriccus andrei* and *Poecilotriccus capitalis* (Rhynchocyclidae), *Ramphotrigon fuscicauda* and *Rhytipterna imunda* (Tyrannidae). Other species are exemplified in Figures 3-7.

Species of birds present in the region and which attest to the good state of conservation of Flona de Carajás and the surrounding areas are the large predators (*Morphnus guianensis*, *Harpia harpyja*, *Spizaetus tyrannus*, *Spizaetus melanoleucus* and *Spizaetus ornatus*), species of high hunting value (*Tinamus spp.*, *Aburria cujubi*, *Pauxi tuberosa* and *Crax fasciolata*), large frugivores (*Ramphastos spp.*, *Selenidera*, *Pteroglossus spp.*, *Procnias albus*) and a high number of insectivore species from the lower strata of the forest considered highly sensitive to micro-climate changes (several Thamnophilidae, Conopophagidae, Grallariidae, Formicariidae, Scleruriidae, Dendrocolaptidae and Furnariidae).

The preservation of the rich bird fauna of Flona de Carajás and the surrounding areas is assured by the fact that a large part of its extension is protected by law. However, the environmental degradation of the unprotected areas surrounding the conservation units is significant, to the point that the mosaic of conservation units associated with Flona de Carajás can be considered a large forest fragment isolated from other areas with continuous forest cover. Therefore, as it has already been well documented for other fragmented Amazonian landscapes (Stouffer, 2020, Moulatlet et al., 2021), it is possible that in the future, the bird fauna of Flona de Carajás and the surrounding areas may lose some more sensitive species which are not able to maintain viable populations in isolated areas. The continuous monitoring of the local bird community will identify any trends of population decline and local extinction, providing the basis for an ongoing diagnosis of the conservation status of these species in response to a possible fragmentation effect.

After almost 30 years of ornithological studies in the region of Serra dos Carajás, it can be said that the balance in terms of knowledge acquired during this period is quite positive. The mining activity in the region led to the conservation of large areas

Figure 7. *Tyrannus melancholicus leucistico* **(tropical kingbird).**

of forest and the performance of continuous ornithological inventories at different sampling points and landscapes, leading to the recording and documentation of an incomparable number of bird species in the national context. This continuous qualified ornithological activity also provided a collection of specimens, images and recordings of vocalizations, which should be used for several systematic and taxonomic studies to validate or describe several species of birds in the future (Aleixo, 2009). At the same time, the infrastructure of the Carajás region has stimulated intense activity among bird watchers, which has opened a new front of important ornithological discoveries and allowed the region to be valued as a hub for eco-tourism in the Amazon (Pacheco et al., 2007). The future challenges for the conservation of the unique bird fauna of Flona de Carajás and the surrounding areas mentioned above will be faced successfully if the same logic that has been working successfully over the last 30 years continues to be applied: sustainable exploration of mineral resources with compensation of preservation and study of the local environment.

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5

The sound of the forest – from soundscape to landscape

Leonardo de Sousa Miranda, Ulysses Madureira Maia, Caroline Oliveira Andrino, Rafael Gomes Barbosa-Silva, Amanda Paracampo, Bruno Garcia Luize, Rafael Melo de Brito, Leonardo Trevelin, Tereza Cristina Giannini

Introduction

Sound plays an important role in the ecology of different animal species and in different types of habitats. It is widely used as a means of exchange of information in different groups of animals (vertebrates and invertebrates) and is fundamental for many ecological processes, such as reproduction, hunting or territorial defense. The propagation and the reception of sound signals emitted by the biodiversity can be affected by the structure of the habitat (in places with denser vegetation, for example, there is greater resistance to sound propagation over longer distances) or by several other emission sources, such as rain, wind, rivers and even human sources, such as cars, planes and chainsaws. Therefore, sound provides valuable information about the environmental status and quality.

Recording ambient sound in several locations simultaneously is technologically possible and relatively less expensive than the traditional environmental assessment methods. Therefore, the collection of biodiversity data from acoustic recorders is feasible and can be automated, requiring only little human intervention. Autonomous acoustic recorders can collect large amounts of data, significantly reduce costs, and avoid invasive sampling of a habitat. This methodology can detect a range of sounds produced by natural and physical phenomena, which define a soundscape by including all sounds that emanate from the habitat.

There are several ways to assess biodiversity through sound recordings. One possibility is to identify all species that vocalize. However, this methodology, if performed manually, can be labour-consuming, requiring the work of several specialists dedicated to listening to the recordings and identifying the species of interest. There are automatic ways of doing this recognition, but this implies the availability of good sound libraries, available for use in computer; however, despite the progress in the area, the records are still incomplete, which makes automatic recognition of many species difficult.

An alternative is to obtain information about biodiversity based on the characteristics of all sounds captured in an area, regardless of the species identification. For this purpose, acoustic indexes have been developed, from which significant information can be extracted quickly from sound recordings without requiring specialized knowledge. Several acoustic indexes have been developed, which are associated with different characteristics of the sound, such as frequency (whether the sound is low or high), amplitude (strong or weak) and rhythm, and can serve to characterize a soundscape (i.e., the signature sound of an environment).

Most studies carried out globally to date use acoustic data for the recognition of vocalizations associated with individual species, e.g., birds and amphibians (Moreno-Gómez et al., 2019; Rajan et al., 2019), or to test the sensitivity of the data to different types of environments (Nascimento et al., 2020); or even to assess the effects of different forms of land use and environmental degradation (Burivalova et al., 2019). However, there are still few studies that analyze the soundscape in better-preserved environments in order to draw baselines for future monitoring projects. Furthermore, little is known about how acoustic patterns behave according to natural fluctuations, especially in the Amazon rainforest.

In this chapter, we assessed different soundscape indexes obtained in Carajás using autonomous recorders. We also examined how landscape affects the acoustic patterns in different years and locations, considering different frequency ranges and times of the day and which soundscape indexes can capture complementary acoustic patterns.

Case study in Carajás

Data was collected on three occasions. The first between November 6th and 14th, 2019, the second between March 22nd and April 5th, 2022, and the third from May 10th to 18th, 2022. At each of the 14 sampling points used in the context of the Natural Capital Project, an autonomous digital recorder (Audiomoth 1.0.0; Figure 1) was placed; it was configured to make one-minute recordings at every ten-minute intervals over a whole day, during the collection events. Each recorder was at least 1.5 kilometers apart, in the forest's understory, and about 1.5 meters from the ground. We analyzed 25,551 minutes of recording in total (~426 hours) in the 14 locations.

For each minute, four indexes were calculated, selected for being commonly used in soundscape studies (Table 1). Among these, some describe the complexity of the sound signal, which were developed specifically for biodiversity assessments and landscape research, such as: (1) acoustic entropy (H) and (2) acoustic

Figure 1. Autonomous digital recorder (Audiomoth 1.0.0) used to capture sounds.

evenness (AEI). Additionally, we also calculate indexes related to physical attributes of the recordings, such as: (3) background noise (BGN); and (4) acoustic activity (AA) (Figure 2).

Table 1. Descriptive summary of acoustic indexes

Abbreviations	**Acoustic indexes**	**Descriptions and references**
H	Acoustic entropy index	In this index, the recordings are divided into one-second time slots, and the number of sound signals with different amplitudes in each of these windows is calculated. The values vary between 0 and 1, greater as there are more sounds with different amplitudes in each range (Sueur et al., 2008).
AEI	Acoustic evenness index	In this index, the recordings are divided into ten frequency bands, and it is calculated how similar one frequency band is to another. The values vary between 0 and 1, greater as the frequency bands are more unequal (Villanueva-Rivera et al., 2011).
BGN	Background noise	This index corresponds to the most common amplitude value in all frequency bands. The values were standardized to vary between -50 and 0 decibels [dB] (Towsey et al., 2014).
AA	Acoustic activity	In this index, the recordings are divided into cells of frequency bands by time bands, and the part of cells in the recording with amplitude values 3 dB greater than the background noise is calculated. The values vary between 0 and 1 (Towsey et al., 2014).

We obtained and measured environmental variables associated with the characteristics of the landscape structure and composition. We calculated (i) the distance from the collection points to the nearest body of water; (ii) the shortest distance from the points to the limits of the protected areas; (iii) the shortest distance to the nearest canga (open vegetation habitat in the form of fragments under iron rock outcrops); (iv) the shortest distance to the nearest mine; (v) the height of the forest; (vi) NDVI vegetation index for the periods of November 2019 and April 2022; (vii) rainfall; (viii) temperature; (ixi) humidity; and (x) wind speed. Data about vegetation from the six plots for the flora survey (see Chapter 2) was also used when all plants with diameter at breast height greater than 10 cm were counted.

We also use (xi) the number of trees; (xii) the number of lianas; and (xiii) the number of palm trees. These variables were chosen because they affect both

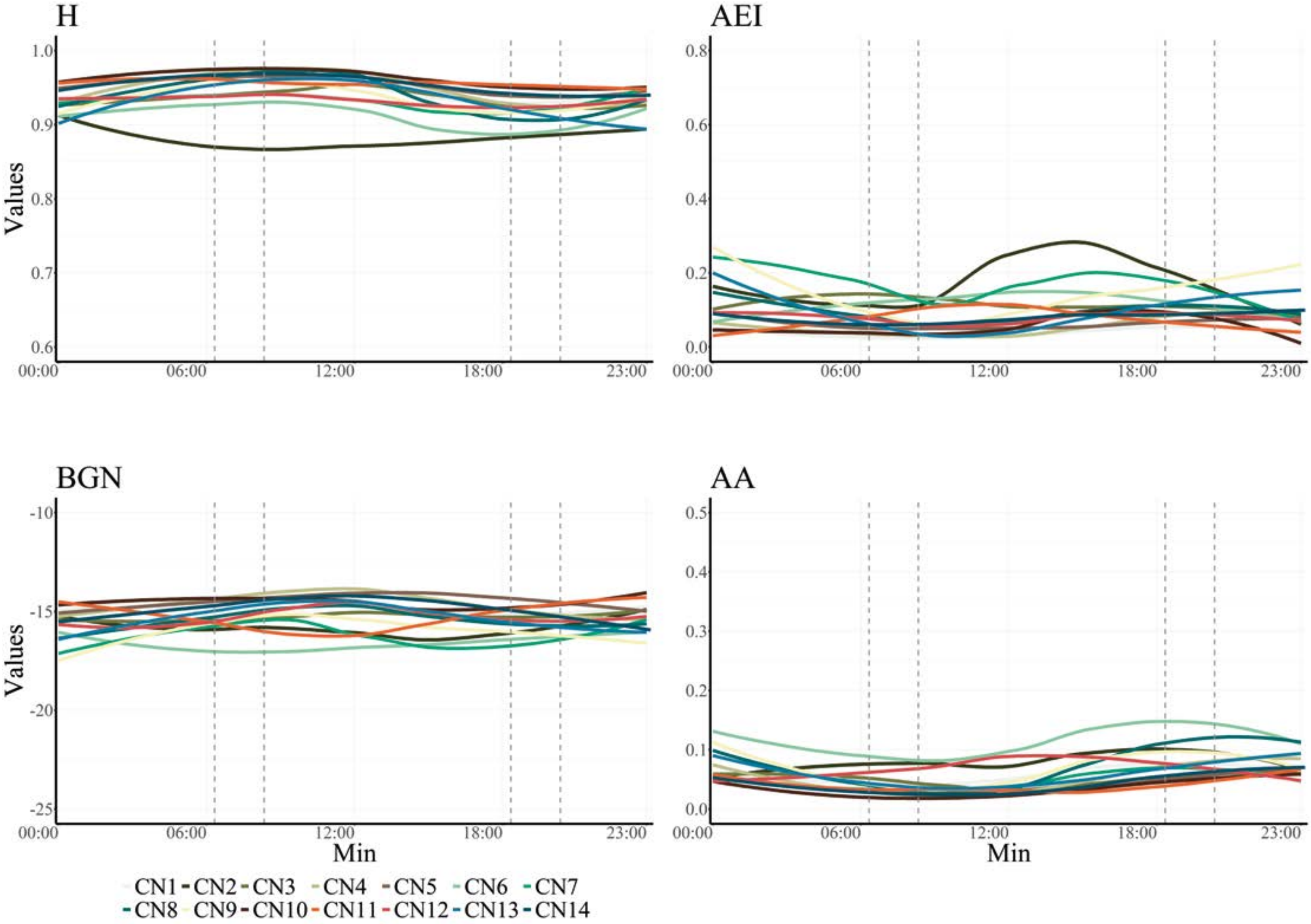

Figure 2. Acoustic entropy (H), acoustic evenness (AEI), background noise (BGN) and acoustic activity (AA) indexes obtained using sound recorders at the 14 sampling points in Carajás.

biodiversity in terms of species composition and behavior (e.g., longer distance from the edge may result in a smaller number of more specialist species; or greater rainfall may cause less vocalization activity), as well as the sound propagation (e.g., longer distance from the edge may result in less wind noise; or greater rainfall may increase the rain noise).

Our results show that the acoustic indexes vary throughout the day, and dawn and dusk have the greatest sound activity (Figure 3). Other authors had already detected that periods of the day (day and night) were relevant to detecting differences between types of natural habitats (Nascimento et al., 2020) (Figure 4).

For some recently published works, the characterization of the soundscape needs to take into account the differences in the animal activity throughout the

day and the vocalization frequencies (Metcalf et al., 2021). However, our results did not indicate variation between the frequency bands, possibly due to the similarity in the habitat structure of the sampled locations.

Our results demonstrated that the distance to a body of water, temperature, air humidity, number of trees and number of palm trees affect the sound indexes. This means that the ambient sound is spatially and temporally heterogeneous, related to the structure of the landscape and the composition of multiple species, having a specific signature of the location. This signature is directly linked to the abiotic and biotic factors, which affect the emission, propagation and reception of the sound (Figure 5).

Figure 3. Evening in the forest.

Figure 4. Moon night in the forest. Animal vocalization is rich in the forest at night.

Figure 5. Howler monkeys (*Alouatta belzebul*), which has a loud and very characteristic vocalization in the forest.

It shall be pointed out that contrary to what we expected, rainfall was a variable that did not show a significant effect on any index. Once in the study area, the levels of rainfall are high and several days of high intensity rain occurred in at least one of the campaigns, we believed that rainfall would be a variable with a very significant effect, at least for BGN; but this expectation did not materialize.

In the Amazon, the acoustic indexes obtained by autonomous recorders have already been used to discriminate habitat types based on the vegetation structure (Nascimento et al., 2020) or to assess degradation levels (Metcalf et al., 2021, Rappaport et al., 2022). All of these works were successful in demonstrating the ability of the acoustic indexes to obtain simultaneous data in multiple locations, in addition to demonstrating the power to detect effects and associations. This work consists of a first effort to develop long-term monitoring protocols in the Amazon, assessing multiple points in more homogeneous, protected and relatively intact areas, which can be used as baselines to distinguish natural fluctuations in the dynamics of the Amazon landscape from potential impacts. Works of this nature are urgent to assist the decision-making in environmental conservation.

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6

Metrics of resilience and irreplaceability in biodiversity assessment

Felipe Martello, Caroline Oliveira Andrino, Rafael Gomes Barbosa-Silva, Rafael Cabral Borges, Amanda Paracampo, Ulysses Madureira Maia, Leonardo de Sousa Miranda, Tereza Cristina Giannini

Role of biodiversity

Biodiversity encompasses all forms of diversity in the living components of the ecosystems, including the richness of species, abundance, ecological interactions, morphology and genetic variability (Girardello et al., 2019). The multidimensionality of biodiversity makes it a fundamental element at all hierarchical levels of the ecosystem functions and services, both as a regulator of ecosystem services, as a final ecosystem service, and as a valued asset, thus being fundamental to the natural capital (Mace et al. al., 2012). This complexity and the regulatory characteristic distinguish biodiversity from other types of assets, such as produced or built capital (human and/or economic capital), which can be depleted and replaced.

Natural capital supported by biodiversity is considered critical when elements of biodiversity perform essential ecological functions that cannot be replaced by other types of capital (e.g. economic capital). Although biodiversity is threatened and is the basis of all ecosystem functions and services, it is an asset often overlooked in accounting. This difficulty arises, in part, from the lack of knowledge about how the multiple dimensions of biodiversity provide benefits to humanity. Furthermore, biodiversity is commonly underestimated as natural capital, as the focus is mainly on highly valued services and benefits, ignoring other functions which maintain the forest and indirectly support services which are difficult to value in financial terms. (Mace, 2019). Thus, the need to use multiple dimensions of biodiversity in accounting for natural capital is evident, also integrating the intrinsic and irreplaceable value of biodiversity (Costanza, 2020, ONU, 2020).

Resilience and irreplaceability

In addition to its intrinsic value and its importance for the provision of ecosystem services, biodiversity plays an essential role in the maintenance of ecological resilience (UN, 2020), defined as the ability of an ecosystem to resist disturbances and maintain a certain state (Brand , 2009). Ecosystems with high biodiversity are more adaptable to changes, in part because the greater the number of species, the greater the number of ecological alternatives for adaptation to changes and impacts (Oliver et al., 2015). In this context, the morphological and behavioral diversities of the communities, known as functional traits, are one of the elementary points for ecological resilience: ecosystems with species more similar in terms of these characteristics are of high ecological redundancy, which can contribute to resilience (Ricotta et al., 2016).

Another important aspect of functional traits can be mapped to guarantee the integrity of an ecosystem and its services: functional uniqueness (Ricotta et al., 2016). This facet of biodiversity refers to how irreplaceable an organism is within the ecosystems and refers to the dimensions of functional traits shared by a few or just a single species. Such traits configure functions or services with high vulnerability to environmental changes, as they cannot be easily replaced (Ricotta et al., 2016). Taken together, these functional measures (redundancy and uniqueness) represent potential tools to assess biological values of natural capital which are still hidden and which are essential to understand the ecosystem integrity and assure the sustainable use of the natural resources in long terms (La Notte et al., 2017).

Case study in Carajás

This study assessed taxonomic and functional diversity metrics using vascular plants, birds, frugivore butterflies, and bees collected in the Carajás National Forest to infer resilience and irreplaceability. Resilience is expressed as the percentage of biological assets (richness of species) required to maintain 95% of the functional integrity of the ecosystem. Irreplaceability is represented by the percentage of this integrity supported by the unique contribution of each species.

Seven hundred eighty-one species sampled in the Carajás National Forest were used, including 348 woody plant species (Figure 1), 259 bird species, 53 butterfly species and 121 bee species. For this purpose, 2,278 tree individuals, 174 frugivore butterflies, 1,580 bee individuals and 3,677 bird songs were identified. These results show the high value of the biodiversity asset of the Carajás National Forest, as they are similar to biodiversity surveys carried out in large intact fragments in the Amazon region and historical data from Carajás in scientific collections (e.g. Borges & Carvalhaes, 2000 and Miranda et al., 2019 for birds; Araújo et al., 2020 for fruit butterflies; Rasmussen, 2009 and Borges et al., 2020 for bees).

In addition to the high diversity found, the degree of threat for each species was also analyzed, highlighting the regional importance of the Carajás Forest for biodiversity conservation. Such analyses showed that around 11% of the bird species and 8% of the vascular plant species sampled within the scope of the project are under some degree of threat (categories "near threatened", "vulnerable", "endangered", and "critically endangered" of IUCN – International Union for Conservation of Nature) (IUCN, 2023) (Figures 2 and 3). The relevance of the Carajás National Forest for species conservation becomes even more evident when considering the regional context, where the predominant landscape around the forest consists of anthropized areas. For bees and frugivores butterflies, none of the species were considered threatened. However, this result must be interpreted carefully due to the lack of knowledge about many invertebrate species and because the conservation actions focus mainly on vertebrates (Cardoso et al., 2012).

The functional redundancy analysis showed that, on average, it is necessary to maintain 83% of the biological assets to keep the integrity of the functional diversity of the Carajás National Forest. In other words, a set of species maintains the ecosystem functions even in the scenario of loss of others. This result evidences resilience supported by biodiversity as an important but neglected asset of natural capital: the capacity to forest persists, under environmental impacts, with the

Figure 1. The Brazil nut tree, standing out above the other trees in the forest.

Figure 2. Examples of species in danger of extinction in the Carajas National Forest: (A) *Pachira tocantina* and (B) *Tynamus tao* (bird known as "grey tinamou"), both considered "endangered" according to the IUCN red list of threatened species.

same functionalities. Despite the lack of studies that apply functional redundancy (or other similar indexes) in natural capital accounting (Smith et al., 2017), it is necessary to include this component in studies of critical natural capital assets (Mace, 2019). From an economic point of view, it is easy (however, incorrect) to believe that there is a percentage of biological assets (17%) which can be interpreted as a "value reserve", i.e., assets that serve as protection against market variations for the investors to protect their net assets (Mankiw, 2012). However, biodiversity is different from other types of economic assets: the biological assets self-regulate, reproduce, interact and evolve without human action. This characteristic adds an important synergistic potential to the natural capital: the conservation of biodiversity above a critical limit enables the natural capital to increase both quantitatively, increasing the local biological populations and their resilience capacity, and qualitatively, generating new ecosystem services and functions due to the emergence of new species or interactions, via evolution, dispersal or migration (Moore & Schindler, 2022).

The analysis of the functional uniqueness, on the other hand, revealed that on average around 60% of the integrity of the functional diversity is maintained by the uniqueness of the species, evidencing that the loss of a few species can have a drastic effect on such integrity. This loss of ecosystem functions worsens to the point where the loss of half of the most functionally unique species (the most unique species) of the Carajás National Forest could lead to a loss of more than 87%

of the integrity of this diversity. Although this analysis of functional uniqueness represents the worst possible scenario of species loss (with species becoming extinct in a decreasing order of uniqueness for the ecosystem functions), the most unique and rare species are in fact, among the most vulnerable to changes anthropogenic environmental factors (Bihn et al., 2010). Thus, the extinction of these species would lead to the functional homogenization of the communities, which can reduce the ecosystem functioning, stability and resistance to environmental changes (Olden et al., 2004), as well as the deterioration of the ecosystem goods and services (Clavel et al. al., 2010). Therefore, it is clear that pessimistic scenarios have to be considered in natural capital studies, especially in risk analyses.

The accounting of the biological assets is one of the most difficult tasks in the assessment of the natural capital due to the complexity of biodiversity (Figures 3 and 4), although it is the basis of all services it provides. With this in mind, the need to avoid using a purely economic approach while accounting for the value of the actions and the non-actions becomes clear (Mace, 2019, Bright et al., 2019). For this approach, different values and levels of biological organization must be considered as biological assets. Here, we propose an approach that follows this direction, examining different dimensions of biodiversity based on functional ecology. By examining the functional redundancy and uniqueness of the Carajás National Forest, our results

Figure 3. Blue macaw, a species considered vulnerable.

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Figure 4. The big trees in the forest.

highlight the importance of including multiple dimensions of biodiversity in the natural capital accounting. Functional redundancy evidenced the stabilizing function of biodiversity for the natural capital, aligned with proposals for assessment of the natural capital that highlight the importance of accounting for the potential to support ecosystem functions and services (Mace, 2019). The analysis of the functional uniqueness, on the other hand, showed the vulnerability of the natural capital to environmental changes. By identifying the worst-case scenario of biodiversity loss, the functional uniqueness can be incorporated into analyses of economic risk and environmental impacts, evidencing the importance of the forest for the regulation and the maintenance of the natural capital, both in a local and regional context.

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7

Taxa of Serra dos Carajás included in official lists of endangered species

Lourival Tyski, André L.R. Cardoso, Cesar de Sá Carvalho Neto

The advancement of scientific knowledge and the objective assessment of the situation of endangered species in Carajás make it possible to establish effective strategies for the protection of biodiversity and the direction of the resources for its conservation. The creation of a list of endangered species in the Carajás region is an important initiative in this regard. Through the *Official list of species of the Brazilian flora in danger of extinction*, updated and recognized by Ordinance MMA n. 300 dated December 13, 2022, the *Red List of the Flora of Pará* (COEMA-PA, 2007) and IUCN *Red List of Threatened Species*, a direct search was carried out in the databases of the Carajás Biodiversity Management Plan (PGBIO), the Herbarium of Carajás (HCJS) and publications of project Flora das Cangas de Carajás about bryophytes (Oliveira-da-Silva & Ilkiu-Borges, 2018), ferns and lycophytes (Salino et al. 2018) and phanerogamous (Mota et al. 2018). The following works were also consulted: Andrino et al. (2020), Barbosa- Silva et al. (2022), Zappi et al. (2020). Regarding fauna, Pinheiro et al. (2012), Martins et al. (2012) and Barbosa et al. (2020) were checked to generate the list of protected species in the Carajás region. For flora and fauna (birds), the data collected at the sample points of the Natural Capital project was also used.

The categories used in these lists follow the method of assessing the risk of species extinction in accordance with the categories and criteria of the International Union for Conservation of Nature (IUCN) (Figure 1), in accordance with national legislation, and under the terms of the Convention on Biological Diversity (CBD).

Flora

The plant species in Carajás protected by the legislation are distributed in 31 families (27 angiosperms, one fern, one lycophyte and three bryophytes), 46 genera and 52 species (Table 1), including six species considered endemic to canga: *Monogereion carajensis*, *Ipomoea cavalcantei*, *Erythroxylum nelson-rosae*, *Mimosa skinneri* var. *carajarum*, *Isoetes cangae*, *Axonopus carajasensis*.

Comparing the latest national list of threatened species (MMA, 2014) with the current one (MMA, 2022), it is clear that some species in Carajás were excluded from the current list, such as *Mimosa acutistipula* var. *ferrea*, which was previously categorized as DD, and there were changes in the status of the species: *Cedrela fissilis* from EN to VU and *Pilocarpus microphyllus* from VU to EN, in addition to the insertion of new species in forest and canga environments: *Daphnopsis filipedunculata* (EN) and *Pilocarpus carajaensis* (VU) (acronyms in the Figure 1).

Although records and studies indicate the existence of 52 taxa protected by the legislation within the mosaic of protected areas of Carajás, not all of them are in areas directly affected (ADAs) by the mining projects. By means of a search in the lists of species of the inventory made over the last five years, it is possible to observe

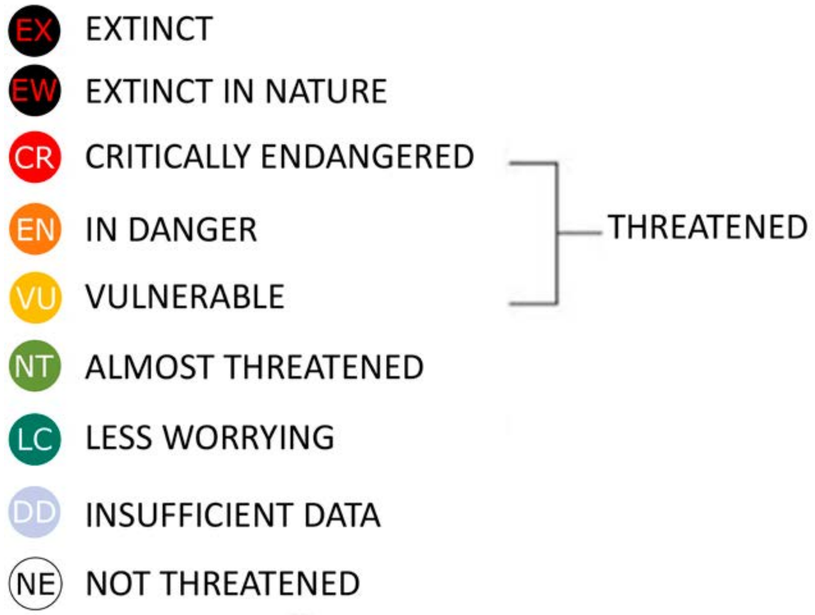

Figure 1. Structure of categories IUCN (2001). "DD" stands for "Deficient Data" and is used to describe species for which the available information is insufficient to determine their risk of extinction; "LC" stands for "Least Concerning" and is used to describe species which do not classify in any of the other IUCN conservation categories. IUCN also considers: "NT" stands for "Near Threatened" and is used to describe species which have not yet reached threat status 1 but are close to doing so; "EN" stands for "Endangered" and is used to describe species which are facing a very high risk of extinction in nature; "NE" stands for "Not Evaluated" and is used to describe species which have not have been evaluated yet for risk of extinction by IUCN; "VU" stands for "Vulnerable" and is used to describe species which face a high risk of extinction in nature in the future.

that 32.7% of the species do not have an interface with ADAs, as only 35 of the 52 listed, i.e., 67.3% , appear in the inventories, as illustrated in Table 1.

However, with the analysis of the lists of species in the inventories, an issue regarding the importance of botanical collections and the encouragement of collections comes to light because, in addition to the species surveyed in this work, the names of 13 other species categorized as protected also appeared in the inventories. :

- *Aspidosperma album* has no confirmed occurrence in Flona; the closest collections are 200 km north and 150 km south of the Carajás mosaic. However, there are other species known as scarlet macaws in the region.
- Species such as *Heteropsis flexuosa* or *H. spruceana* have been incorrectly identified. These species are probably present in inventories because lianas of the genus *Heteropsis* are known as cipó-titica. The only species of *Heteropsis* collected in the Carajás region is *H. tenuispadix*.
- *Protium giganteum* is a species widely distributed in the Amazon. This species has two varieties differentiated by certain characteristics of its leaves: *P. giganteum* var. *crassifolium* and *P. giganteum* var. *giganteum*. Only the *giganteum* variety was collected in the region. According to Flora and Funga of Brazil (2023), *P. giganteum* var. *crassifolium* is a variety that does not occur in Brazil.
- *Protium heptaphyllum* is a species widely distributed in South America. This species has three subspecies and six published varieties, in addition to almost fifty published synonyms, which demonstrates the complexity of determining of these taxa. Although *P. heptaphyllum* subsp. *chordatum* is mentioned in the inventory lists in the Carajás region, in the herbarium, only specimens of *P. heptaphyllum* subsp. *heptaphyllum* are found..
- *Talisia subalbens* is a shrub restricted to the savanna Chapada dos Guimarães (MT). In the Carajás inventories, it appears as a large tree in a forest. The tree species of the genus in the mosaic are *Talisia retusa* and *Talisia mollis*, which are also known by the vernacular name pitomba.
- *Eschweilera amazoniciformis*, *Pouteria minima*, and *Pouteria vernicosa* have confirmed occurrence only in the state of Amazonas. *Tabernaemontana muricata* has confirmed occurrence only in the states of Amazonas and Acre. In the Carajás mosaic, there are other species of these genera, and all have vernacular names similar to those of these taxa, which may have led to the misunderstanding.
- *Vouacapoua americana* prefers sandy soils, and the closest collections are 200 km to the North, in the region influenced by Lake Tucuruí. This species' vernacular name is acapu, and *Campsiandra laurifolia* is commonly found in the region, whose vernacular name is acapurana or false-acapu.
- *Ptychopetalum olacoides* prefers sandier soils, and the closest collections are 400 km to the North, in the Amazon channel, and to the west, in the Xingu Basin.

The distribution data of these taxa indicates that they occupy areas which are distant and/or unconnected with the mosaic and probably do not occur in Carajás. However, these are species with very popular vernacular names, which can lead to mistakes on occasions when there are not enough taxonomic parameters to be observed (fertile material) which can confirm the identification. For cases in which there are suspicions that the identified individual corresponds to a protected species, vouchers representing it must be collected and registered in reference collections, such as the Carajás Herbarium, where they will be part of the collection, acting as a mark in the registration of the species for the region and contributing to the expansion of the knowledge about the regional biodiversity.

Table 1. Species of the flora of Serra dos Carajás included in lists of endangered plants.

Family	**Species/ Variety**	**IUCN**	**MMA 2022**	**COEMA 2007**	**Voucher HCJS**
Annonaceae	*Guatteria procera*	VU			
Apocynaceae	*Aspidosperma desmanthum*	LC		VU	HCJS_4815
Asteraceae	*Monogereion carajensis*		CR	CR	HCJS_2007
Bartramiaceae	*Philonotis uncinata*	VU			
Bignoniaceae	*Handroanthus serratifolius*	EN			HCJS_4035
Bignoniaceae	*Jacaranda carajasensis*			EN	HCJS_1872
Blechnaceae	*Blechnum heringeri*	LC	VU		
Calymperaceae	*Calymperes erosum*	CR			
Chrysobalanaceae	*Hirtella lancifolia*		VU		
Convolvulaceae	*Ipomoea carajasensis*		VU	EN	HCJS_11123
Convolvulaceae	*Ipomoea cavalcantei*		EN	EN	HCJS_088
Cyperaceae	*Hypolytrum paraense*		EN	VU	HCJS_5156
Dioscoreaceae	*Dioscorea asperula*		VU		
Dioscoreaceae	*Dioscorea trilinguis*	LC	EN		
Erythroxylaceae	*Erythroxylum nelson-rosae*		EN	EN	HCJS_608
Fabaceae	*Inga calantha*	VU			
Fabaceae	*Apuleia leiocarpa*		VU		HCJS_9775
Fabaceae	*Centrosema carajasense*		VU	VU	HCJS_2398

Table 1. Species of the flora of Serra dos Carajás included in lists of endangered plants.

Family	**Species/ Variety**	**IUCN**	**MMA 2022**	**COEMA 2007**	**Voucher HCJS**
Fabaceae	*Dalbergia spruceana*	VU			HCJS_5437
Fabaceae	*Mimosa acutistipula var. ferrea*			VU	HCJS_4005
Fabaceae	*Mimosa skinneri var. carajarum*		CR	VU	HCJS_2572
Fabaceae	*Hymenaea parvifolia*	LC	VU		
Fabaceae	*Leptolobium glaziovianum*	EN	EN		HCJS_2526
Isoetaceae	*Isoetes cangae*	CR			HCJS_4093
Lauraceae	*Aiouea impressa*	EN			
Lauraceae	*Mezilaurus itaúba*	VU	VU	VU	HCJS_2831
Lauraceae	*Ocotea tabacifolia*		EN		HCJS_7108
Lecythidaceae	*Couratari guianensis*	VU			
Lecythidaceae	*Bertholletia excelsa*	VU	VU	VU	HCJS_3558
Lythraceae	*Physocalymma scaberrimum*	LC		VU	HCJS_1667
Malpighiaceae	*Heteropterys megaptera*		EN		
Malvaceae	*Pachira tocantina*	EN	EN		HCJS_1403
Malvaceae	*Christiana mennegae*	VU			HCJS_5393
Meliaceae	*Cedrela fissilis*	VU	VU		HCJS_4036
Meliaceae	*Cedrela odorata*	VU	VU	VU	HCJS_1139
Meliaceae	*Swietenia macrophylla*	VU	VU	VU	HCJS_1757
Moraceae	*Sorocea guilleminiana*	VU			HCJS_2312
Myrtaceae	*Campomanesia aromatica*	VU			HCJS_3254
Myrtaceae	*Eugenia belemitana*	VU	VU		HCJS_388
Myrtaceae	*Eugenia longifolia*		EN		HCJS_2859
Peraceae	*Pera membranacea*	EN	EN		
Poaceae	*Axonopus carajasensis*		EN	VU	HCJS_6800
Portulacaceae	*Portulaca sedifolia*	EN			HCJS_5819
Pylaisiadelphaceae	*Isopterygium tenerum*	EN			

Table 1. Species of the flora of Serra dos Carajás included in lists of endangered plants.

Family	**Species/ Variety**	**IUCN**	**MMA 2022**	**COEMA 2007**	**Voucher HCJS**
Rutaceae	*Pilocarpus carajaensis*	EN	EN		HCJS_3472
Rutaceae	*Pilocarpus microphyllus*	VU	VU	EN	HCJS_4107
Rutaceae	*Angostura quinquefolia*	VU	VU		HCJS_3226
Sapotaceae	*Pouteria krukovii*	VU			
Sapotaceae	*Pradosia granulosa*	VU	EN		
Thymelaeaceae	*Daphnopsis filipedunculata*		EN		HCJS_4415
Vitaceae	*Cissus apendiculata*		EN	VU	HCJS_522

Terrestrial vertebrate fauna

We listed 16 mammals, 34 birds, six reptiles and two amphibians threatened in the Carajás region (Table 2). Among mammals, the family with the highest number of representatives is Felidae (4), followed by Canidae (2); the others have only one taxon each. In birds, Psittacidae has six threatened taxa in the region, followed by Cracidae (3) and Dendrocolaptidae (3); the other families have one or two taxa each. All reptiles and amphibians located in the region belong to different families.

The mammals *Alouatta belzebul* and *Furipterus horrens* are endemic to Brazil. In addition to it, *Atelocynus microtis*, which is restricted to the south of the Amazon River, as well as *Saguinus niger* and *Chiropotes utahicki*, are also endemic with Amazonian distribution, endemic to the Xingu-Tocantins interfluve. The distribution of birds *Penelope pileata*, *Pyrrhura lepida*, *Pyrrhura amazonum*, *Pyrilia vulturina*, *Capito dayi*, *Pteroglossus bitorquatus*, *Hypocnemis striata*, *Lepidothrix iris*, *Contopus nigrescens*, *Hylopezus paraensis*, *Dendrocolaptes retentus* is restricted to East Amazon, to the south of the Amazon river. *Psophia dextralis*, *Psophia interjecta*, *Pyrrhura anerythra* and *Xiphocolaptes carajaensis* are endemic of the Xingu-Tocantins interfluve. The amphibian *Pseudopaludicola canga* was once considered endemic to Carajás but currently has a known distribution in other locations in Pará, Maranhão and Tocantins (Pansonato et al., 2012). The other threatened species in Carajás are widely distributed in South America (Table 2, Figures 2-4).

Figure 2. Bush dog (*Speothos venaticus*) no BioParque Vale Amazônia.

Table 2. Species of the terrestrial vertebrate fauna of Serra dos Carajás included on the lists of endangered animals.

Class	**Order**	**Family**	**Species**	**IUCN**	**MMA 2022**	**COEMA 2007**
Amphibia	Anura	Bufonidae	*Atelopus spumarius*	VU		
Amphibia	Anura	Leiuperidae	*Pseudopaludicola canga*	DD		VU
Reptilia	Testudines	Podocnemididae	*Podocnemis unifilis*	VU		
Reptilia	Testudines	Testudinidae	*Chelonoidis denticulata*	VU		
Reptilia	Squamata	Gymnophthalmidae	*Colobosaura modesta*	LC		VU
Reptilia	Squamata	Teiidae	*Tupinambis merianae*	LC		VU
Reptilia	Squamata	Colubridae	*Chironius flavolineatus*	LC		VU
Reptilia	Squamata	Dispsadidae	*Pseudoboa nigra*	LC		VU
Aves	Tinamiformes	Tinamidae	*Tinamus tao*	VU	VU	
Aves	Passeriformes	Furnariidae	*Campylorhamphus multostriatus*		VU	
Aves	Piciformes	Picidae	*Celeus undatus*	EN	EN	
Aves	Passeriformes	Furnariidae	*Dendrexetastes rufigula*	EN	EN	
Aves	Passeriformes	Dendrocolaptidae	*Dendrocolaptes picumnus*		VU	
Aves	Passeriformes	Grallariidae	*Grallaria varia Boddaert*		VU	

Table 2. Species of the terrestrial vertebrate fauna of Serra dos Carajás included on the lists of endangered animals.

Class	Order	Family	Species	IUCN	MMA 2022	COEMA 2007
Aves	Columbiformes	Columbidae	*Patagioenas speciosa*	VU		
Aves	Passeriformes	Thamnophilidae	*Phlegopsis nigromaculata*		VU	
Aves	Strigiformes	Strigidae	*Pulsatrix perspicillata*	VU	VU	
Aves	Piciformes	Ramphastidae	*Ramphastos schistaceus*	VU		
Aves	Piciformes	Ramphastidae	*Ramphastos vitellinus*	VU		
Aves	Passeriformes	Vireonidae	*Tunchiornis ochraceiceps*		VU	
Aves	Galliformes	Cracidae	*Penelope pileata*	VU	VU	
Aves	Galliformes	Cracidae	*Aburria cujubi*	VU	VU	
Aves	Galliformes	Cracidae	*Crax fasciolata*	VU		
Aves	Accipitriformes	Accipitridae	*Morphnus guianensis*	NT	VU	
Aves	Accipitriformes	Accipitridae	*Harpia harpyja*	VU	VU	
Aves	Gruiformes	Psophiidae	*Psophia dextralis*	EN	VU	
Aves	Psittaciformes	Psittacidae	*Anodorhynchus hyacinthinus*	VU		VU
Aves	Psittaciformes	Psittacidae	*Pyrrhura lepida*	VU		
Aves	Psittaciformes	Psittacidae	*Pyrrhura amazonum*	NT	VU	
Aves	Psittaciformes	Psittacidae	*Pionites leucogaster*	VU		
Aves	Psittaciformes	Psittacidae	*Pyrilia vulturina*	LC	VU	
Aves	Apodiformes	Trochilidae	*Lophornis gouldii*	NT	VU	
Aves	Piciformes	Capitonidae	*Capito dayi*	VU	VU	
Aves	Piciformes	Ramphastidae	*Pteroglossus bitorquatus*	EN		
Aves	Passeriformes	Thamnophilidae	*Hypocnemis striata*	LC	VU	
Aves	Passeriformes	Dendrocolaptida	*Xiphocolaptes carajaensis*		VU	
Aves	Passeriformes	Pipridae	*Lepidothrix iris*	VU	EN	
Aves	Passeriformes	Tyrannidae	*Contopus nigrescens*	LC	VU	
Aves	Gruiformes	Psophiidae	*Psophia interjecta*		EN	
Aves	Psittaciformes	Psittacidae	*Pyrrhura anerythra*		VU	
Aves	Passeriformes	Grallariidae	*Hylopezus paraensis*		VU	
Aves	Passeriformes	Dendrocolaptida	*Dendrocolaptes retentus*		VU	
Mammalia	Artiodactyla	Tayassuidae	*Tayassu pecari*	VU	VU	
Mammalia	Carnivora	Canidae	*Speothos venaticus*	NT	VU	
Mammalia	Carnivora	Felidae	*Leopardus wiedii*	NT	VU	
Mammalia	Carnivora	Felidae	*Panthera onca*	NT	VU	VU
Mammalia	Carnivora	Felidae	*Puma concolor*	LC		VU
Mammalia	Carnivora	Mustelidae	*Pteronura brasiliensis*	EN	VU	VU
Mammalia	Lagomorpha	Leporidae	*Sylvilagus brasiliensis*	EN		
Mammalia	Perissodactyla	Tapiridae	*Tapirus terrestris*	VU	VU	
Mammalia	Cingulata	Dasypodidae	*Priodontes maximus*	VU	VU	VU

Table 2. Species of the terrestrial vertebrate fauna of Serra dos Carajás included on the lists of endangered animals.

Class	**Order**	**Family**	**Species**	**IUCN**	**MMA 2022**	**COEMA 2007**
Mammalia	Pilosa	Myrmecophagidae	*Myrmecophaga tridactyla*	VU	VU	VU
Mammalia	Primates	Atelidae	*Alouatta belzebul*	VU	VU	
Mammalia	Primates	Cebidae	*Saguinus niger*	VU	VU	
Mammalia	Primates	Pitheciidae	*Chiropotes utahickae*	VU		VU
Mammalia	Carnivora	Canidae	*Atelocynus microtis*	NT	VU	
Mammalia	Chiroptera	Furipteridae	*Furipterus horrens*	LC	VU	
Mammalia	Chiroptera	Natalidae	*Natalus macrourus*	NT	VU	

Figure 3. Harpy eagle (*Harpia harpyja*) in BioParque Vale Amazônia.

Figure 4. Tapir (*Tapirus terrestris*) in BioParque Vale Amazônia.

Identifying and protecting rare, endemic and threatened species occurring in the region are important human actions for maintaining natural capital. The protection of natural habitats stands out as one of the most relevant actions for the protection and conservation of threatened species. Furthermore, field studies aimed at locating populations of these species contribute to better knowledge of the geographic distribution and natural history of the species, being essential for increasing knowledge of threatened taxa and for planning and implementing effective conservation measures for the threatened biota present in the Carajás region.

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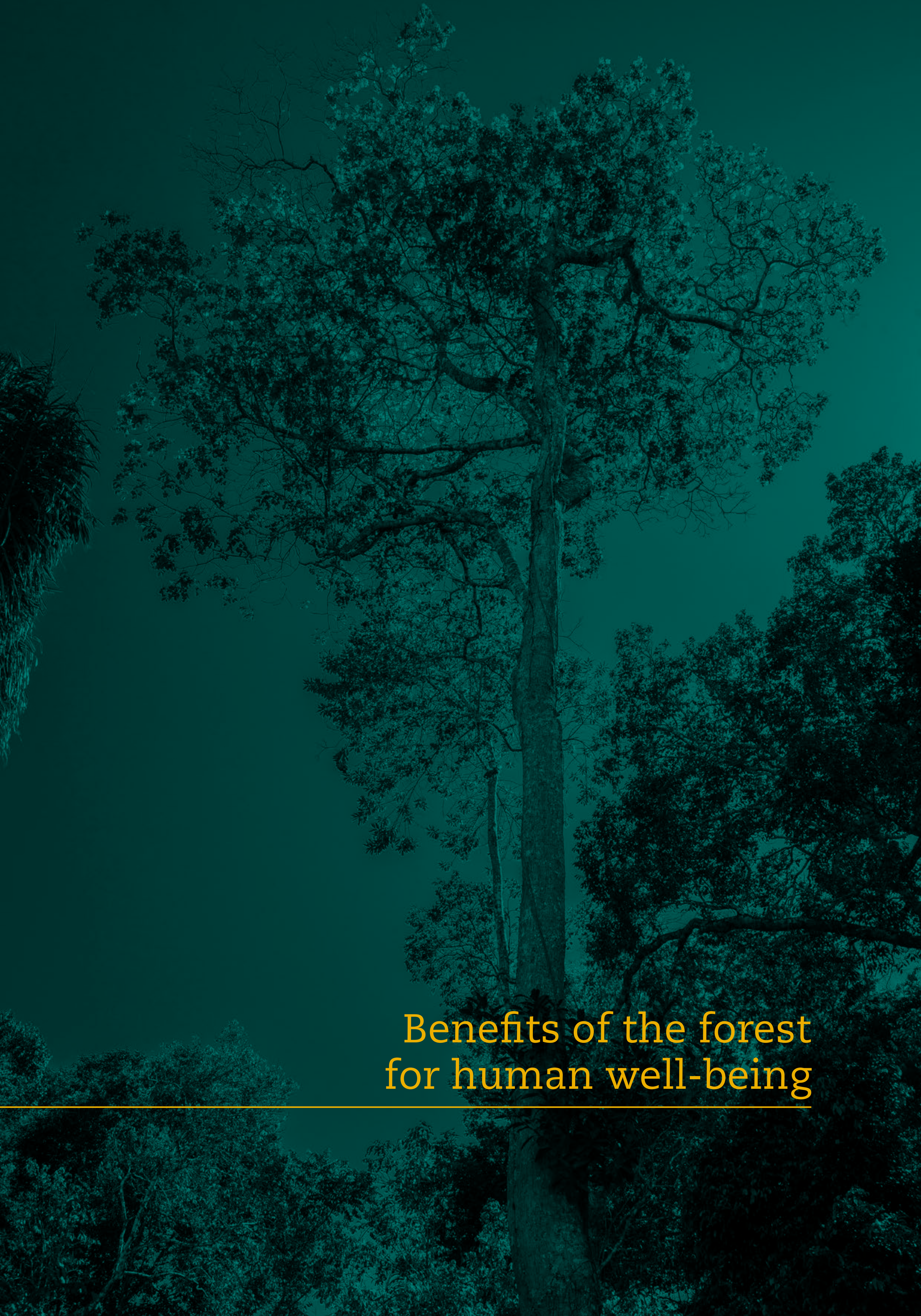

Benefits of the forest for human well-being

8

Life in the soil

Rafael Borges da Silva Valadares, Felipe Costa Trindade, Leandro Argolo, Isa Rebecca Chagas da Costa, Caio Yoshiura, Luciana Patrícia Silvestre de Souza, Silvio Ramos, José Augusto Bittencourt

Introduction

Soils are dynamic environments with very different physical, chemical and biological characteristics. It is clear to most people that productive soils must be rich in nutrients and have physical characteristics that facilitate the development of the plants. However, the soil microorganisms perform crucial functions for the maintenance of the terrestrial ecosystems and are generally neglected.

Microorganisms perform a diversity of essential functions in the soil. Fungi form symbiosis with the roots of 90% of the plant species (mycorrhizae), facilitating the access to microsites where the roots alone would not be able to reach water and nutrients. Bacteria also act in biological nitrogen fixation both free-living in the soil and in association with plants. Some solubilize phosphate from rocks, and others act actively in the promotion of the plant growth or in the natural bio-control of insects and nematodes which may cause plant diseases. These combined functions help to establish the balance between species and are essential for the forest maintenance.

The soil microorganisms are responsible for the cycling of nutrients including nitrogen, phosphorus and sulfur, elements which are extremely limiting for the productivity of an ecosystem. They act in the decomposition of plant and animal residues and in subsequent transformations of organic matter until the incorporation of carbon into the soil in stable forms. Therefore, natural or anthropized ecosystems are extremely dependent on microbial activity to be sustainable, and these organisms are excellent indicators of the current status of the soil. This relevance is even greater where soil fertility is low. Therefore, each nutrient must be cycled efficiently, so that there are no significant losses in the system. Healthy, protected or well-managed soils tend to be biologically active and favor the increase of carbon in the soil reducing the loss.

Molecular techniques enable accessing microbial diversity and functionality accurately and on a large scale. Most microorganisms are not cultivable and are difficult to be characterized or differentiated by morphological means. Massive DNA sequencing enables identification of the soil microorganisms, while large-scale protein analysis shows the most abundant biochemical processes in each environment.

Since 2016, ITV has been carrying out works with soil molecular biology to access the microbial diversity and functionality in natural or anthropized ecosystems. Pioneering studies focused on native areas, such as the Carajás cangas (Costa, 2019, Gastauer, 2019), caves and areas undergoing rehabilitation (Trindade, 2020). In the present study, we used the analysis package mentioned in the forest phytophysiognomies of Carajás within the context of the Natural Capital project. It is expected that microbial functional diversity reflects the biota existing above the soil, as well as the geochemical and environmental complexity of the studied plots.

Microbial diversity in the dry and rainy seasons

With the purpose to understand the structure and the diversity of the microbial communities in the phytophysiognomies of the Carajás forests, the microbial functional diversity of the soil was accessed using DNA sequencing techniques. In general, the analyses show little variation in the abundance of bacterial genera between areas and seasons. Despite that, some genera seem to be more associated with the type of phytophysiognomy (Figure 1), such as *Acidibacter* and *Acidothermus* (open rainforest) and *Bryobacter* (forests). As for fungi, rain seems to influence the abundance of the most present genera and diversity positively.

The most abundant pf the genera of bacteria and archaea (Archaea domain) identified are common in soils considered healthy, including *Candidatus Xiphinematobacter*, a nematode endomicrobion (Mobasseri et al, 2019) and *Candidatus Udaeobacter*, linked to the production of antibiotics and dissolution of minerals (Willms et al, 2020). Furthermore, in most points, we found *Bradyrhizobium* sp., a nitrogen-fixing bacterium which is associated with several tree species. As for the most present and identified fungal genera, we found *Saitozyma* and *Apiotrichum*, both are common yeasts in soils rich in iron and aluminum (Moreira & Vale, 2018).

It is still not possible to identify most surveyed microorganisms, which is more valid for fungi. This is a reflection of limited research with Amazonian soils (Kroeger et al, 2018).

Active diversity and soil enzymes

Metaproteomics is a technique which enables accessing more precise information about what is happening physiologically in the cells within the microbial communities,

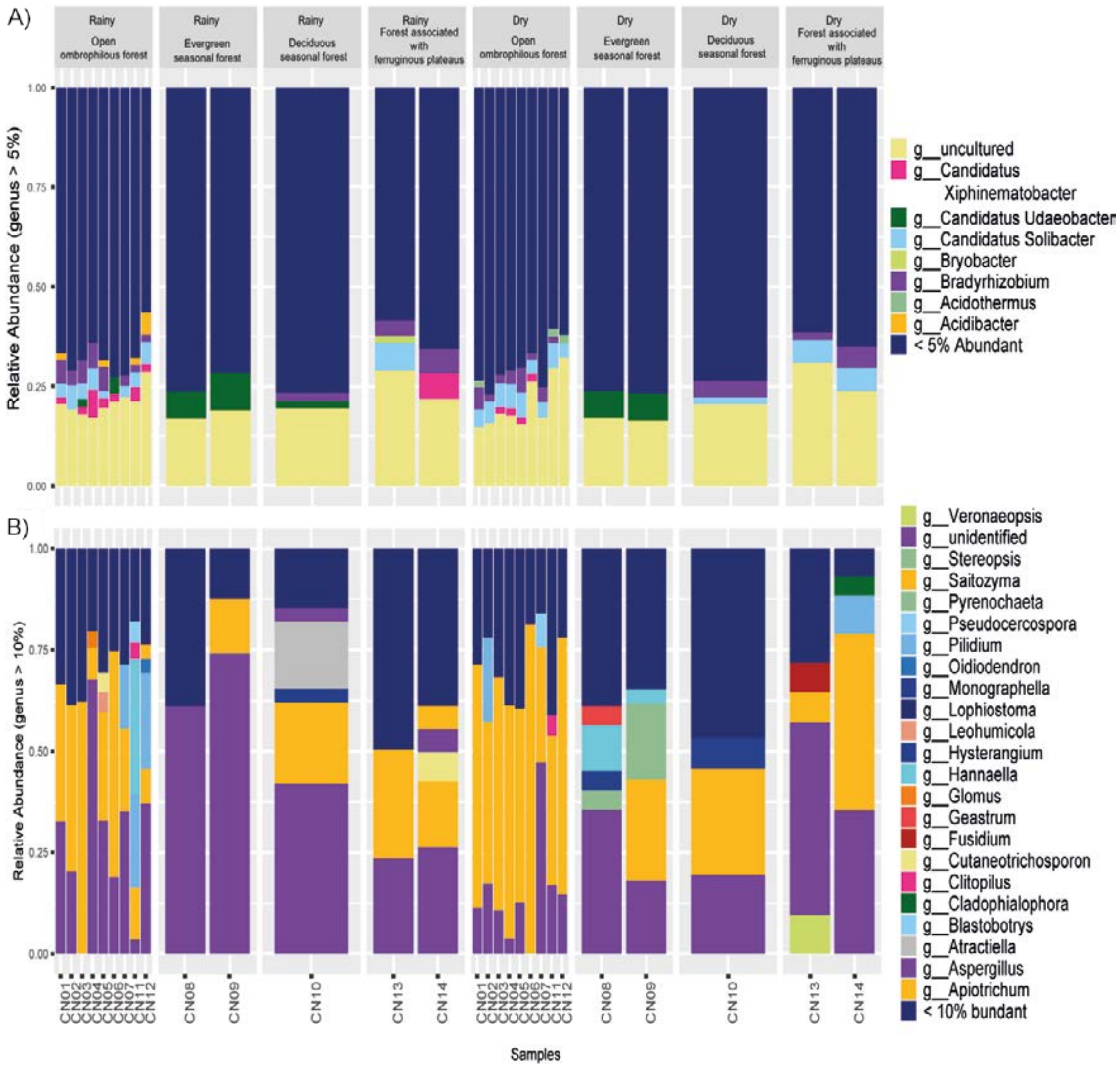

Figure 1. Average relative abundance of microbial genera, (A) bacteria and archaea and (B) fungi, associated with the soil samples.

relating the structure of the microbial community to active physiological processes in the environment.

From proteins, it is possible to obtain a taxonomic view of the most active microorganisms in the environment (Figure 2). 592 peptides were observed distributed among the kingdoms of bacteria, fungi and archaea, which made up more than 93% of the total peptides identified. It was possible to observe 46 orders of bacteria, 5 orders of fungi and 1 of archaea. 554 unique functions were detected in 190 metabolic pathways.

Although in smaller numbers in the soil metaproteome, it was possible to identify groups of fungi important to the soil health, such as those in phylum Ascomycota, with several saprophytes and Helotiales which also form mycorrhizae; in addition to the phylum Basidiomycota with the subdivision Agaricomycotina: saprophytes and mycorrhizae.

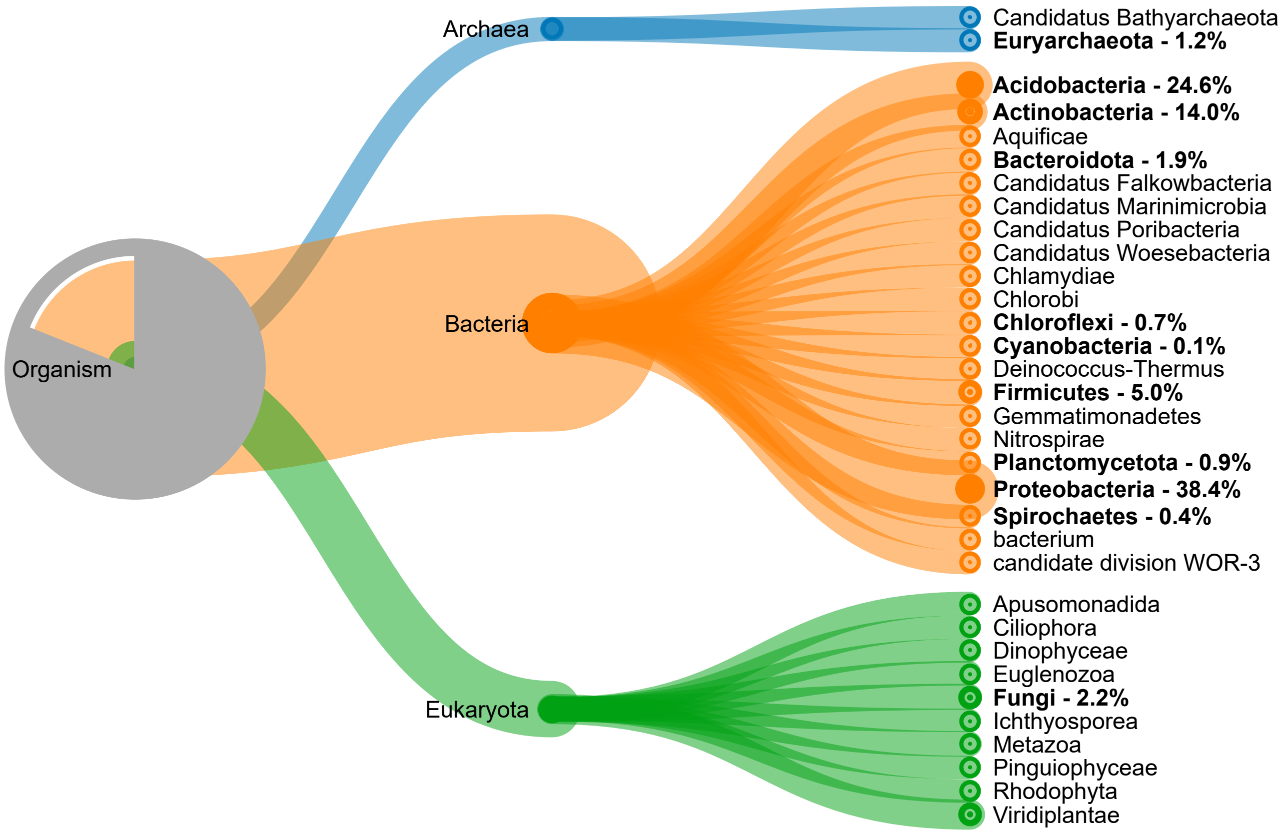

Figure 2. Taxonomic groups related to the peptides found, gathering all sampled plots. The percentage indicates the groups with the highest relative abundance in the soil.

Carbon fixation in native forest soil of the eastern Amazon and nutrient cycling

The conservation of native areas is necessary to protect biodiversity (Figures 3 and 4), the ecological functions and to avoid greater losses of carbon to the atmosphere through CO2. Little is known about the metabolisms of the microorganisms in soils in the Brazilian Amazon, although by means of the molecular functioning of these organisms, it is possible to observe carbon fixation in the soil, mineralization of organic matter and nutrient cycling (Bastida et al, 2014) . With the help of the diversity of functions performed by the soil microorganisms, the Amazon ecosystem keeps its exuberance even if it is located under a nutrient-poor soil, as the soils sampled in this study.

From the soil metaproteomics, it was possible to observe 13 proteins involved in the mineralization of the soil organic matter (SOM) (Table 1) and 26 proteins involved in the carbon fixation in the soil.

Table 1. Enzymes related to the mineralization of Organic Matter in the Soil and their respective target substrates.

Protein (EC number)	Substrate
Chitinase (3.2.1.4)	Chitin
Isocitrate lyase (4.1.3.1)	Glyoxylate Cycle
Malate synthase (2.3.3.9)	Glyoxylate Cycle
Laccase (1.10.3.2)	Lignin
Pectate lyase (4.2.2.2)	Pectin
Pectinesterase (3.1.1.11)	Pectin
Alpha-amylase (3.2.1.1)	Starch
Pullulanase (3.2.1.41)	Starch
Cellulase (3.2.1.4)	Cellulose
Rhamnogalacturonan endolyase (4.2.2.23)	Pectin
Beta-glucosidase (3.2.1.21)	Cellulose
Arabinogalactan endo-beta-1,4-galactanase (3.2.1.89)	Arabinogalactan
Alpha-glucosidase (3.2.1.20)	Oligosaccharides

Figure 3. Myriapoda (snake louse) on the litter on the ground of the Carajás National Forest.

In the sampled soils, there is a higher number of proteins related to the increase of carbon in the soil than those related to the natural loss of carbon upon mineralization of MOS. This shows the importance of the maintenance of the native ecosystem, which protects these microbial communities from anthropogenic pressure (stress). As a result, groups of bacteria responsible for the carbon fixation, such as cyanobacteria and actinobacteria, thrive and play a major role in the atmospheric carbon sequestration.

Even though MOS mineralization occurs with release of CO2 arising from microbial respiration, generally, the stress on the microbial community is reduced in protected ecosystems, avoiding greater CO2 emissions (Cardoso et al, 2013; Malik et al, 2018). Therefore, the carbon balance in the soil in the studied areas is favorable to the storage. Furthermore, in a stable ecosystem, the products of MOS mineralization are better reused by the soil microbiota and carbon is incorporated into the microbial biomass.

Figure 4. Soil as a structure for flora.

Figure 5. Fungi fixed to substrate in Carajás.

It is worth pointing out that enzymes belonging to the five different carbon fixation pathways in prokaryotes were found, namely: (i) the citric acid reductive cycle; (ii) the Wood-Ljungdahl metabolic pathway; (iii) the 3-hydroxypropionate pathway; (iv) the hydroxypropionate-hydroxybutyrate cycle and (v) the dicarboxylate-hydroxybutyrate cycle (Kanehisa et al, 2022). This shows the metabolic diversity in the bacteria in the sampled soils, where, by several active pathways, the community of bacteria absorbs CO2 and transforms it into a wide variety of molecules.

As a remarkable example of direct sequestration of CO2 of the atmosphere detected in the forest soils sampled in the Natural Capital project, within the Wood-Ljungdahl metabolic pathway, we can observe enzyme CO dehydrogenase (EC 1.2.7.4), which catalyzes the reduction of CO2, and the subsequent reaction carried out by enzyme Acetyl-CoA synthase (EC 2.3.1.169), which combines the resulting CO with a methyl group, resulting in acetyl-CoA.

These carbon incorporation pathways into the environment, observed thanks to metaproteomics, are mostly carried out by bacteria belonging to phyla Proteobacteria (38.4%), Acidobacteria (24.6%), Actinobacteria (14.0%) and Firmicutes (5. 0%), as well as others in lesser abundance. However, although in smaller quantities, the detected fungi are extremely important, as they play a fundamental role in the decomposition of complex and recalcitrant carbon sources in the soil (Thangarajan et al., 2013), such as lignin and chitin (Table 1, Figure 5).

Conclusions

The soil microorganisms are essential for the maintenance of the natural ecosystems, especially the Carajás forests. They act in nutrient cycling and carbon fixation, promoting the soil health and mitigating global warming. Molecular tools have proven to be powerful for description and interpretation of the microbial activity in the soil and its relationships with the forest ecosystem services.

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9

The role of the forest in the protection of the water resources

Paulo Rógenes Monteiro Pontes, Rosane Barbosa Lopes Cavalcante,
Edivaldo Afonso de Oliveira Serrão

The role of the forests for the water resources

The forests promote water-related ecosystem services, such as regulation of climate and river flow, improvement of the water quality, stabilization of the soil and maintenance of the water infiltration into the soil (Brauman et al., 2007). When compared to pasture areas, for example, the greater number of leaves in forest areas retains more rainwater in the leaves (interception), which protects the soil and increases the amount of water which returns to the atmosphere through evaporation. The deeper roots also allow the plants to keep the water withdrawal from the soil for longer periods. The resulting greater transport of water to the atmosphere contributes to the regulation of the local and regional climate. The observed greater infiltration of water into the soil causes less surface runoff, helping to reduce flood peaks of some rain events, reduce erosion and improve the quality of water. This set of services provided by the forest, regulating the climate and the river flows provides well-being for people and the biodiversity in their surroundings (Figure 1).

The assessment of hydrological ecosystem services provided by the forest is important for its conservation. To achieve that, hydrological modeling techniques, field monitoring and remote sensing can be used, seeking to understand the relationship between the forest and the water. In this chapter, research results of Instituto Tecnológico Vale (ITV) about the role of the Carajás mosaic in the water cycle of the Itacaiúnas river basin will be presented focused on climate regulation and surface runoff regulation. This mosaic is formed by a set of conservation units, including the Carajás National Forest, and it is called herein Mosaic of Carajás (MoC).

What is the effect of the deforestation on the water balance?

Figure 1. A river inside Carajás National Forest.

In general terms, the behavior described by several authors and shown in Figure 2 is expected as a result of deforestation (Bosch & Hewlett, 1982, Peel et al., 2010, Zhang et al., 2001, 2017). The figure shows two hypothetical river basins of the same size and subject to the same climate, only the land use varies. Larger vegetation, such as forests, tend to intercept a greater volume of rain in the tree canopy and absorb water from greater depths in the soil through their roots. On the other hand, a pasture area, for example, has less capacity to intercept water in its canopy and a smaller root system. Therefore, in a basin in which the forest was replaced by pasture, reduction in the water which returns to the atmosphere through direct evaporation and the water which has passed through the plants (evapotranspiration) is expected, consequently, increase in the average flow of the rivers is expected. Despite that, rainfall and flow can be influenced in different ways by deforestation, depending on the size of the basin, the local geology, the soil management and the soil compaction (Zhang et al., 2017).

In the Amazon, a review study of the effects of deforestation on the hydrological processes follows the same pattern (D'Almeida et al., 2007). The authors made a review, analyzing research which assesses the deforestation in the Amazon on a local scale (< 10^2 km^2), regional scale (10^2 – 105 km^2) and in hypothetical deforestation scenarios. In summary, the results indicate that the local deforestation cannot affect the rainfall, but it is possible to identify reduction in evapotranspiration and increase in runoff. In the most extreme scenario, drastic reduction in evapotranspiration and rainfall is expected.

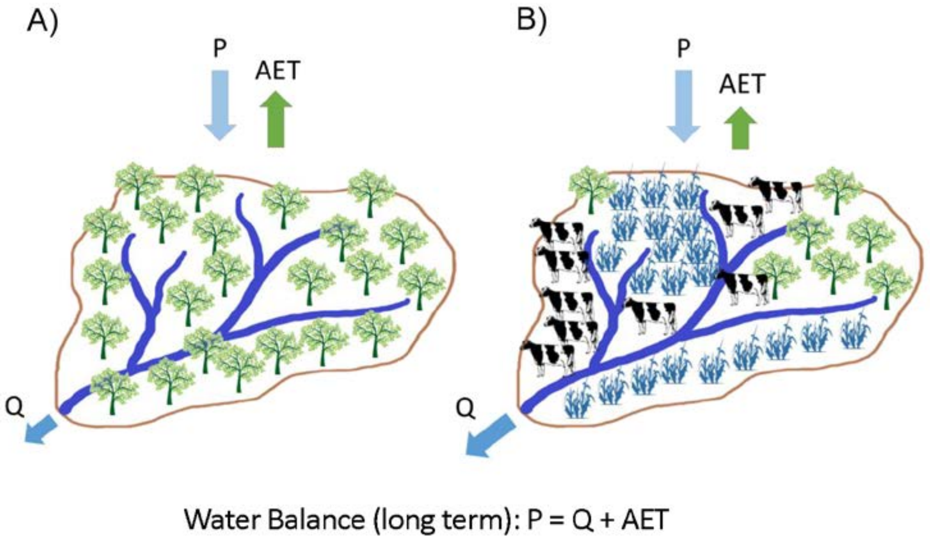

Figure 2. Effect of the change of the land cover on the water balance of two hypothetical river basins, according the literature, where (A) has greater land cover and (B) is more deforested. (P: rainfall; AET: evapotranspiration; Q: runoff.)

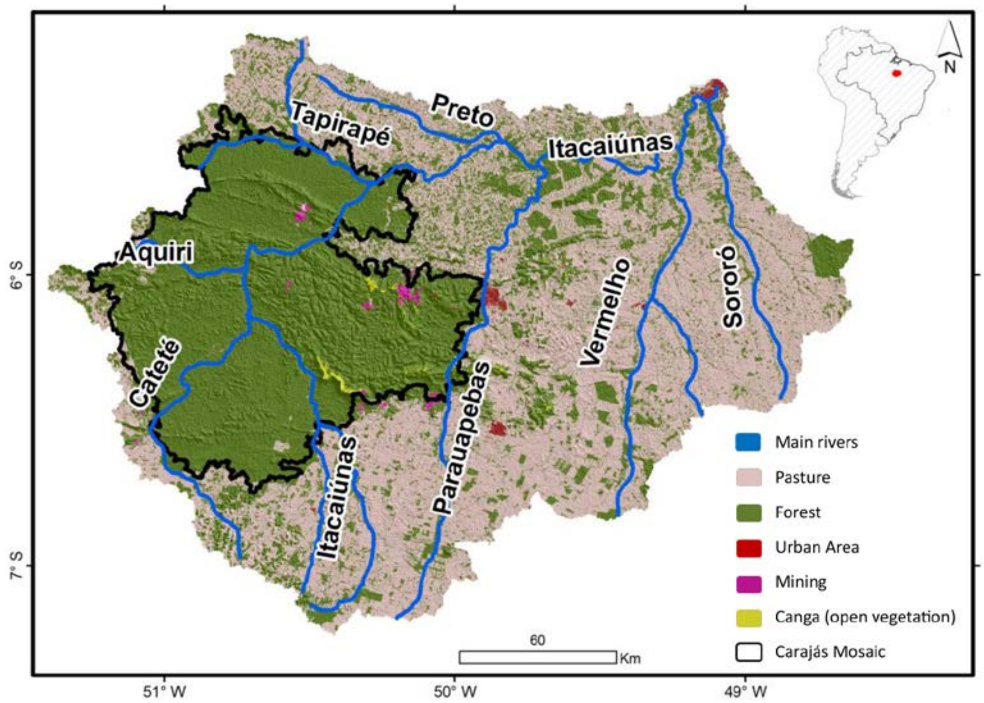

Figure 3. Itacaiúnas River basin, its main rivers and recent land use and occupation.

Specifically, in the Itacaiúnas River basin (BHRI) (Figure 3), where the Carajás National Forest is located, ITV used the water balance to understand the hydrological processes considering the deforestation from 1980 to 2016. During this period, the area of the basin forest cover was reduced from 95% to 51%. Using different methods, Cavalcante et al. (2019) showed that, in the period, because of deforestation in the basin, the flow of the Itacaiúnas River measured close to the mouth increased, and evapotranspiration reduced. The impact of deforestation would be even greater if the climate had not exerted influence in the opposite direction, although less relevant.

Hydrological modeling as a tool to assess the role of the forest in the hydrological processes

One of the ways to estimate evapotranspiration and runoff in a river basin is by means of hydrological modeling. The use of mathematical models which can simulate the real behavior of a basin enables generating data for periods for which measured data is not available, and thus, analyze hypothetical scenarios.

To understand the importance of the forests in protected areas within the Itacaiúnas River Basin (BHRI), ITV used the hydrological model MGB (Large Basin Model). Due to the proximity and even overlaps between protected areas, it was decided to assess the effect of all protected areas surrounding the MoC.

MGB is a mathematical model which simulates the hydrological cycle processes in a river basin (Pontes et al., 2019). The first step in using MGB is to define the topographic characteristics, type and use of the land in the river basin. For this purpose, an algorithm is used to divide the basin into smaller units, called "mini-basins". Each mini-basin has an associated river stretch and physical characteristics (slope, length, area) and land type and use; the combination of these two maps is called Hydrological Response Units – URH. The calculations are made by the model in URH (Figure 4). There, energy and water balances are first made, with which interception, evapotranspiration and the volume of water that flows on the surface, subsurface of the soil and which reaches the aquifers are calculated. These flows are propagated along the river stretches, resulting in their flow.

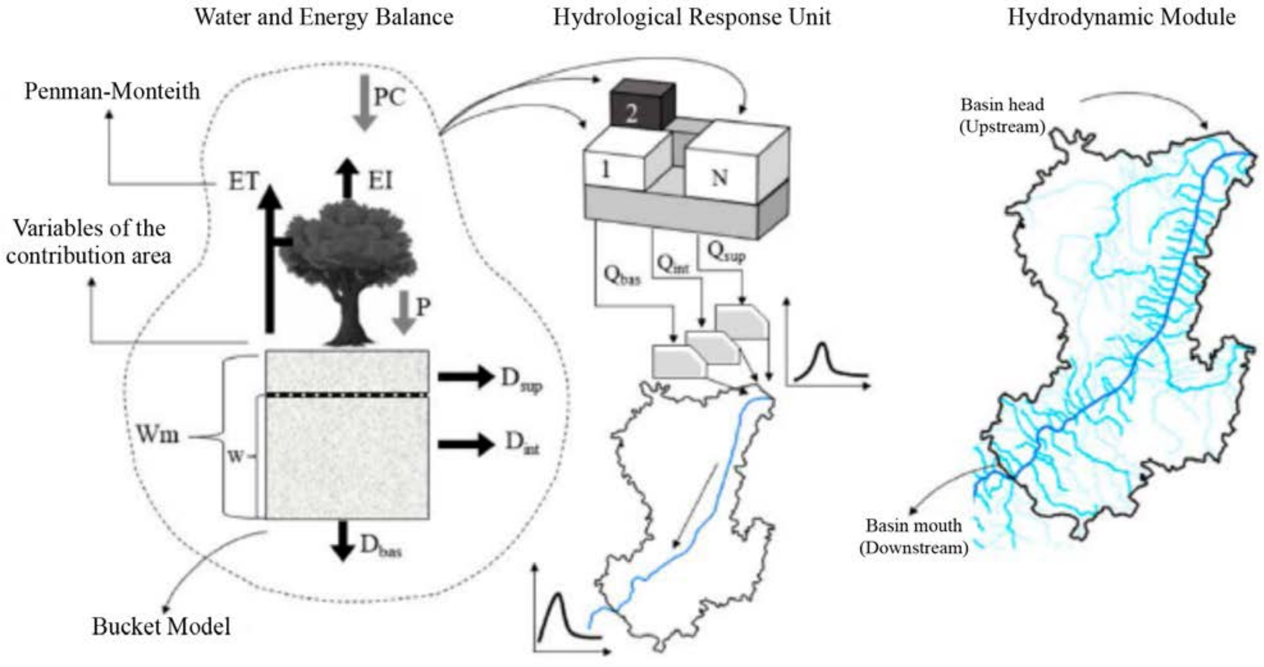

Figure 4. Hydrological processes simulated in the MGB model. Where, PC is the rainfall that reaches the tree canopy; P is the rainfall deducted from the losses (evapotranspiration); ET is the evaporation of the water in the soil and transpiration of the plants; EI is the evaporation of the water intercepted in the tree canopy; the variables D and Q are the flows and the volumes, respectively, which flow superficially (sup), subsurface (int) and to the aquifers (sub).

The model was calibrated using data measured in the field between 1998 and 2007. It was concluded that it can satisfactorily simulate the hydrological processes in the basin. To divide BHRI into 1,246 mini-basins and simulate the hydrological processes, the following were used:

- Digital Elevation Model: Alos World 3D with 30 m spatial resolution (Takaku et al., 2016).
- Soil type map: Digital Soil Map of the World (https://www.fao.org/soils-portal).
- Soil cover: classification using images Landsat 5 to 8 (Souza-Filho et al., 2016).
- Meteorological/climatic and hydrological data: Climate Research Unit data base; Merge (rain); National Water Agency (flow data).
- Vegetation data: height, leaf area index, albedo and surface resistance of the vegetation were obtained from the literature.

As a result, it was seen that evapotranspiration is greater and runoff is lower inside the Carajás Mosaic than in the areas outside (Figure 5). This occurs because the protected areas are predominantly covered with native vegetation (Figure 6), while the areas outside the Carajás Mosaic have been heavily deforested.

The greater interception of rainwater within the Carajás Mosaic is the result of the interception exerted by the canopy and greater transpiration, and it is observed in terms of annual average values, daily values and maximum values (Table 1). In terms of average annual values, the amount of water returned to the atmosphere is 1,005 mm/year outside the Mosaic (57% of annual rainfall) and 1,277 mm/year (72% of annual rainfall) inside the Mosaic.

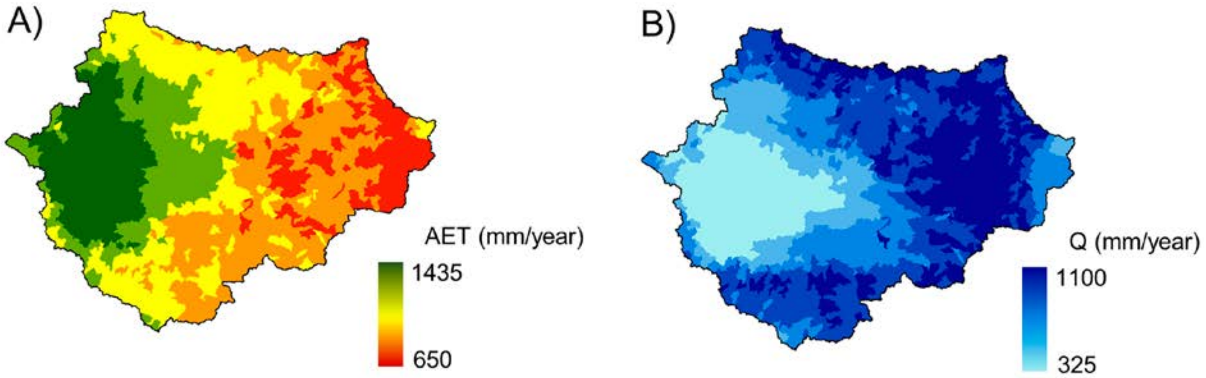

Figure 5. Results of the MGB model. A) Evapotranspiration (AET; sum of EI and ET) and B) runoff (Q) specialized in BHRI. Parts. (EI – Evaporation of the water intercepted in the tree canopy; ET – Evaporation of the water in the soil and transpiration).

Figure 6. River inside forest.

Table 1. Evapotranspiration (AET) and its parts (EI – Evapotranspiration of intercepted water in the tree tops; ET – Evaporation of water in the soil and transpiration) calculated using the MGB method, inside and outside Carajás' Mosaic (MoC).

Evapotranspiration and its parts simulated by the MGB model (mm/day or mm/year)		Average		Maximum	
		Daily	Annual	Daily	Annual
Inside MoC	EI+ ET	3.54	1277	6.36	1354
	EI	1.08	383	2.72	446
	ET	2.46	894	3.64	908
Outside MoC	EI + ET	2.78	1005	4.81	1057
	EI	0.66	236	1.73	263
	ET	2.12	769	3.08	794

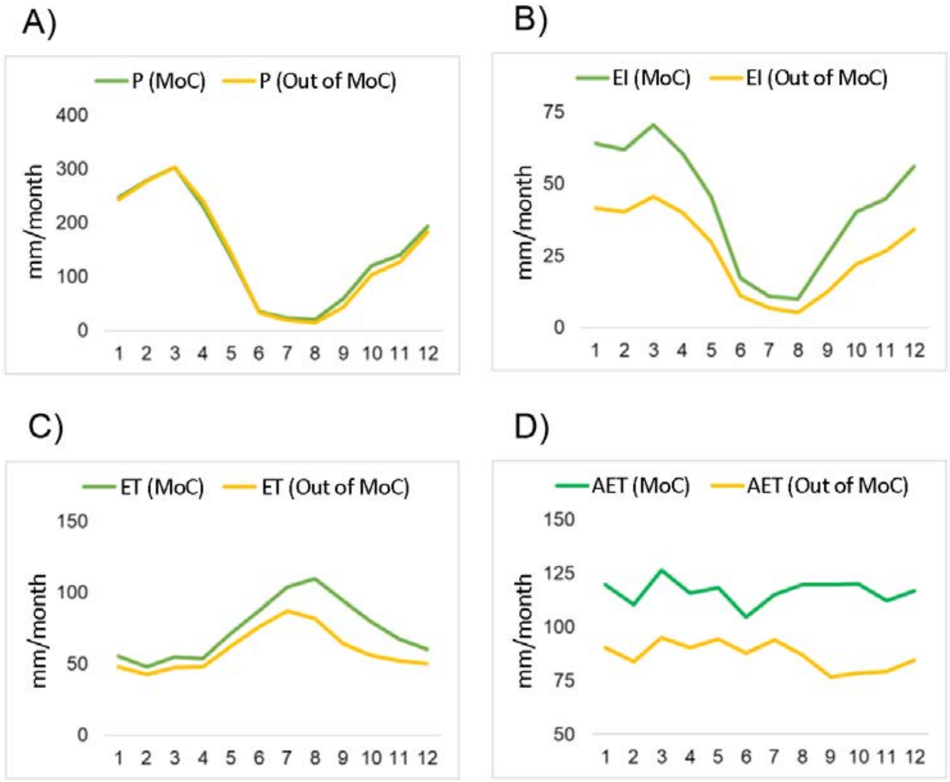

Figure 7: A) Rainfall; B) evaporation of intercepted water; C) evaporation of the water in the soil and plant transpiration; and D) evapotranspiration, inside and outside the mosaic. (P: rainfall; AET: evapotranspiration; EI: evaporation of the water intercepted in the tree canopy; ET: evaporation of the water in the soil and plant transpiration).

The results indicate that around 30% of the evapotranspiration in the mosaic comes from water intercepted in the tree canopy. The rest is evaporation from the soil and transpiration. The interception in the pasture area is lower, which is justified by the reduction in the vegetation canopy in the deforested area. This variable follows the rainfall pattern, i.e., when there is reduction in the rainfall, the intercepted water is also reduced, impacting the value of evapotranspiration of the intercepted water (Figure 7A, B). Water interception by the canopy helps protect the soil from the direct impact of the raindrops and reduces the amount of rain reaching the soil. Due to the high slopes and the presence of areas with shallow soil observed within the Carajás Mosaic, this protection is very important to avoid erosion processes.

On the other hand, soil evapotranspiration and transpiration are higher in the period without rain, as there is greater availability of solar radiation and the plants are able to take water stored in the soil to maintain their transpiration for the most of the dry season (Figure 7C). This means that the total amount of water that returns to the atmosphere as water vapor is approximately constant throughout the year within the Mosaic, contributing to the maintenance of the regional climate.

Figure 8. Aerial view of the Parauapebas River in the middle of the forest.

In regions outside the Mosaic, greater reduction in total evapotranspiration is observed in the dry season (Figure 7D). This seasonal variation can be seen in the following figures, which analyze rainfall and evapotranspiration (interception and soil) within the Carajás Mosaic and outside this region.

Considering the Carajás Mosaic area of around 12 thousand km^2, around 15 km^3 of the water is transferred to the atmosphere annually through evapotranspiration, feeding the rivers (Figure 8), reducing the local temperature and contributing both to the local climate and for the formation of rain in other regions of Brazil.

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10

Regulation of the local climate

Claudia Wanzeler da Costa, Renata Gonçalves Tedeschi, Everaldo Barreiros de Souza

The role of the forest in the regulation of the local climate

The benefits provided by the forests, especially the tropical ones, to maintain the planet climate go far beyond just storing carbon on the Earth surface. The forests maintain the local climate regulation thanks to inherent biophysical processes, such as the emission of biogenic volatile organic compounds, which serve as aerosols in the atmosphere, reflect the received solar energy and form clouds (Lawrence et al., 2022).

In the global context of climate change, new patterns in climate variables are already observed and lead to serious problems for society, their regional impacts are reinforced by changes in the land cover. In tropical regions such as the Amazon, for example, these impacts act directly on the temperature of the air, evapotranspiration and rainfall, which, in turn, alter the hydrological cycle (Dias et al., 2015, Souza-Filho et al., 2016). The land cover is intrinsically related to the regional climate, for which scientific literature reports the existence of feedback between climate and vegetation cover thanks to biophysical elements, such as albedo, changes in sensible heat and latent heat, surface roughness, among others (Shukla et al., 1990, Foley et al, 2003, Bagley et al., 2014). These changes, in turn, can cause changes in temperature, rainfall and solar radiation absorbed by the Earth surface. This cycle can also occur the other way around, i.e., global warming can affect the vegetation cover by means of changes in temperature, rainfall and net radiation. Changes in the vegetation cover and the surface properties can change the regional climate, and in long terms, the global climate.

A previous study (Souza-Filho et al. 2016) investigated the possible consequences of the changes in the land cover and use on the hydroclimatology of the Itacaiúnas River Basin (BHRI), located in the southeast of the Amazon (Figure 1). The

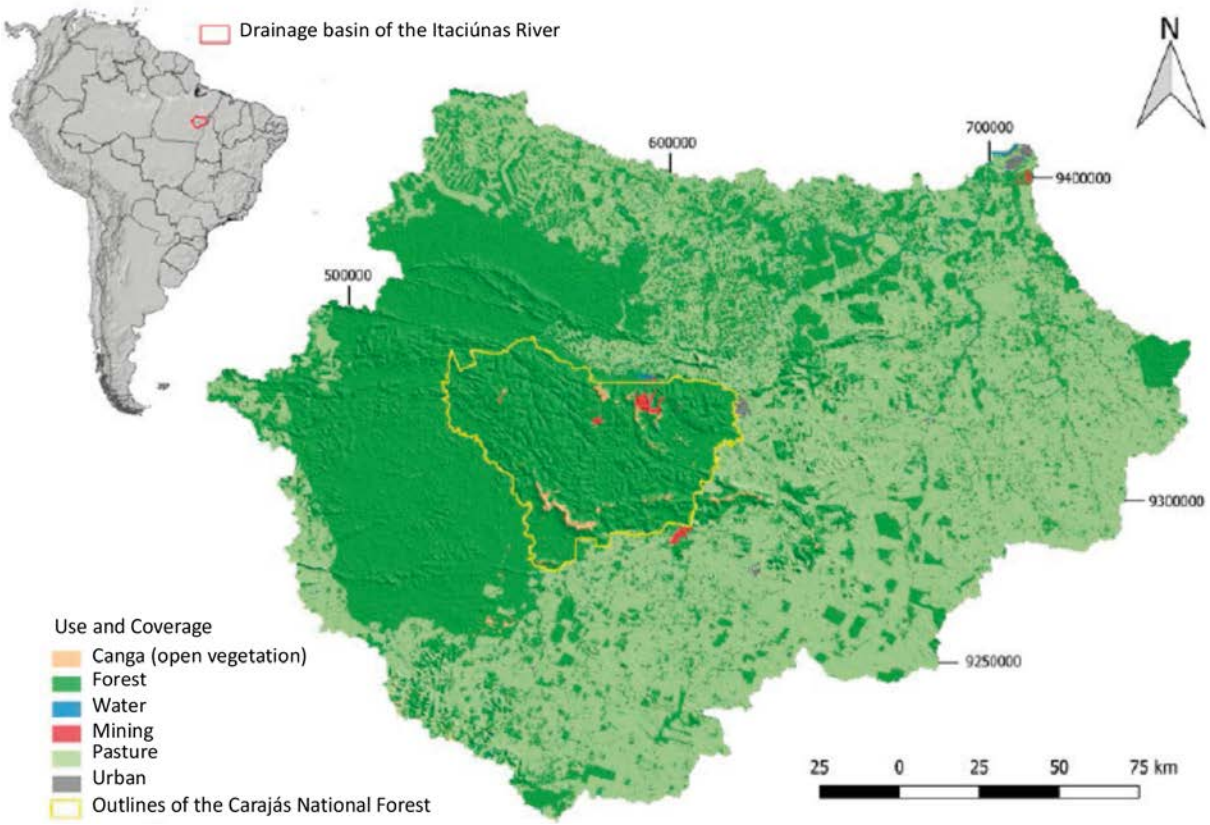


Figure 1. Study area: Drainage basin of the Itacaiúnas River (prepared by Wilson Nascimento Jr.; data from 2019).

authors observed that the current scenario of land use and cover in the basin, which has lasted since 2004, is composed of the primary forest in the protected areas, in the central-western part, while the other areas are composed of pastures/agriculture/urbanization. According to this study, transformations in the landscape in BHRI in the period from 1973 to 2013 resulted in changes in the hydro-climatology of the basin.

Effects of the land cover changes on the regional climate of the Drainage Basin of the Itacaiúnas River (BHRI)

A new study carried out by researchers from Instituto Tecnológico Vale (ITV) in 2022, in the context of the Natural Capital project, sought to analyze what the effects of possible changes in the land cover in the Itacaiúnas River Water Basin would be on the regional climate, particularly on the energy balance and the water balance. For this purpose, the following experiments were made on BHRI (Figure 2): [a] an experiment called Control, which refers to the maintenance of the current forest cover in the region without modifications; [b] partial replacement (only Carajás National Forest) with pasture/forest mosaic and; [c] total replacement of the forest cover (all protected areas)

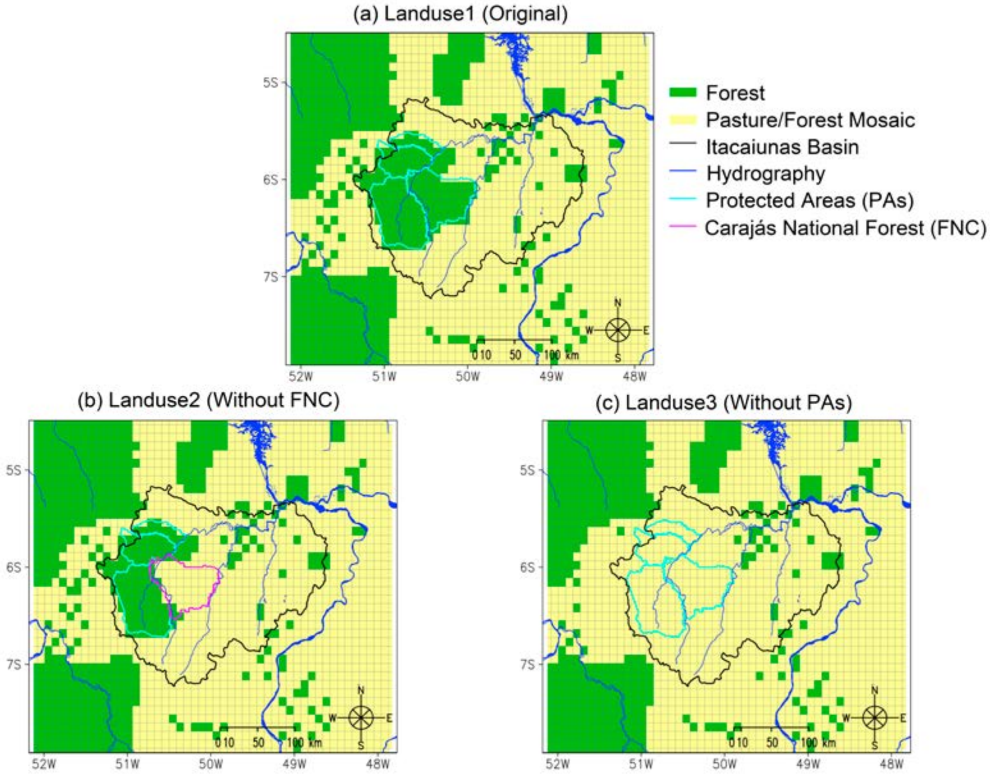
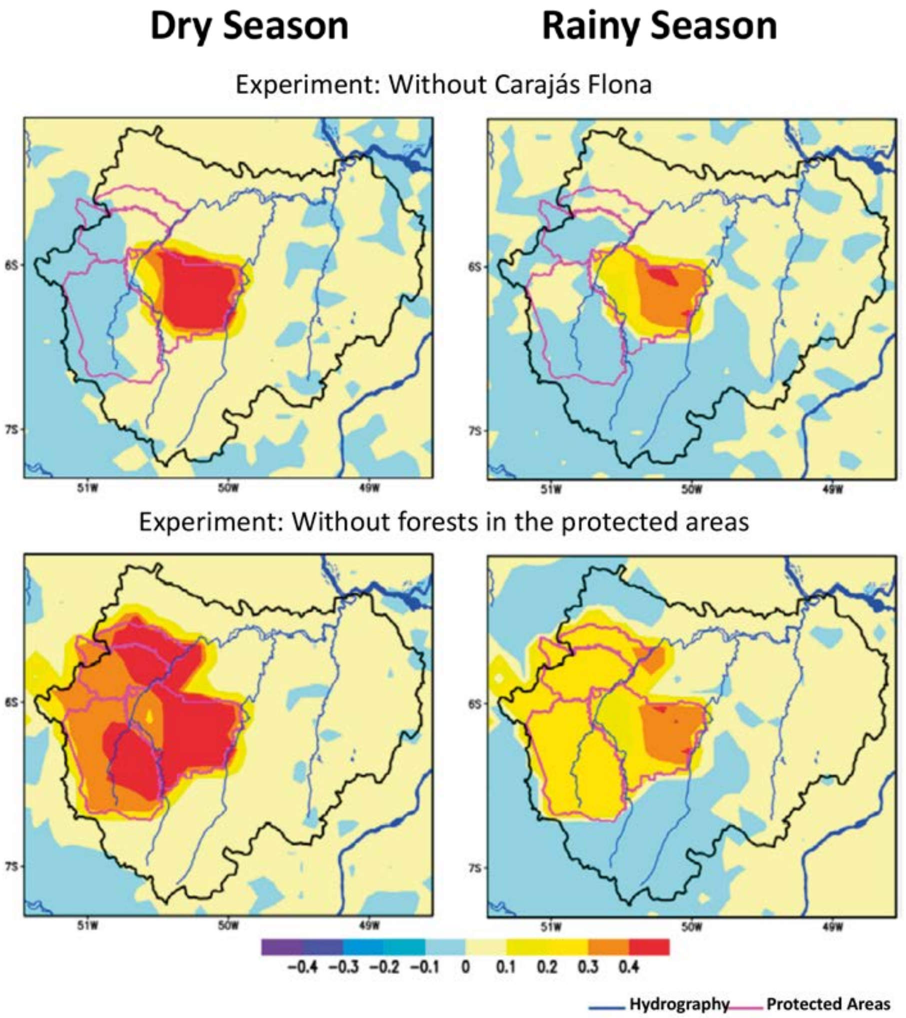


Figure 2. Configurations of the experiments on changes in the forest cover in the Itacaiúnas River Basin (BHRI) in the climate model: a) Current cover according to recent IBGE maps; b) replacement of the forest with pasture/forest mosaic, considering only the Carajás National Forest (FNC) and; c) replacement of all protected areas (PAs) in BHRI with pasture/forest mosaic. The grid resolution of the climate model used: 0.09º (~10 km).

with pasture/forest mosaic. The experiments were conducted with climate model RegCM4, which is the fourth generation of the regional 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 represented the different land covers on BHRI. The investigation of what the effects on the regional climate could have been should the forest cover on the protected areas had been replaced by pasture was carried out for the period from 1994 to 2018.

The surface energy balance (Hartmann, 1994) refers to the amount of energy available for physical processes and air heating. This energy is a function of solar energy that arrives at the planet surface, which, in turn, is partitioned among other forms of heat (watts.m-2), such as sensible heat, latent heat and heat flow in the soil. Latent heat and sensible heat are related to the energy released or absorbed in the atmosphere, respectively. Phase changes of given substance are related to latent heat (e.g., transition from liquid to vapor state and vice versa). Sensible heat is related to the change in temperature without a phase change in the substance. In a



Dry Season

Rainy Season

Experiment: Without Carajás Flona

Experiment: Without forests in the protected areas

Figure 3. Seasonal changes in air temperature (in °C) associated with changes in the forest cover on the Itacaiúnas River Basin, considering partial change – without the Carajás Flona (upper panels) and total change – without forests in the protected areas (bottom panels). The colored bar refers to changes in temperature, with positive values indicating increase and negative values, reduction.

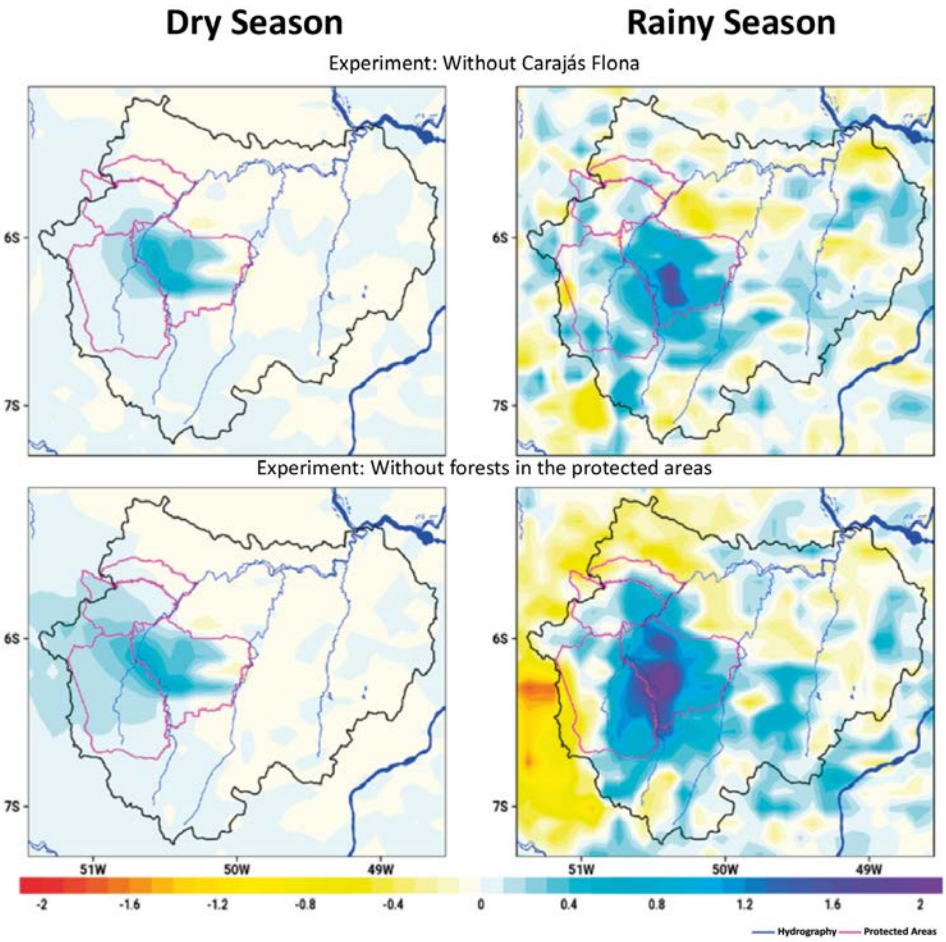
region of forest, latent heat is greater than sensible heat. However, when the forest cover is removed, there is increase in the sensible heat and decrease in the latent heat flow. This scenario favors increase in the air temperature locally.

In the regional water balance, water storage in the basin will depend on the contribution of rainfall, evapotranspiration and moisture convergence, which comes from the transport of moisture in the atmosphere by the wind (Satyamurty et al., 2013).

Analyses of the experiments demonstrated that changes in the forest cover on the protected areas in BHRI alter the regional characteristics of the energy balance, especially in the dry season. These changes result in increase in the temperature (positive values in the legend of Figure 3) in most of the Basin, mainly on the Carajás Flona (difference above 0.3ºC), in both experiments. This occurs due to the replacement of the forest cover with pasture. The increase in the air temperature near the surface is associated with increase in the sensible heat flow and decrease in latent heat flow. This result is consistent with that found in scientific studies, such as those by Foley et al. (2003), Von Randow et al. (2004), De Oliveira et al. (2018) among others.

According to Llopart et al. (2018), changes in the vegetation alter photosynthesis and impact transpiration. The low vegetation cover, represented by the pasture mosaic in the experiments, has lower transpiration capacity than the forest, where less energy will be used for the evaporation process. The excess energy is then used to heat the atmosphere just above the surface, thus, altering the local energy balance.

Regarding the impacts of changes in the forest cover on BHRI, which were made with the climate model on the regional water balance, changes in the rainfall


Dry Season

Rainy Season

Experiment: Without Carajás Flona

Experiment: Without forests in the protected areas

Figure 4. Seasonal changes in rainfall (in mm/day) associated with changes in the forest cover on the Itacaiúnas River Basin, considering partial changes – without the Carajás Flona (upper panels); and total – without forests in the protected areas (lower panels). Dry season (maps on the left) and rainy season (on the right). The colored bar refers to changes in the rainfall, with positive values indicating increase and negative values, reduction.

Figure 5. Fog covering part of the forest.

are also observed (Figure 4), with intense increase in the rainy season (up to 2mm/day). This increase must be counterbalanced in the water balance equation in terms of evapotranspiration (decrease) and moisture convergence, the latter is influenced by the steep relief observed in the region. This causes differences in the flow of humidity (transport of atmospheric moisture by wind), altering the regional rainfall in the dry and rainy seasons in different ways. This causes this humidity to converge on the area whose cover has been modified.

In a climatological way, we have a pattern of divergence of wind before the steepest relief and convergence of humidity over this same topography, which, in turn, will favor the formation of clouds, and therefore, rainfall. In the experiments carried out in this ITV study, the removal of forest located on steep relief (Flona

Figure 6. Sun among clouds in the forest.

de Carajás), initially causes increase in the wind runoff (flow), and therefore, the humidity due to the loss of surface roughness. Without the presence of the forest, there is decrease in the wind divergence (which carries humidity) before the steep relief, while convergence over this relief increases, which will reflect in increase in the rainfall over the location.

Conclusion

From experiments on changes in land cover in the protected forest areas on BHRI – partial and total replacement of the forest cover by pasture/forest mosaic –, it was possible to analyze the effects on the regional energy and water balance in the basin. The results demonstrate that the conversion of forest cover into pastures would cause changes in the water and energy balance over BHRI, both in the dry and rainy seasons. Such evidence indicates the fundamental role of the protected areas with forest cover in the domain of river basins, such as BHRI, within the Amazon deforestation arc for the regional climate regulation.

The forests protected by ICMBio and Vale in BHRI, as well as actions to recover degraded areas, are essential to maintain the regional climate regulation and mitigate the effects of global warming (Figures 5 and 6). Furthermore, they guarantee biodiversity and generate income for the communities close to the mining project, contributing to a more sustainable mining industry.

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11

The forest carbon stock

Rosane Barbosa Lopes Cavalcante, Emily Ane Dionizio, Markus Gastauer, Rafael Gomes Barbosa-Silva, Caroline Oliveira Andrino, Sâmia Nunes

Tropical forests as carbon reservoirs

Plants take carbon dioxide from the atmosphere through photosynthesis and incorporate carbon into the trunk, branches, leaves, and roots. Around 50% of the dry weight (biomass) of a tree is carbon. Carbon dioxide is an important gas that causes the greenhouse effect, so this service of nature plays a fundamental role in any scenario to mitigate climate change, as pointed out by the Intergovernmental Panel on Climate Change (IPCC). Due to the high density of tree species, the forests have great potential to sequester and store carbon, in addition to several benefits for biodiversity and the communities that live in the surrounding area.

The forest areas could provide up to a third of the required mitigation to limit global warming, mainly through conservation and reforestation initiatives (IPCC, 2019), representing one of the most cost-efficient options for this purpose. Currently, however, areas of intact and recovering forests absorb as much carbon as it is released by deforested and degraded areas (Mitchard, 2018). Therefore, it is essential to maintain the standing forests.

In Brazil, deforestation and forest degradation are the main responsible for greenhouse gas emissions. Due to deforestation and fires, eastern Amazon, which originally had a large carbon stock, is currently one of the main emitting regions. In this scenario, protected public areas, such as the Carajás National Forest (Flona), have important carbon stocks, among other ecosystem services, which must be preserved.

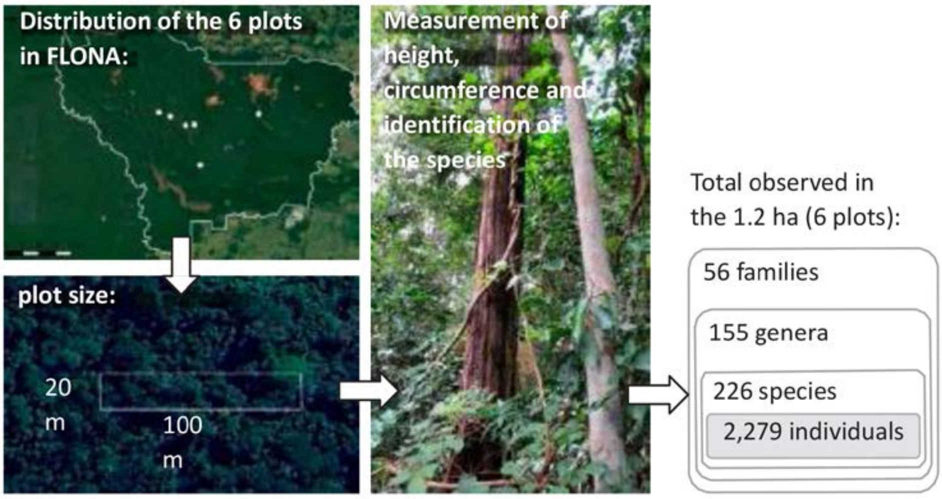

Figure 1. Location of the inventoried forest plots, sampling design used in the forest inventory, and total number of individuals measured.

Estimating the carbon content in the trees

The carbon stock in terrestrial systems is usually separated into pools of organic matter in the soil, litter, dead wood, and in the aboveground (trunk, branches, and leaves) and belowground (roots) live biomass (Figure 1). Due to measurement difficulties and costs, it is common to use coefficients to estimate carbon in roots, dead organic matter, and smaller vegetation based on the total aboveground carbon of larger trees.

To get the exact value of a tree carbon stock, it would be necessary to cut it down to measure its weight or measure its entire volume and take samples to measure its density. The data obtained by this destructive method is used to develop allometric equations, which relate the volume or biomass of trees with some variables which are more easily measured in the field and that do not require cutting trees, such as total height (Ht) and diameter (DBH) or circumference (CBH) at breast height (approximately 1.3m height) (Figure 2).

In forest inventories, the measurements are usually made on all individuals with a diameter (or circumference) and height greater than a minimum value in a given area called a sample plot. The number of plots, location, size, and shape of the plot depend on the methodology and objective of the forest inventory and the characteristics of the local vegetation (Figure 3). Although average wood density values can be used for species in a region, identifying the species of each individual tree improves carbon estimates, in addition to being essential for understanding the richness and diversity of the forest species. Other methods, based on data from remote sensors, for example, are also alternatives for estimating carbon stocks, but they depend on field data to calibrate or validate them.

Figure 2. Measuring the diameter at breast height (DBH).

The carbon stock in the Carajás National Forest

With the purpose to quantify the carbon stock in the Carajás National Forest, the Instituto Tecnológico Vale carried out a forest inventory of six plots across different forforest formations (Table 1). All trees, bamboos, lianas, and palm trees in the ts with CBH equal to or greater than 10 cm (equivalent to DBH of 3.18 cm) and their respective Ht were measured. The small minimum diameter used and the identification of species by taxonomists are a distinguishing feature of this work, enabling a better analysis by species.

The carbon stock was initially estimated for the aboveground live biomass (trunk and canopy) of the forest species. The choice of equations to estimate the biomass based on height and diameter data were made considering the type of vegetation

reported by the field teams, as shown in Table 1. To convert the value of biomass into carbon, the coefficient of 0.47 recommended by the IPCC for tropical forests was used.

Figure 3. Flora of the Carajás National Forest, with emphasis on the presence of lianas.

Table 1. Allometric equation and tons of carbon in aboveground live biomass estimated for the six sample plots in Carajás National Forest.

Type of vegetation	**Allometric equation***	**Number of plots**	**Carbon in the living biomass above the soil (t-C/ha)**
Seasonal semi-deciduous forest	Scolforo, 2008	1	41,4
Open rainforest with presence of bamboo	Chave et al., 2014, and density from the Global Wood Database	1	112,4
Open rain forest	Chave et al., 2014, and density from the Global Wood Database	4	Average 182.5 (141.9 to 228.3)

* The equations of Goodman et al. (2013), Gehring et al. (2004) and Mognon et al. (2017) were used to calculate the biomass of palm trees, lianas and bamboo.

The average carbon stock in the aerial part of the vegetation was 173 tons of carbon per hectare (t-C/ha). The value observed for seasonal semi-deciduous forest was lower than the average value used in the Brazilian inventory of anthropogenic emissions and removals of greenhouse gases. On the other hand, the value obtained for open rainforest was higher, emphasizing the importance of local data.

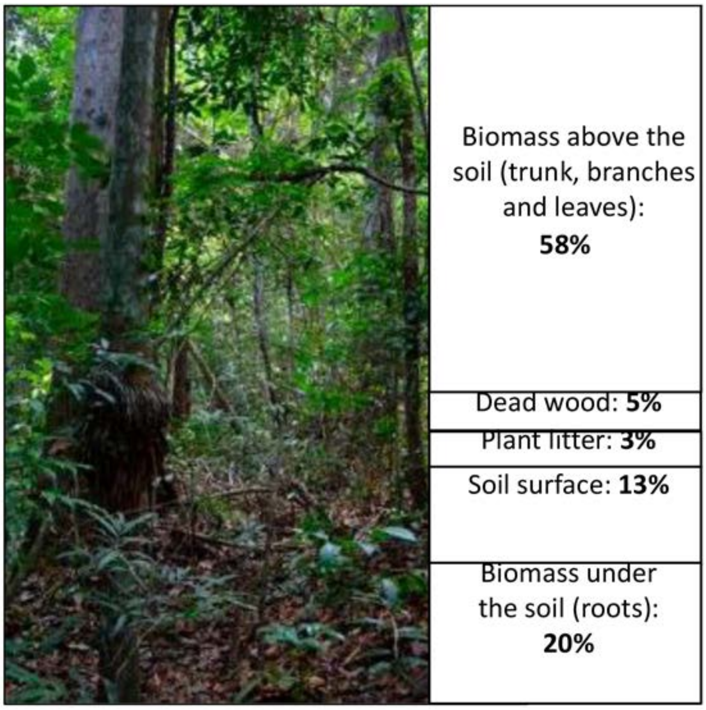

Figure 4. Average distribution of the carbon stocks by forest compartment estimated for the plots of open rainforest of Flona of Carajás.

For the open rainforest, the bellowground biomass, litter, and dead wood corresponds to around 35%, 5%, and 8% of the carbon observed in the aerial part of the vegetation, respectively (MCTI 2020). In Flona, organic carbon in the surface layer of the soil (0 to 20 cm) represents 22% of that observed in the aerial part of the vegetation (values reported in Chapter 11 for the same plots). Considering these values, the total carbon stock for the inventoried plots reaches 312 t-C/ha. This means that there are more than 1,100 tons of CO2 equivalent in one hectare of this type of forest, a value similar to that emitted by 247 cars driven for one year (values estimated using the calculator available at https://www.epa.gov/energy/ greenhouse-gas-equivalencies-calculator). The distribution by compartments is presented in Figure 4.

The role of the big trees

Large trees are an essential part of the forest ecosystem: they store huge amounts of carbon, provide important habitats for animals, support epiphytic plants and regulate the trees under their canopy by means of shading and fall of organic matter. They take decades or centuries to reach their maximum size, making the ecosystems of mature primary and secondary forests unique. However, they are becoming increasingly scarce due to deforestation and forest degradation.

In measurements made in Flona de Carajás, the average DBH was 10.82, varying between 3.18 and 200.22 cm, with an average height of 9.88, varying from 2 to 42 m. The thinnest trees (DBH < 10cm) are equivalent to just 4% of the carbon stock (varying between 2% and 10% across plots), but 72% of the total number of trees. The eight trees with DBH >= 100 cm correspond to less than 1% of the individuals measured in all plots, but represent 33% of the carbon stock (Figure 5).

The species that presented the largest carbon stock was *Erisma uncinatum* Warm. (called cinzeiro) (Figure 6). The 14 individuals of this species identified in the inventoried area totaled 43 t-C, corresponding to 21% of the total biomass. Then,

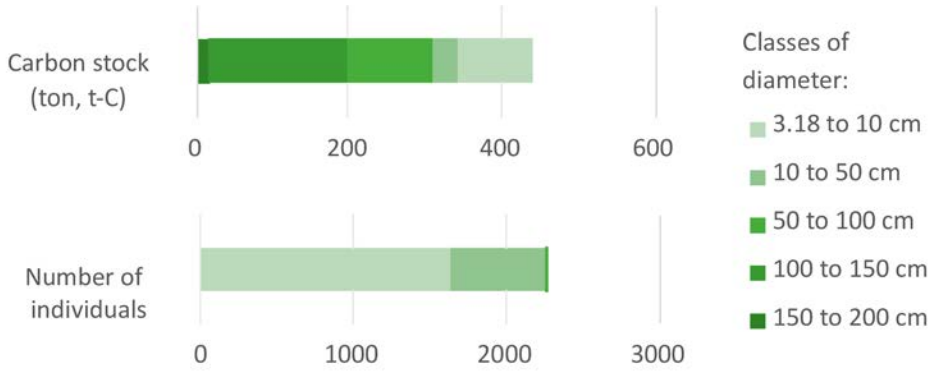

Figure 5. Number of individuals and carbon stock (t-C) in the six plots by diameter class.

Figure 6. *Erisma uncinatum* (cinzeiro) tree flower, with details of the branches at the top of the crown in the upper left image. In the lower image, the tree flowers are highlighted, and on the right, the fruits.

appear species *Marlimorimia psilostachya* (DC.) L.P. Queiroz & Marc.F. Simon (*timborana*) (Figure 7) and *Bertholletia excelsa* Bonpl. (Brazil nut tree) (Figure 8) with around 27 t-C and 17 t-C. The Brazil nut tree is a species assessed according to the criteria of the International Union for Conservation of Nature (IUCN) and included in the "vulnerable" threat category; it is also listed on the National List of Endangered Species of the Ministry of the Environment (Ordinance MMA n. 148).

Figure 7. In the upper left corner of the image, we have the crown of the *Marlimorimia psilostachya* (timborana) tree. In the upper right corner, we can see young individuals of the same species. In the lower left image, there is the inflorescence, and on the right, branches with pendulous fruits of the tree.

In magnitude, we can say that the loss of a single "cinzeiro" tree, with DBH = 200 cm and Ht = 30m, would correspond to the emission of 58 tons of CO2eq, corresponding to the burning of 25 thousand liters of gasoline (Table 2). The relationship between the occurrence of species and carbon stock is dynamic, depending on factors intrinsic to the species, such as mortality and growth rates,

Figure 8. *Bertholletia excelsa* (Brazil nut) tree in the middle of the pasture on the left; fruit with seeds of the Brazil nut tree on the right and, below, a detail of the flower.

and extrinsic factors, such as climate, seed dispersal, and soil fertility. For example, the fall of a large tree causes (Figure 9), temporarily, a big reduction in the aboveground live carbon stock of a plot, but opens space for the beginning of an ecological succession with an increase in the number of light-dependent pioneer plants direct, with a consequent change in the stored carbon.

Figure 9. Big tree in the Carajás National Forest.

Table 2. The five trees with the highest estimated carbon stocks (C), and their characteristics: species, diameter at breast height (DBH), total height (Ht) and wood density (D).

Order	**Species**	**DBH (cm)**	**Ht (m)**	**D (kg/m³)**	**C (t-C)**
1	*Erisma uncinatum* Warm.	200.2	30	0.57	15.7
2	*Bertholletia excelsa* Bonpl.	139.1	38	0.62	10.6
3	*Marlimorimia psilostachya* (DC.) L.P. Queiroz & Marc.F. Simon	125.0	40	0.64	9.4
4	*Marlimorimia psilostachya* (DC.) L.P. Queiroz & Marc.F. Simon	132.7	35	0.64	9.2
5	*Marlimorimia psilostachya* (DC.) L.P. Queiroz & Marc.F. Simon	110.8	42	0.64	7.7

Recommendations to improve the estimation of carbon stock in the Carajás

To protect high-carbon and biodiverse ecosystems is an important part of a comprehensive approach to mitigating climate change, and investments are required to protect them effectively. The carbon stock in the Carajás is primarily concentrated in large trees, but the understory, where small trees live, is more biodiverse, and due to its slower growth, can play an important role in the stability of the stored carbon and carbon removal. Therefore, it is necessary to balance the sampling effort, considering both the importance of the individual trees for carbon estimation purposes and their role in the forest biodiversity.

We believe that, in the near future, the study of the carbon, and biomass estimates above the soil in the Carajás will be associated with modern approaches using LIDAR technologiy, which seek to optimize efforts and make data collection faster and more numerous. Field data will remain essential to validate these approaches and must be improved with the development of allometric equations specific to the region and the largest trees, with the need to increase the number of measured plots to improve the representation of the vegetation variation. Furthermore, it is essential to make these studies periodic and long-term, aiming at a growing understanding of the carbon in the forest with the purpose of valuing its natural capital.

It is a challenge to understand how biodiverse regions of woody plants, such as the Carajás National Forest, with diverse forest phytophysiognomies in the same conservation unit, contribute to carbon sequestration. However, we are on the way to understanding this forest dynamics.

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12

Carbon stock and soil quality

Wendel Valter da Silveira Pereira, Paula Godinho Ribeiro, Gabriel Caixeta Martins, Rafael Borges Valadares, José Augusto Bitencourt, Silvio Ramos

Carbon in the soil

The soils represent the largest reservoir of carbon (C) in the terrestrial ecosystems, mainly tropical forest soils (Sayer et al., 2021). The soils of the Amazon rainforest, for example, absorb around 25% of the terrestrial carbon annually (Damian et al., 2021). Due to the large amount of this gas retained in the soil, small losses can cause strong impacts on its concentration in the atmosphere. These losses are mainly controlled by climatic factors, such as temperature and humidity, by soil characteristics, such as clay content and mineralogy, and by human actions that modify the landscape.

The carbon in the soil can be found in inorganic and organic forms. Inorganic carbon comprises carbonates and bicarbonates resulting from the weathering of the source material and soil processes, while organic carbon results from the decomposition of organic residues and by-products of microbial activity (Kim et al., 2021). Depending on the environmental conditions, organic carbon may have a shorter residence time in the soil when compared to inorganic carbon and is widely used as a quality indicator in response to the impacts of the management on the ecosystems.

Organic carbon can be found in active (labile) and passive (recalcitrant) forms in the environment. Active fractions are the main natural source of nutrients in the soil, composed of plant roots, microorganisms and derivatives, and non-humic substances that decompose quickly and are more sensitive to management variations. Passive fractions, in turn, have longer residence time in the environment due to a series of compounds that increase the resistance to decomposition, representing a stable reservoir of carbon in the soil.

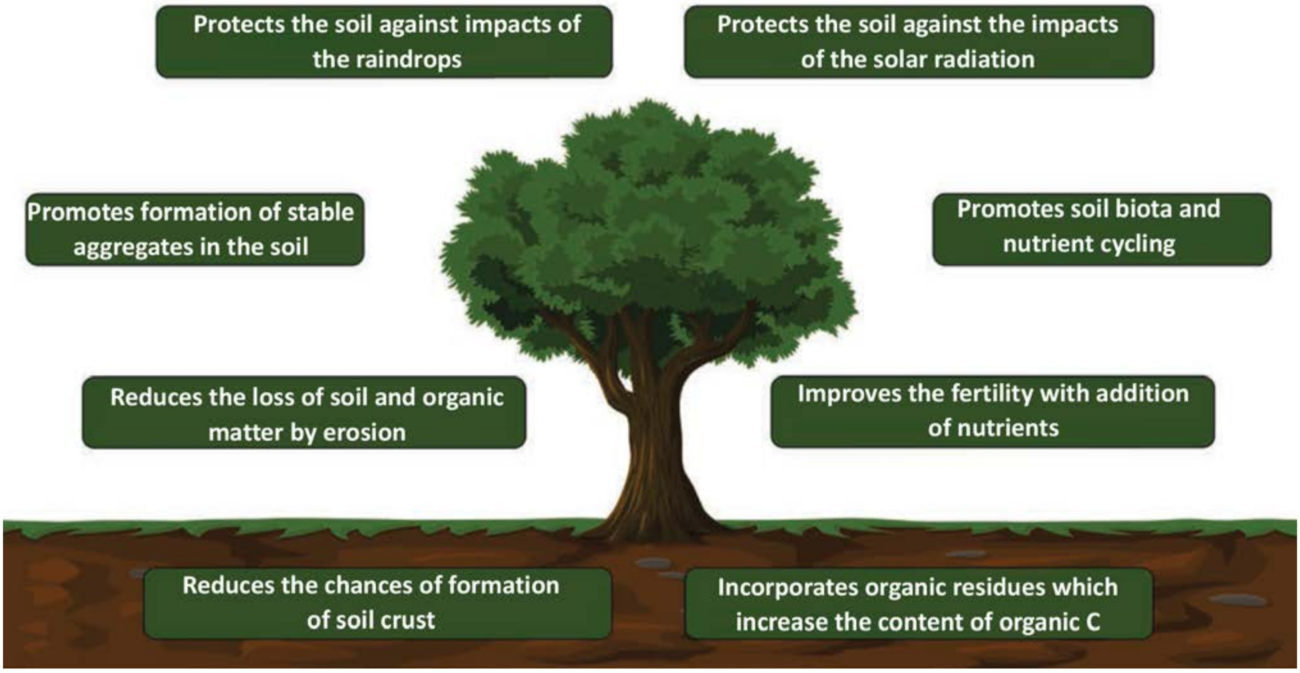

Figure 1. Importance of the vegetation cover for the soil quality.

Carbon in the soil and vegetation cover

The vegetation cover contributes to the incorporation of materials that constitute important sources of organic matter and organic carbon for the soil. The association between organic matter and mineral particles promotes the formation of aggregates that are essential for reducing soil losses. Losses of organic carbon occur mainly with the disorganization of the soil structure, generally by erosion in unprotected areas.

Changes in the vegetation cover can modify the stability of the soil carbon stocks and contribute to the progress of climate change. The conversion of natural areas into agricultural areas, for example, accelerates the rate of mineralization of organic matter and significantly reduces carbon levels in the soil. It is estimated that the conversion of tropical forests into agricultural areas causes the loss of more than 75% of the soil organic carbon content (Lal, 2004). Therefore, the maintenance of the vegetation cover is crucial for mitigating carbon losses and maintaining or improving the soil fertility (Figure 1).

In tropical regions, such as the Amazon, heavy rains and high temperatures favor the loss of soil and organic matter by erosion, as well as the accelerated decomposition of the organic residues. In these regions, the maintenance of the vegetation cover is essential for mitigating the impacts of the raindrops, reducing the speed of water runoff, and reducing the incidence of solar radiation, which favor the protection of the soil, and consequently, the carbon in the soil.

Carbon stock and soil quality

Organic carbon has several functions in the soil, affecting its chemical, physical, and biological properties. The cation exchange capacity (CEC) is one of the main chemical properties influenced by it, especially in the Amazon, where there is the predominance of sand and low-activity clays in the soil. This property is crucial for the soil fertility, as it contributes to the retention of cationic nutrients. Due to this capacity, organic carbon also has the potential to mitigate the impacts of potentially toxic elements, pesticides, and herbicides, reducing the bioavailability and the leaching of these contaminants. In addition to CEC, organic carbon also increases the soil buffering potential (Figure 2).

Several physical properties of the soil are favored by organic carbon, mainly the formation and the stability of aggregates, which improve the structure, increase infiltration and water retention, and reduce the soil susceptibility to the erosion process. Soils with better aggregation also show lower density, greater aeration and are less susceptible to the formation of crusts and compacted layers, which favors the development of the plant roots (Figure 3) and boosts microbial activity (Nziguheba et al., 2015).

Organic carbon positively affects several biological properties of the soil, including the activity of microorganisms and fauna. It is a source of energy for microorganisms which work in the decomposition of organic residues, which is fundamental for the nutrient cycling. Different organisms use it and act in the soil mixing and redistribution of nutrients, as well as in the aggregation and the formation of

Figure 2. Effects of the carbon stock on the quality of the soil.

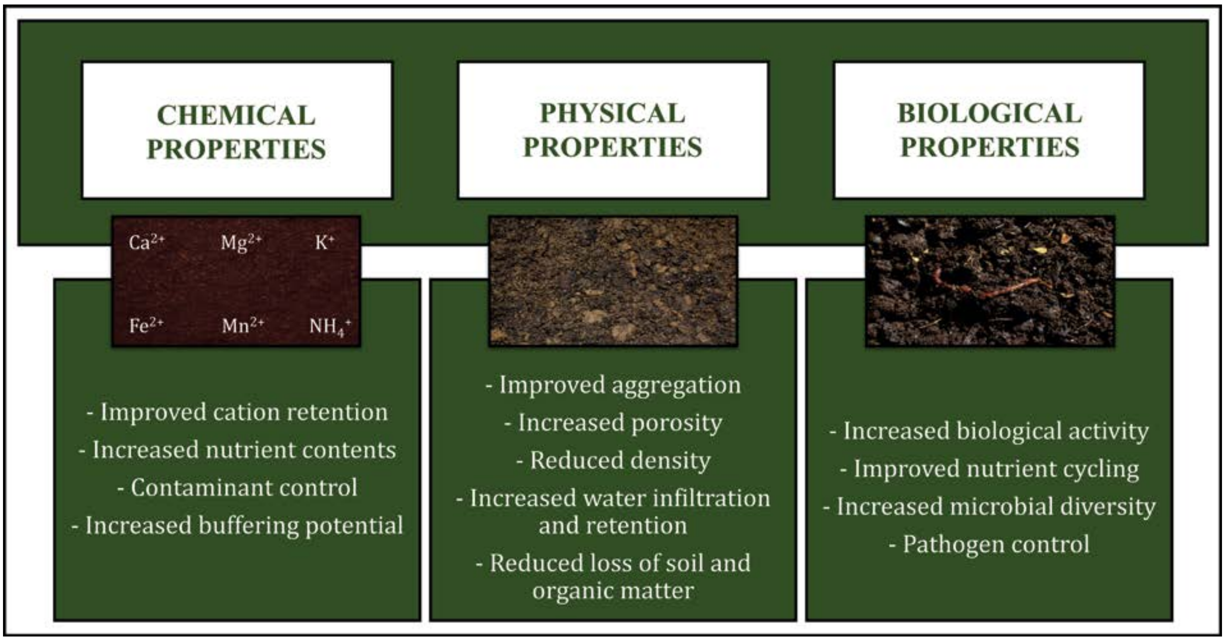

Figure 3. Tangled roots on the forest soil.

galleries that improve aeration. Furthermore, pathogenic organisms are regulated by adequate levels of organic carbon in the soil due to the growth of the population of saprophytic organisms (Obalum et al., 2017).

Quantification of the soil carbon stocks

There are several *ex situ* and *in situ* methods for the determination of the concentration of organic carbon in the soil. Wet methods *ex situ* include oxidation of the soil organic matter with potassium dichromate, sulfuric acid, and phosphoric acid, and quantification of CO_2 released by gravimetry, titrimetry, and manometry. Dry methods *ex situ* include mass loss by ignition; in them, the samples are heated in a muffle furnace at temperature of 430 ºC, and the carbon is quantified by gravimetry. An automated carbon analyzer can also be used, which is a simple, fast and accurate method, but is more expensive than the others.

Proximal sensors are used for the prediction of soil carbon *in situ*. An example is spectroscopy in the visible and near infrared regions, which represents a reliable tool with similar precision to laboratory measurements (Biney et al., 2022). In addition, portable X-ray fluorescence and remote sensing techniques, alone or combined with spectroscopy, have also been used to predict soil carbon (Greenberg et al., 2023).

Carbon stocks are typically estimated using the formula EC = C × DS × P, where EC is the carbon stock (Mg ha^{-1}), C is the carbon concentration in the soil sample (%),

Figure 4. Soil with organic matter as substrate for the flora.

Figure 5. Organic matter on the forest ground, next to a tree with a tabular root.

DS is the soil density (g cm^{-3}) and P is the depth (cm). These estimates are essential for understanding carbon dynamics in terrestrial ecosystems, especially in tropical forest soils, which have been the target of strong environmental impacts as a result of human activities.

Carbon stocks in the Carajás National Forest

Different types of forests occur in the Carajás National Forest (Flona), including areas covered by dense and open rainforest, and open vegetation locally known as canga. Ramos et al. (2022a) observed organic carbon contents approximately three times higher in canga areas than in native forest areas in Flona de Carajás. In another research carried out in the same Flona, soils of native forests (0-10 cm) adjacent to mining areas had organic carbon contents ranging from 4.5 to 6%, and carbon stocks ranging from 28 to 38 Mg ha^{-1} (Guedes et al., 2021). Ribeiro et al. (2022), in turn, estimated approximately 50 Mg ha^{-1} of carbon in native forest soils (0-20 cm) in Carajás Flona.

In the context of the Natural Capital Project, in a study developed by Ramos et al. (2022b), soil samples were collected in the surface layer (0-20 cm) at the 14 sampling points already mentioned (Chapter 1) in Carajás. Estimated carbon stocks ranged from 18.04 to 95.36 Mg ha^{-1}, with average stock of 41.6 Mg ha^{-1}. Similar stocks (34.91 – 41.88 Mg ha^{-1}) were found in the surface layer (0-20 cm) of forest soils in the states of Pará and Maranhão (Cardozo et al., 2022) and in conservation agricultural production systems (~37.5 Mg ha^{-1}) in the state of Mato Grosso (Soares et al., 2020). On the other hand, carbon stocks (4.57 Mg ha^{-1}) were considerably lower in unprotected soils (0-20 cm) from sandstone mines in the southeast of the state of Pará (Ribeiro et al., 2022). These results demonstrate the importance of the protection of the forest soils (Figures 4 and 5) and the canga areas for the maintenance of the soil organic matter and reduction of the carbon emissions to the atmosphere.

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13

Stock of forest pollinators for agricultural production

Rafael Cabral Borges, Ulysses Madureira Maia, Tereza Cristina Giannini

The tropical forests around the world shelter the greatest diversity of animal and plant species on our planet (Brown, 2014). They are responsible for protecting a large stock of biodiversity capable of delivering benefits to people, including pollinators and their pollination service. Such a service is fundamental, as it directly contributes to the food production, supporting food security. A big part of the nutrients in people's diets are of vegetable origin, and the consumed vegetables come mostly from local agriculture, associated with the variety of native plants exploited commercially.

In this chapter, the importance of pollination in agriculture will be emphasized, highlighting the main crops in the areas surrounding the Carajás National Forest (Flona) and which species of bees identified there are agricultural pollinators. The purpose is also to demonstrate how the stock of pollinators in the forest can be used to support agriculture.

Importance of agriculture

In the state of Pará, agricultural production is of great importance not only to meet the local demand for food, but also because it is an essential component of the state economy, generating around 3 billion dollars in 2016 (Borges et al., 2020). This value is due to the production of 36 different crops, 20 of which depend on animals for pollination. In other words, without pollinators, the productivity of these crops can drop by up to 100%, as for the passion fruit, or in smaller percentages, as for açaí and other crops (Giannini et al., 2015).

The monetary value of the pollination service, delivered by pollinating animals and which contributes to the agricultural productivity in the state of Pará, was estimated at around 1 billion dollars, given the importance of pollination for the agricultural crops, for example, açaí, cocoa, soybeans and watermelon. In addition to the most commonly used crops, in the Amazon region, there is a great diversity of local plants used in local food and which contribute to driving the economy. Examples include soursop (*Annona muricata* L.), jackfruit (*Antocarpus heterophyllus* Lam.), peach palm (*Bactris gasipaes* Kunth) (Figure 1), babaçu (*Orbignya phalerata* Mart) (Figure 2) and uxi (*Endopleura uchi* (Huber) Cuatrecasas).

188 plant species used by traditional people in the Amazon, whether for food or other cultural purposes, have already been previously analyzed, which represents a huge potential for agricultural diversification. For more than half of these species (54%), the bees are potentially the most important pollinators, followed by beetles (14%) and moths (7%), for the production of fruits and seeds (Paz et al., 2021). When considering agricultural production based on agroforestry systems used in the same biome, 24 of the 33 agricultural species used depend on pollination, and once again, bees stand out as the main group of pollinating animals for these crops (Sabino et al., 2022).

Thus, the importance of the bees for food production becomes evident. However, bees need not only the foraging area, but also natural areas so that they can maintain themselves in the long-term, so that they are able to disperse and use the resources available in the agricultural areas, pollinating them wherever they are.

Agricultural crops in the surroundings of Carajás

The area surrounding Carajás was defined as the municipalities located up to 30 km far from the boundaries of Flona de Carajás. This limit was used because it is the maximum flight range of the collected bees (see Chapter 3). The municipalities included within this limit are Marabá, Parauapebas, Canaã dos Carajás, Água Azul do Norte and Curionópolis (Figure 3). According to the Brazilian Institute of Geography and Statistics (IBGE), 20 crops are cultivated in these municipalities (IBGE, 2023), 13 of which depend on animal pollinators (according to Giannini et al. 2015). Three crops (cocoa, passion fruit, and watermelon) have an essential degree of dependence on pollinators, i.e., virtually 100% of the production depends on the pollination service. Two crops (açaí and tomatoes) have a high degree of dependence (65% of the production is due to pollinators). Four crops have modest dependence, corresponding to 25% of the production due to pollination; and three crops (beans, papaya, and tangerine) have little dependence, around 5% of the production is due to animal pollination. Considering the annual production of each crop listed by IBGE, it was possible to calculate the value of the pollination service for 2021. This value corresponds to around 23.8 million reais in these municipalities in the surrounding of Carajás, showing the importance of pollinators for agriculture and the local economy.

Figure 1. A bunch of peach palm fruits, fruits of an important palm tree in the Amazon region.

Identified agricultural pollinators

Among the 122 species (37 genera) of bees identified from the 14 sampling areas of the Natural Capital project, 28 species (23%) and 24 genera (65%) are mentioned as pollinators of agricultural crops in previous studies in Brazil (Giannini et al. 2020). Most agricultural pollinator species identified belong to the Meliponini tribe (16 species), as the bees of genus *Melipona* Illiger, 1806. These are species that can be managed to provide pollination services in agricultural crops. Ten of the 28 identified pollinator species belong to the Euglossini tribe. Although Euglossini is best known mainly as pollinators of orchids, only males visit orchid flowers looking for sexual resources (aromatic essences), while females visit flowers looking for food resources. One species of pollinating bee with a nocturnal habit (*Megalopta amoena* Spinola, 1853) was also identified.

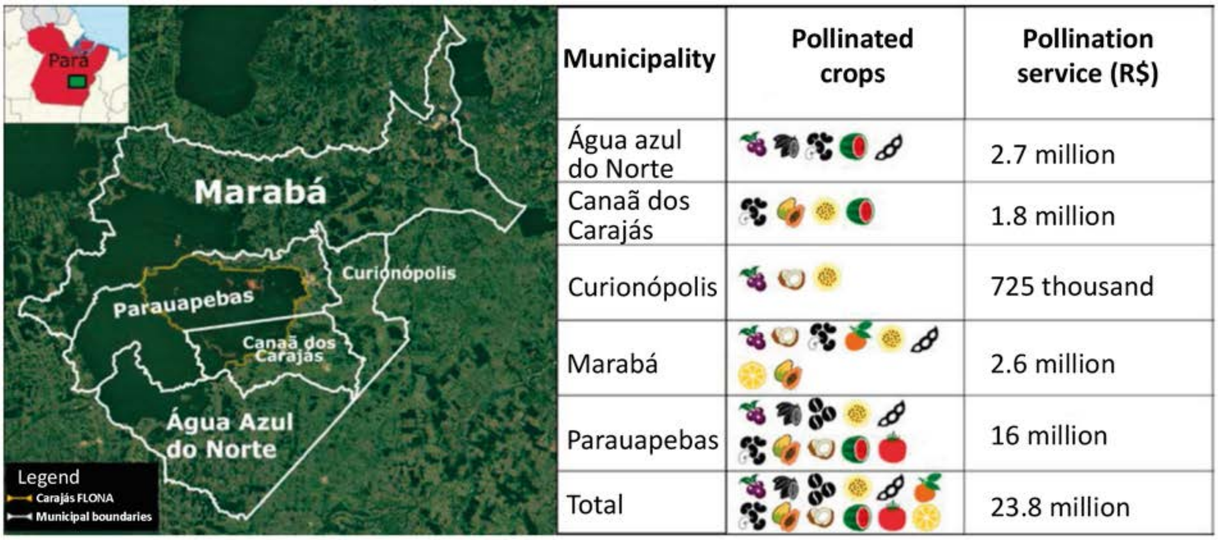
The females of this species are nocturnal, guided by chemical attractants to the flowers. An example of an agricultural crop visited by this bee is guaraná.

Bumblebee bees (for example, species *Xylocopa frontalis* Olivier, 1789 and *Eulaema bombiformis* Packard, 1869) were also identified in Carajás. These bees are big, solitary, with long flight range, and are the main pollinators of plants such as passion fruit and Brazil nut trees. Another important bee species collected in Carajás is *Apis mellifera* Linaeus, 1758. This is an invasive bee in Brazil, but it is an extremely generalist species (it is now spread throughout the country), it visits a high number of plant species, in addition to being an excellent pollinator of agricultural crops. The bees from both the Meliponini tribe and the *Apis mellifera* species have social behavior, i.e., more than one generation (mother, daughter, granddaughter) are present in the same nest. The nests of these species can be quite populous, from hundreds to thousands of individuals per nest. The nests are perennial, requiring food throughout the year, which means that these bees are always flying searching for resources.

Flight range and dispersal capacity

Figure 2.
Babaçu being sold in a municipal market. Babaçu flowers depend on pollinators for fruit production.

The flight range of the bees is directly related to their body size, to fly longer, the bees need bigger wing muscles. Each foraging flight (resource collection) of a bee has to consider the round trip distance, as the resources have to be brought back to a fixed point: the nest. Thus, very small bees (about 1 mm in intertegular distance, which corresponds to the width of the area where the wing muscles are located) will tend to forage in areas of about 100 to 200 m diameter, while larger bees (intertegular distance > 7.5 mm) are capable of flying over areas of around 40 km diameter. Thus, crops of passion fruit and Brazil nut trees in the surrounding area, for example, can benefit from the bees of Flona de Carajás. Body size is a direct



Municipality	Pollinated crops	Pollination service (R$)
Água azul do Norte		2.7 million
Canaã dos Carajás		1.8 million
Curionópolis		725 thousand
Marabá		2.6 million
Parauapebas		16 million
Total		23.8 million

Figure 3. Location of the Carajás National Forest (Flona), the surrounding municipalities, the agricultural crops that require pollinators for their production in each municipality and the estimated value of the pollination service.

limit on the daily flight capacity of the bees to collect resources. However, these bees also have dispersal movements, when they will occupy new environments. When they reach their maximum size, nests of social bees can divide (swarm), causing a dispersal event that will not be limited to the species' flight capacity, once there is no need to return to the nest. The dispersal capacity can benefit agricultural crops with very small flowers, such as the açaí flower (Euterpe oleracea Mart.). Açaí is a monoecious plant (produces separate male and female flowers), its flower is small and requires species of bees of corresponding size to visit flowers of both sexes for pollination to occur (Campbell et al. 2018). The stock of pollinator species of Flona de Carajás can then support the maintenance of pollinators in agricultural areas in the surrounding areas in the long-term, taking into account the capacity of the bee species to spread throughout the space (whether due to the flight capacity or dispersal) and the stability of the pollinator stock in Flona, once this is a protected area.

Pollinator management

Another important activity for the maintenance of the pollination service is the management of pollinators for agricultural areas (Lundin et al. 2021). This can be done using both social and solitary species of bees, depending on the agricultural crop. Considering the high stock of pollinator species found in Flona de Carajás (28 species), this protected area has a high potential to provide bee nest matrices

Figure 4. Interior of a rational stingless bee box.

for agricultural areas which may present a pollination deficit (which is a drop in productivity due to the lack of pollinators). Stingless bee species appear as the main candidates for management, because they are social species, which live mainly in pre-existing cavities and can be mimicked to ensure the success of rational breeding (Figure 4). These bees also produce bee products, such as honey, pollen, wax, and propolis, thus providing another income generation option for the farmers. However, some agricultural crops require solitary species to assure their pollination, such as passion fruit and Brazil nut trees. In these cases, it is possible to provide nesting sites to attract females to come and nest close to the production area, or even transport nests from the forest to cultivation areas, if there is a high demand. The bee management shows yet another potential use for the large stock of pollinators in the forest.

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14

Visit to BioPark in Carajás: the trees on the trails

Rafael Gomes Barbosa-Silva, Caroline Oliveira Andrino, Felipe Martello,
Cesar de Sá Carvalho Neto, Nikolas Jorge Carneiro, Ronnie Alves, Lourival Tyski,
Tereza Cristina Giannini

BioPark Vale Amazônia, created in 1985, is located in the city of Parauapebas, Pará, on road Raymundo Mascarenhas, n/n, km 26, in the Urban Center of Carajás, and its area is 30 hectares of native forest. The site is a space for visits, research, and environmental projects, where the visitors have the opportunity to enjoy a unique experience of immersion in the biodiversity of the Amazon rainforest, in addition to conserving species of the Amazonian fauna and flora. The search for ways to communicate to the public the richness and diversity of this biome is a challenge, especially in a context in which the sustainable use of natural resources gains relevance and urgency. In the Parauapebas region, the population growth and the use of finite natural resources suggest an urgency to optimize processes which disclose and bring human beings closer to nature. Within this context, the public knowledge about the Amazon Rainforest is often underrepresented, indirectly implying the loss of a big source of abiotic and biotic resources which, without due attention and protection, will be depleted without awareness of their vastness.

Just as the animals in BioPark Vale Amazônia stand out in the search of the visitors, it is important to rise interest in the knowledge about the plants. There are many studies that show that most people do not pay attention to the plants in their everyday lives (Parsley, 2020), and that their attention is captured more strongly and for longer when observing animals (Balas & Monsen, 2014). Furthermore, the names of animals are remembered more than those of plants (Schussler & Olzak, 2008) and there is even evidence that students do not perceive plants as living beings (Yorek et al., 2009). Therefore, there is a clear need to improve the public perception and knowledge about these beings which are so important to the ecosystem where we live and show the numerous environmental services the trees offer. Therefore, with the purpose of integrating information and


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providing social contribution more effective, we developed self-educational activities, accessible to the residents of Parauapebas, Vale employees and collaborators, and interested public in general, within the scope of Flona de Carajás, opening new perspectives of leisure and education for the local population in the BioPark. Within the Natural Capital Project, a possibility of making a link between the scientific study of flora plots and marking trees with tags containing QR codes was provided. Furthermore, in order to access the DNA of the plants, their genetic diversity, and the subsequent availability of this data, the inner bark of each individual was collected.

On the trails of BioParque Vale Amazônia, 100 trees were marked with stainless steel tags containing a QR code (Figure 1), and biological data was collected

Figure 1. Example of a tree containing a tag with a QR code.

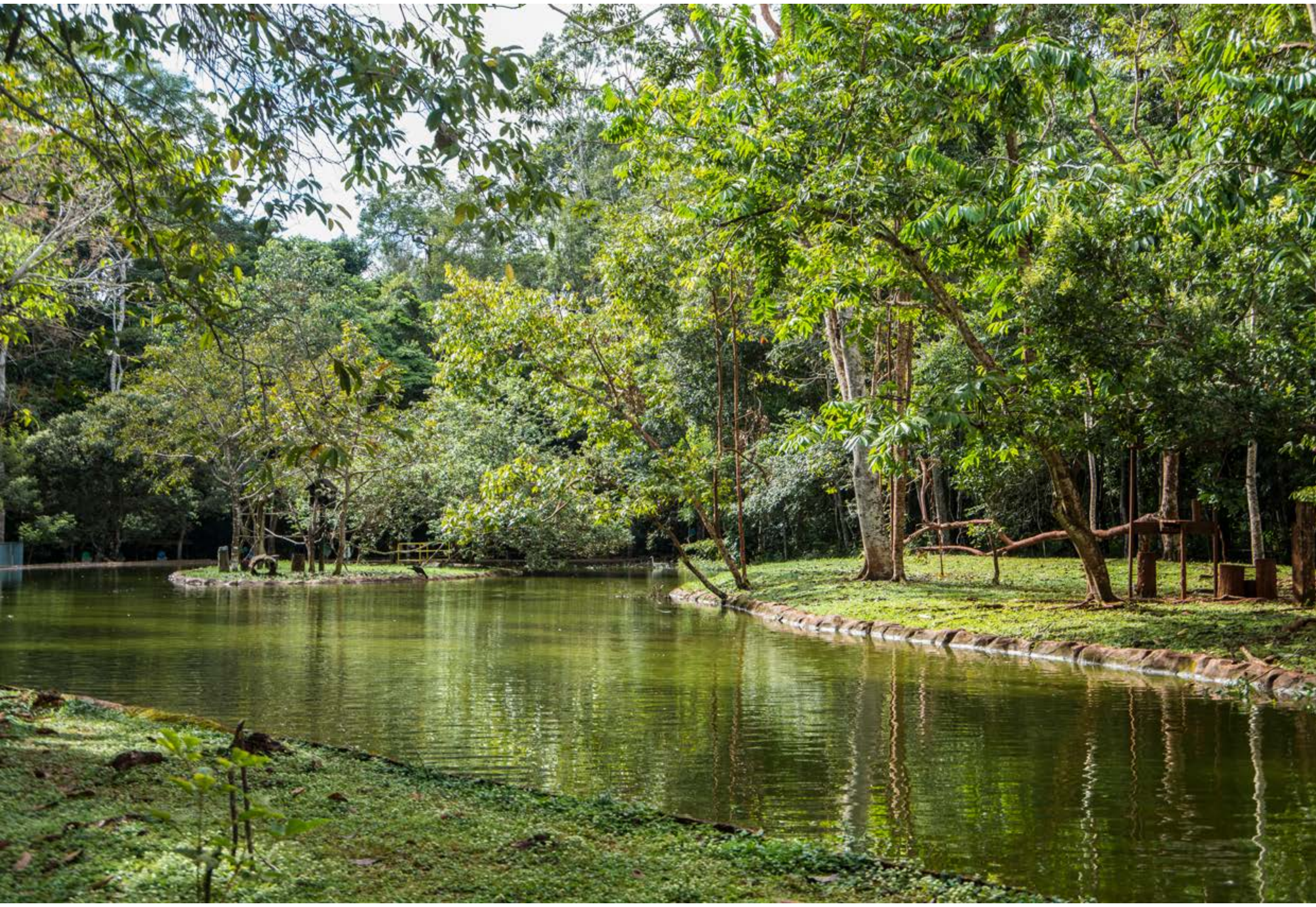

Figure 2. Lake in BioParque.

of each marked individual, such as height, circumference of the tree, species identification, photographs, as well as DNA samples, and georeferencing of each one on the trail (Figure 2), with the purpose of supporting on-site research and making the data available for the visiting public. The association between the species name and other information with the selected individuals will be made by reading the QR code using a cell phone camera reader (Figure 3). For this purpose, an application suitable for public use will assist in accessing this information. The application does not require internet access, which makes it easier to use in different locations in BioParque. The system aims to inform the general public, but will also serve scientists and environmental technicians who visit the site.

Figure 3. Visitor in the park accessing the data on one QR code tag..

Along the BioPark trail, 100 individuals were mapped and marked, representing 85 species, the visitors will be able to learn about their biology data, kinship with other plants, uses, curiosities, whether they are threatened or not and what the threat category is. Among the marked trees, there are both typical species of the Amazon Forest and Carajás Forest and rare species, which the visitors will have the unique opportunity to discover. Species, such as *Dipteryx odorata* (Aubl.) Forsyth f. (Cumarú), popularly called Amazonian vanilla and known for its very fragrant seeds and its use in food, in addition to being commercially important wood; *Bertholletia excelsa* Bonpl. (Brazil nut tree, Amazon nut), a species which, in addition to its known importance in the Amazonian food and culture, was planted in BioParque in 1991 by the King of the United Kingdom Charles III and his then wife, Lady Diana Spencer; *Handroanthus serratifolius* (Vahl) S.Grose (Yellow Ipê), from the Bignoniaceae family and which has great ornamental interest; *Bellucia grossularioides* (L.) Triana (araçá-de-anta, guava-de-anta), a species with very bright flowers and a fruit which is highly sought by the native fauna; *Matisia ochrocalyx* K.Schum. which is from the Malvaceae family, with several species that are economically important, such as cocoa, cupuaçu, cotton and okra. Along the BioPark trail, we also found rare plants, such as *Christiana mennegae* (Jans.- Jaq. & Westra) Kubitzki (Figure 4), which was not known until recently. It is a dioecious species, i.e., some individuals produce only male flowers and others produce only female flowers.

The Carajás National Forest (Flona) has several trails used by visitors and tourists, and we hope that the BioPark initiative will be applied to other trails in the Carajas Flona, consolidating a great tool for environmental education and bringing the local population closer to nature and to the forest they inhabit.

Table 1. Individuals selected on the BioParque path marked with QR Code and for whom there will be information made available to the visitors by means of the application.

Family	**Species**	**Common name**
Anacardiaceae	*Anacardium giganteum* W.Hancock ex Engl.	cajuaçu, caju-açu, caju-da-mata, cajuí
	Astronium lecointei Ducke	arueira, muiracatiara
	Spondias mombin L.	cajá, cajazeira
Annonaceae	*Annona mucosa* Jacq.	graviola-brava, fruta-de-condessa, fruta-de-conde, fructa-da-komdessa, condessa, biribá e araticum
	Duguetia flagellaris Huber	pina'y, caniceiro-preto, ameju-preto
Araliaceae	*Didymopanax morototoni* (Aubl.) Decne. & Planch.	mandioqueira, morototó, mucututu, matataúba, para-pará, marupá-uba-falso ou sambacuim
Arecaceae	*Astrocaryum aculeatum* G.Mey.	tucumã
	Euterpe oleracea Mart.	açaí
	Oenocarpus distichus Mart.	bacaba
Bignoniaceae	*Handroanthus serratifolius* (Vahl) S.Grose	ipê-amarelo, pau-d'arco-amarelo
	Jacaranda copaia (Aubl.) D.Don	parápara
Boraginaceae	*Cordia bicolor* A.DC.	chapéu-de-sol, freijó, freijó-branco, pau-de-jangada
Burseraceae	*Protium decandrum* (Aubl.) Marchand	breu-branco
	Protium paniculatum Engl.	breu-branco
	Trattinnickia burserifolia Mart.	amesclao
	Trattinnickia rhoifolia Willd.	almécega, almecegueira, amesclão, sucurubeira, amescla-aroeira, breu e breu-sucuruba
Caryocaraceae	*Caryocar villosum* (Aubl.) Pers.	pequiá, piquiá
Chrysobalanaceae	*Licania* Aubl.	–
	Moquilea tomentosa Benth.	oiti, oiti-da-praia
Combretaceae	*Terminalia argentea* Mart. & Zucc.	pau-garrote, pau-de-bicho, mirindiba, capitão-do-cerrado, capitão-do-campo, capitão, miringiba, tanimbuca-amarela, garote, canudeiro
	Terminalia argentea Mart. & Zucc.	pau-garrote, pau-de-bicho, mirindiba, capitão-do-cerrado, capitão-do-campo, capitão, miringiba, tanimbuca-amarela, garote, canudeiro
	Terminalia corrugata (Ducke) Gere & Boatwr.	cambuy, pau-pilão, mirindiba, mijol, cuiarana, tarumarana, merindiba, piá-banheira, pebanheira, biriba, miringiba, imbuzeiro
	Terminalia grandis (Ducke) Gere & Boatwr.	cuia-rana
	Terminalia parvifolia (Ducke) Gere & Boatwr.	tanimbuca
Elaeocarpaceae	*Sloanea parviflora* Planch. ex Benth	pateiro (genero Sloanea spp)
Euphorbiaceae	*Sapium glandulosum* (L.) Morong	burra-leiteira, janaguba, seringarana, leiteiro

Table 1. Individuals selected on the BioParque path marked with QR Code and for whom there will be information made available to the visitors by means of the application.

Family	**Species**	**Common name**
Fabaceae	*Abarema jupunba* (Willd.) Britton & Killip	saboeiro
	Amphiodon effusus Huber	gema-de-ovo, cumaru-de-rato
	Anadenanthera colubrina (Vell.) Brenan	angico-branco (*Anadenanthera colubrina* var. *colubrina*), Angico-Vermelho (*Anadenanthera colubrina* var. *cebil*)
	Apuleia leiocarpa (Vogel) J.F.Macbr.	amarelo, amarelão, mitaroá, muiratauá, muirajuba, cumaru-ferro, cumaru-cetim, mulateira, garapeira, garapa, garapa-branca, grapiapunha, grapiá
	Chamaecrista bahiae (H.S.Irwin) H.S.Irwin & Barneby	sucupira-preta, coração-de-negro
	Copaifera duckei Dwyer	podói, copaíba
	Copaifera martii Hayne	copaíba
	Dialium guianense (Aubl.) Sandwith	jataipeva, beiju-de-coco, tamarina, pau-ferro, roxinho, jataipeba, jitai-preto, jitai-amarelo, pororoca, tamarindo, huitillo, cacho, granadillo, tamarindo-de-montaña, comenegro, paleta, tamarino prieto, guapigue, ironwood, durinho, quebra-machado, sucupembinha, cururu, parajuba, jutaicica, jutaí, jutaí-pororoca
	Diplotropis purpurea (Rich.) Amshoff	sucupira-preta
	Dipteryx odorata (Aubl.) Forsyth f.	cumaru, cumaru-ferro, cumbaru, cumburu, paru, cumaru-verdadeiro, cumaru-amarelo, cumaru-do-amazonas
	Enterolobium schomburgkii (Benth.) Benth.	tamboril, orelha-de-negro
	Hymenaea courbaril L.	jatobá, jari, farinheira
	Hymenaea intermedia Ducke	jatobá-curuba
	Hymenaea parvifolia Huber	jutaí
	Inga alba (Sw.) Willd.	ingá-vermelho
	Marlimorimia psilostachya (DC.) L.P. Queiroz & Marc.F. Simon	timborana
	Myrocarpus frondosus Allemão	cabriúva, bálsamo, pau-bálsamo, sapuvão
	Ormosia paraensis Ducke	tenteiro, tento
	Parkia gigantocarpa Ducke	visqueiro, faveira-atanan, fava-barriguda
	Samanea tubulosa (Benth.) Barneby & J.W.Grimes	bordão-de-velho
	Samanea tubulosa (Benth.) Barneby & J.W.Grimes	bordão-de-velho
	Stryphnodendron pulcherrimum (Willd.) Hochr.	caubi, cobi, tamanqueira, tambaipé, taimbapé, tamba-em-pé, barbatimão, juerana-branca, juerana, munzê, muanza, paricá, favinha, paricá, baginha-de-são-joão, baguinha, baginha, camuzé, paricarana, timborana, timbó-da-mata, timbaúba, fava
	Tachigali glauca Tul.	tachi-de-formiga
Humiriaceae	*Endopleura uchi* (Huber) Cuatrec.	uxi, uxi-amarelo
Lamiaceae	*Vitex triflora* Vahl	tarumã

Table 1. Individuals selected on the BioParque path marked with QR Code and for whom there will be information made available to the visitors by means of the application.

Family	**Species**	**Common name**
Lauraceae	*Aniba ferrea* Kubitzki	louro-ferro
	Ocotea cernua (Nees) Mez	louro-canelinha
	Rhodostemonodaphne grandis (Mez) Rohwer	–
Lecythidaceae	*Bertholletia excelsa* Bonpl.	castanheira, castanha-do-brasil, castanha-do-pará
	Eschweilera obversa (O.Berg) Miers	matamatá
	Lecythis pisonis Cambess.	sapucaia
	Lecythis serrata S.A.Mori	matamatá-branco
Malvaceae	*Christiana mennegae* (Jans.-Jaq. & Westra) Kubitzki	–
	Guazuma ulmifolia Lam.	araticum-bravo, cabeça-de-negro, mutamba
	Matisia ochrocalyx K.Schum.	inajarana
	Sterculia apeibophylla Ducke	xixá-da-casca-grossa
	Sterculia apetala (Jacq.) H.Karst.	xixá (gênero *Sterculia*)
Melastomataceae	*Bellucia grossularioides* (L.) Triana	araçá-de-anta, goiaba-de-anta
	Miconia manauara R.Goldenb., Caddah & Michelang.	tinteiro
	Mouriri cearensis Huber	manipuça
Meliaceae	*Carapa guianensis* Aubl.	andiroba
	Swietenia macrophylla King	mogno
Moraceae	*Brosimum acutifolium* Huber	mururé, caucho, muiratinga
	Brosimum alicastrum Sw.	manité, guaimaro, ramon
	Perebea mollis (Poepp. & Endl.) Huber	cauchorana
Myristicaceae	*Virola michelii* Heckel	casca-de-vidro, ucuuba-preta
Myrtaceae	*Eugenia* L.	(gênero *Eugenia*) cagaita-vermelha, maria-preta
Opiliaceae	*Agonandra brasiliensis* Miers ex Benth. & Hook.f.	marfim-de-espinho, pau-marfim-do-campo, cerveja-de-pobre, pau-marfim-da-mata, cervejinha
Rubiaceae	*Chimarrhis turbinata* DC.	pau-de-remo, paraka'y
	Genipa americana L.	cabaçu, janapabeiro, janipaba, janipapeiro, janipapo, jenipá, jenipapo-bravo e jenipapo-do-mato, jenipaba, jenipaca, jenipapinho, jenipapo, jenipapo-da-américa, jenipapo-branco, jenipapo-comum, jenipapo-manso, jenipapo-de-cavalo, jenipava
	Genipa americana L.	cabaçu, janapabeiro, janipaba, janipapeiro, janipapo, jenipá, jenipapo-bravo e jenipapo-do-mato, jenipaba, jenipaca, jenipapinho, jenipapo, jenipapo-da-américa, jenipapo-branco, jenipapo-comum, jenipapo-manso, jenipapo-de-cavalo, jenipava
Rutaceae	*Zanthoxylum apiculatum* (Sandwith) P.G.Waterman	tamanqueira
Salicaceae	*Casearia pitumba* Sleumer	cabelo-de-cotia
	Laetia procera (Poepp.) Eichler	apijó, jacaré, paparaúba-da-serra, pau-jacaré, taxauá

Table 1. Individuals selected on the BioParque path marked with QR Code and for whom there will be information made available to the visitors by means of the application.

Family	Species	Common name
Sapindaceae	*Matayba arborescens* (Aubl.) Radlk.	espeturana-liso
	Talisia subalbens (Mart.) Radlk.	cancudo, cascudo, cascudinho
Sapotaceae	*Micropholis guyanensis* (A.DC.) Pierre	abiurana-balatarana, abiurana-branca, abiurana-mangabarana, abiurana-rosada, balata-brava, balata-rosada, balata-rosadinha, mangabarana, pau-doce, rosada-brava, rosadinha, rosadinha-brava
	Pouteria anomala (Pires) T.D.Penn.	abiu-rosadinha
	Pouteria manaosensis (Aubrév. & Pellegr.) T.D.Penn.	cucutiribá-folha-peluda
Simaroubaceae	*Simarouba amara* Aubl.	amarelinho, marupá, marupá-preto
Vochysiaceae	*Erisma uncinatum* Warm.	bruto, cedrinho, quarubarana
	Vochysia maxima Ducke	cedro-rana, quaruba

Figure 4. *Christiana mennegae* in BioParque.

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15

Trees with potential for urbanization in the cities in the region of Carajás, Pará, Brazil

Daniela C. Zappi, Juliana Lovo, Caroline O. Andrino, Rafael G. Barbosa-Silva, Felipe Martello

Urban afforestation in Brazil

The cities in the North region of Brazil are growing very quickly, changing the local microclimate and paying little attention to the biodiversity of the region, with urban afforestation made almost exclusively of exotic plant species. The benefits of urban afforestation are not only directly linked to biodiversity, climate and ecological functions which, at the same time, indirectly impact the cities and beyond. International objectives, such as the Aichi biodiversity targets (CBD, 2013, target 14 and 15), aim to assure that urban greening, including tree planting, is legally protected by the signatory countries of such convention.

In the present study, our intention was to use a floristic list of forests in the Carajás area as a robust source of information, using it to make a ranking of the most adequate species for the urbanization of the cities in the region of the Itacaiúnas river basin (Parauapebas, Canaã dos Carajás, Marabá, Ourilândia do Norte and Tucumã) (Figure 1). Different characteristics of the species, such as size, ornamental value, ecological role, resilience and minimally known propagation methods, were used for this ranking.

Selection of species

To select the species to be analyzed, a list of species occurring in the Carajás National Forest (Flona) and the Campos Ferruginosos National Park (PNCF) was used, prepared by the Instituto Tecnológico Vale between 2016 and 2019. 375 species were analyzed. The species recorded in the list have voucher specimens

Figure 1. View of the city of Parauapebas, close to the Carajás National Forest and the Parauapebas River.

deposited in the herbaria of Museu Paraense Emílio Goeldi (MG) and/or the Herbarium of Carajás (HCJS). Using information from virtual repositories (speciesLink, 2022, REFLORA, 2022), species with varied habits were excluded, as well as those with very large buttress roots, thorny trunks, toxic or invasive potential, which could become problematic in an urban environment. The ranking of the remaining species was based on tree size, ornamental value, ecological impact, predominantly Amazonian distribution, known propagation methods and resistance to sunlight (Zappi et al. 2022). These variables had the same weight during this selection phase. We present the results from the ranking using the InteractiVenn software (Heberle et al., 2015), which helps in the visualization of different attributes and the selection of species most adequate for urbanization (Figure 2). For the species that met five or six established criteria, the pollination syndrome (set of plant attributes that indicate the preferred potential pollinator) (Faegri & Pijl, 2013) and flowering time were researched, using the same repositories mentioned above, our experience in the field and specialized bibliography. The complementarity among the 49 selected species was also investigated to guide afforestation using the greatest possible biodiversity in a sustainable way. The following three variables were analyzed i) pollination syndrome, ii) beauty and iii) flowering season. The similarities and the differences between species were measured using an adequate statistical test (Generalized Distance of Gower; Pavoine et al., 2009). Another test was applied to help people identify a group of species as complementary as possible (Principal Coordinate Analysis, PCoA) (Figure 3). Species with edible fruits were also considered with the purpose of supporting greater animal diversity, representing them graphically in PCoA. The analyses were made on the R platform (R Core Team, 2021), using packages "ade4" (Thioulouse et al., 2018) and "vegan" (Oksanen et al., 2010).

Trees selected for planting

Once the selection was made, only seven species met the six criteria defined as desirable (Figure 4), while a group of 42 species met five of the six criteria (Table 1).

Table 1. Forty-nine tree species that meet six (*) or five criteria, with information about pollination and phenology (fl=flower, fr=fruit; I-January, II-February, III-March, IV-April, V-May, VI-June, VII-July, VIII-August, IX-September, X-October, XI-November, XII-December, AT-all year round). Criteria analyzed A. Appropriate height; B. Vast flowering; C. Fruits attractive to fauna and humans; D. Amazon distribution; E. Known propagation; F. Sunlight/heat resistance.

	Family	**Species**	**Criteria**	**Pollinator**	**Phenology**
1	Annonaceae	*Annona exsucca* DC.	A,C-F	Beetle	Fl XI–V, Fr III–VI
2	Annonaceae	*Xylopia aromatica* (Lam.) Mart.	A-C,E,F	Beetle	Fl VIII–V, Fr III–VIII
3	Apocynaceae	*Tabernaemontana flavicans* Willd. ex Roem. & Schult.	A-C,E,F	Bee	Fl VIII–X, Fr IX–VII
4	Bixaceae	*Cochlospermum orinocense* (Kunth) Steud.	A-C,E,F	Bee	Fl IV–X, Fr VI–IV
5	Boraginaceae	*Cordia goeldiana* Huber	A,B,D-F	Bee, fly	Fl VI–X, Fr IX–XII
6	Burseraceae	*Protium sagotianum* Marchand	A,C-F	Bee	Fl VIII–I, Fr XI–VI
7	Chrysobalanaceae	*Hirtella racemosa* Lam.	A,B,D-F	Butterfly	Fl II–VII, Fr VIII–X
8	Clusiaceae	*Clusia panapanari* (Aubl.) Choisy	A-C,E,F	Bee	Fl II–XI, Fr IX–I
9	Clusiaceae	*Symphonia globulifera* L.f.	A-C,E,F	Bird	Fl VII–II, VI–V, Fr VIII–II
10	Ebenaceae	*Diospyros vestita* Benoist	A,C-F	Insect	Fl VII–II, Fr VI–VII
11	Fabaceae	*Abarema cochleata* (Willd.) Barneby & J.W.Grimes	A,B,D-F	Bat, moth	Fl VIII–I, Fr AT
12	Fabaceae	*Bauhinia acreana* Harms	A,B,D-F	Bat	Fl X–V, Fr XI–VI
13	Fabaceae	*Bowdichia nitida* Spruce ex Benth.	A,B,D-F	Bee	Fl IV–VII, Fr VI–IX
14	Fabaceae	*Campsiandra laurifolia* Benth.	A,B,D-F	Bat	Fl V–I, Fr VI–IV
15	Fabaceae	*Cassia fastuosa* Willd. ex Benth.	A,B,D-F	Bee	Fl VII–XI, Fr XI–VIII
16	Fabaceae	*Cenostigma tocantinum* Ducke	A,B,D-F	Bee	Fl IV–II, Fr V–XII
17	Fabaceae	*Hymenaea parvifolia* Huber	B-F	Bat	Fl XI–III, Fr AT
18	Fabaceae	*Inga disticha* Benth.	A-C,E,F	Bee, butterfly	Fl VI–IX, Fr XI–VII
19	Fabaceae	*Inga heterophylla* Willd.	A-C,E,F	Bee	Fl XII–VI, IX, Fr V–XI, I
20	Fabaceae	*Inga marginata* Willd.	A-C,E,F	Bee	Fl VII–XII, Fr IX–IV

Table 1. Forty-nine tree species that meet six (*) or five criteria, with information about pollination and phenology (fl=flower, fr=fruit; I-January, II-February, III-March, IV-April, V-May, VI-June, VII-July, VIII-August, IX-September, X-October, XI-November, XII-December, AT-all year round). Criteria analyzed A. Appropriate height; B. Vast flowering; C. Fruits attractive to fauna and humans; D. Amazon distribution; E. Known propagation; F. Sunlight/ heat resistance.

	Family	**Species**	**Criteria**	**Pollinator**	**Phenology**
21	Fabaceae	*Inga nobilis* Willd.*	A-F	Bat	Fl X–V, Fr II–VI
22	Fabaceae	*Inga stipularis* DC.	A-E	Moth, bat	Fl II–VI, XI, Fr I–VII
23	Fabaceae	*Inga umbellifera* (Vahl) DC.*	A-F	Moth	Fl V–IX, Fr VI–X
24	Fabaceae	*Platymiscium filipes* Benth.	A,B,D-F	Bee	Fl III–XI, Fr VII–III
25	Fabaceae	*Senna multijuga* (Rich.) H.S.Irwin & Barneby	A,B,D-F	Bee	Fl IV–XII, Fr VII–XII
26	Fabaceae	*Swartzia arumateuana* (R. S. Cowan) Torke & Mansano*	A-F	Bee	Fl II–V, Fr IV–XII
27	Fabaceae	*Swartzia brachyrachis* Harms*	A-F	Bee	Fl III–VI, Fr VI–II
28	Fabaceae	*Tachigali paniculata* Aubl.	A,B,D-F	Bee	Fr VI–XI, Fr VIII–II
29	Fabaceae	*Zollernia paraensis* Huber	A-C,E,F	Bee	Fl VIII–X, Fr XI–XII
30	Lecythidaceae	*Eschweilera obversa* (O.Berg) Miers	B-F	Bee	Fl V–VI, XI–I, Fr V–VI, XII
31	Malpighiaceae	*Byrsonima spicata* (Cav.) DC.	A-C,E,F	Bee	Fl VII–IV, Fr X–V, VII
32	Malpighiaceae	*Byrsonima stipulacea* A.Juss.	A-C,E,F	Bee	Fl X–I, Fr V–VII
33	Malpighiaceae	*Lophanthera lactescens* Ducke	A,B,D-F	Bee	Fl V, X, Fr V
34	Malvaceae	*Matisia ochrocalyx* K.Schum.	A,B,D-F	Bat	Fl I–VIII, Fr VIII–X, III
35	Malvaceae	*Theobroma speciosum* Willd. ex Spreng.*	A-F	Fly	Fl VIII–XI, Fr X–II
36	Melastomataceae	*Bellucia grossularioides* (L.) Triana*	A-F	Bee	Fl V–II, Fr VIII–IV
37	Melastomataceae	*Bellucia mespiloides* (Miq.) Macbr.	B-F	Bee	Fl IX–II, VII, Fr X–II
38	Melastomataceae	*Miconia ampla* Triana	A,C-F	Bee	Fl I–IV, Fr III–VII
39	Melastomataceae	*Miconia egensis* Cogn.	A,C-F	Bee	Fl III, IX–XI, Fr III, X–XI
40	Melastomataceae	*Mouriri acutiflora* Naudin*	A-F	Bee	Fl VIII–XII, Fr X–II
41	Melastomataceae	*Mouriri brachyanthera* Ducke	A,C-F	Bee	Fl I, IV–V, XII, Fr I, V–VII
42	Melastomataceae	*Mouriri cearensis* Huber	A-C,E,F	Bee	Fl X–XII, Fr IV–V, X, XII
43	Melastomataceae	*Mouriri vernicosa* Naudin	A-E	Bee	Fl V–VIII, X–XII, Fr VII–XI
44	Myrtaceae	*Eugenia anastomosans* DC.	A,C-F	Bee, fly	Fl X–XII, Fr VII
45	Myrtaceae	*Eugenia ramiflora* Desv. ex Ham.	A,C-F	Bee	Fl. X–XII, Fr I
46	Myrtaceae	*Myrcia pyrifolia* (Desv. ex Ham.) Nied.	A,C-F	Bee, fly	Fl X–I, Fr. III–VI, VIII, XII
47	Myrtaceae	*Psidium acutangulum* DC.	A,C-F	Bee	Fl VI–X, Fr. IV–VI, IX
48	Verbenaceae	*Citharexylum macrochlamys* Pittier	A,C-F	Moth	Fl I–IV, VIII, Fr I–IV, VIII
49	Vochysiaceae	*Erisma uncinatum* Warm.	B-F	Bee	Fl VIII–XI, Fr VII–I

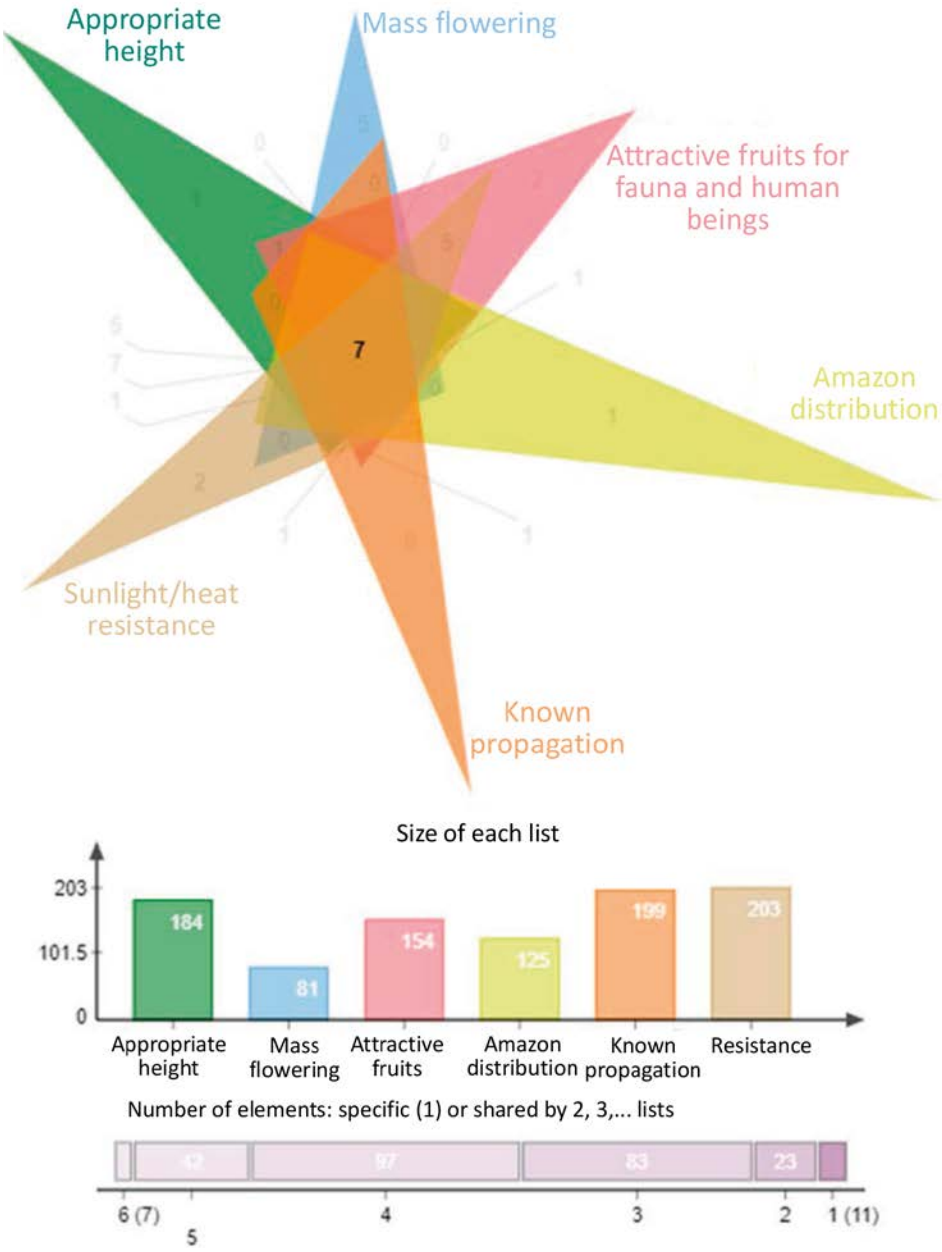

Figure 2. A. Venn diagram showing the species selected according to the six desirable characteristics. B. Graph showing the number of tree species grouped by criteria (A. Appropriate height, B. Mass flowering, C. Fruits attractive to fauna and humans, D. Amazonian distribution, E. Known propagation, F. Resistance to sunlight/ heat).

In terms of exclusion of species from the list, the determining criteria were ornamental value (69.2%) and geographic distribution (52.5%), followed by those with inedible fruits (41.4%), excessive height (30 %), lack of knowledge about propagation (24.3%) and poor resistance to sunlight (22.8%). If parks and open areas are considered for afforestation, it is possible to make a list without height limitation, which includes species such as *Hymenaea parvifolia* (Fabaceae), *Eschweilera obversa* (Lecythidaceae)

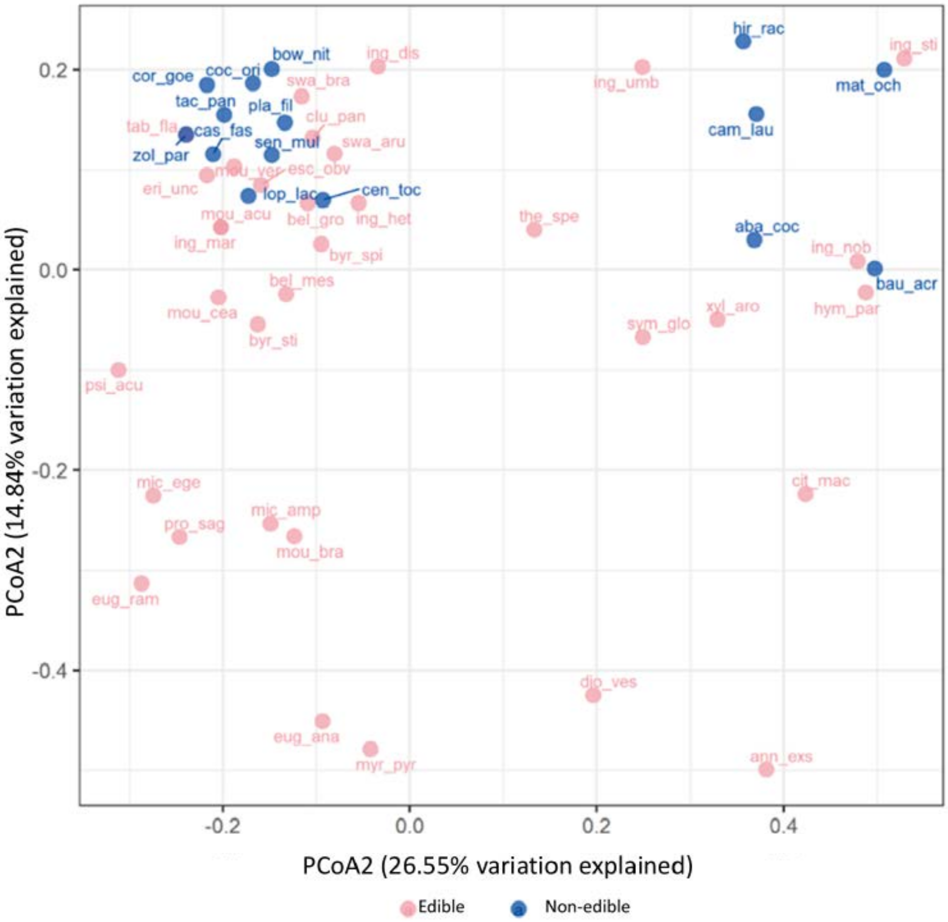

Figure 3. Principal Coordinate Analysis (PCoA) based on the dissimilarity of the trees calculated using the Generalized Gower Distance. Species are indicated by a 6-letter code (separated by a dash "_"), the first three letters are the genus and the last three are the first letters of the species name, considering edible and inedible fruits for fauna.

and *Ersima uncinatum* (Vochysiaceae). In the PCoA analysis, the species represented close to each other are more similar than those located far from each other (Figure 3).

The selection of plants with ornamental value is justified (Figure 4), as it is one of the most frequently expressed desires by the local population and also makes more sense for the people's connection with nature, following targets 1 and 2 of Aichi (CBD, 2013). The choice of trees with edible fruits aims to encourage wildlife (birds, mammals) to in the greening of cities. We also point out that the lack of knowledge about propagation and cultivation of different species is a subject of interest for conservation and horticulture professionals, and therefore, our work also lists which genera need more research regarding seed germination (see Zappi et al., 2022). Thanks to the resistance criterion, we tried to avoid indication of trees from flooded ecosystems (floodplains, igapó, dry land forest understory), as these may not survive under the typical exposure conditions of an urban environment.

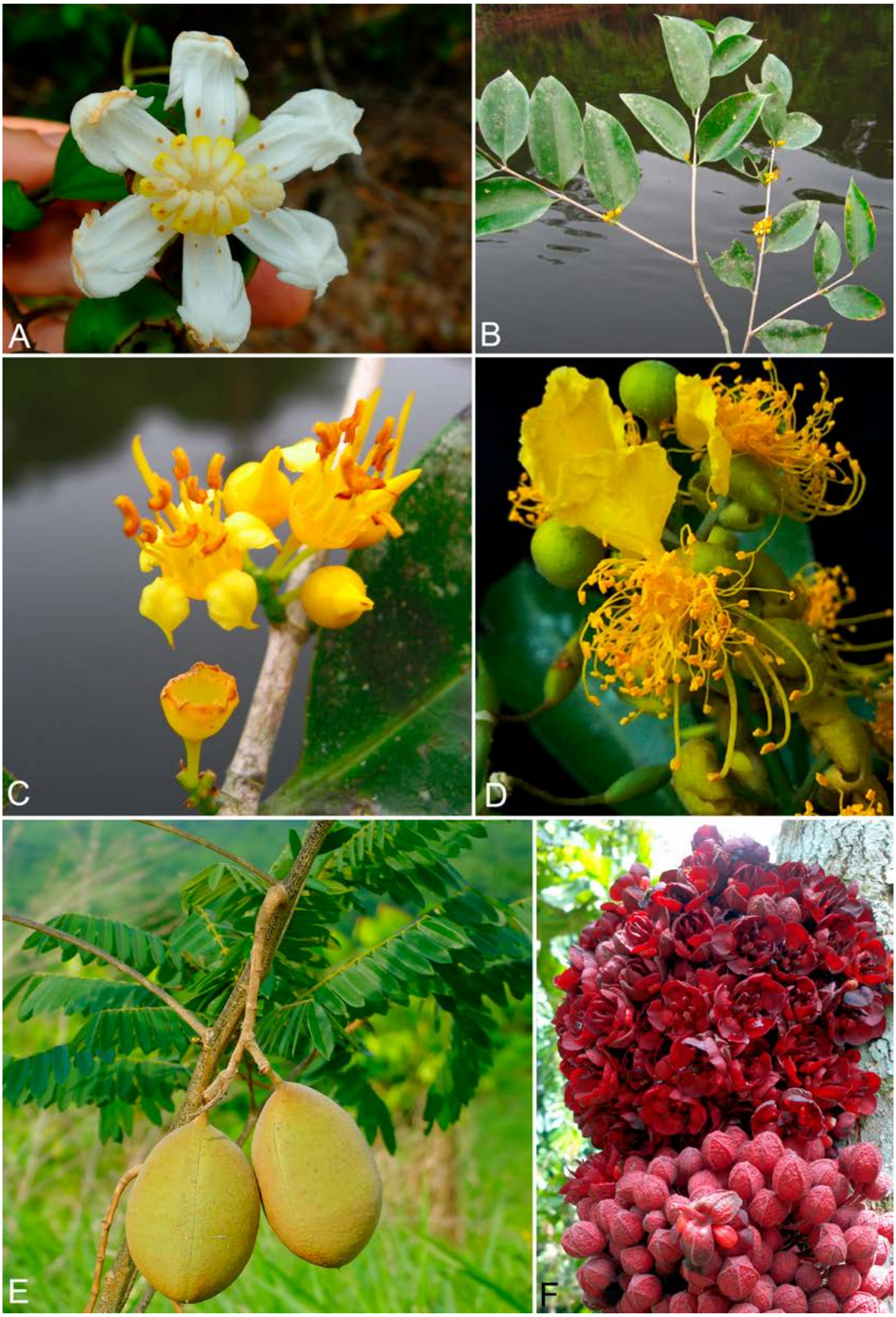

Figure 4. Images of tree species selected by means of the ranking system and which meet all six criteria (A. Flower of *Bellucia grossularioides*, B-C. Mouriri acutiflora, habit and flower, D. Flowers of *Swartzia brachyrhachis*, E. Fruit of *Swartzia arumateuana*, F. Cauliflory in *Theobroma speciosum* (D, F courtesy of L.O.A. Teixeira).

The lack of knowledge on obtaining and cultivating seedlings of native tree affects the planning of the local governments but can present an opportunity for rural producers to collect seeds to planting seedlings intended for urban areas (Ronquim et al., 2020). However, such involvement aligns with the arguments about the value of the standing forest, potentially generating employment.

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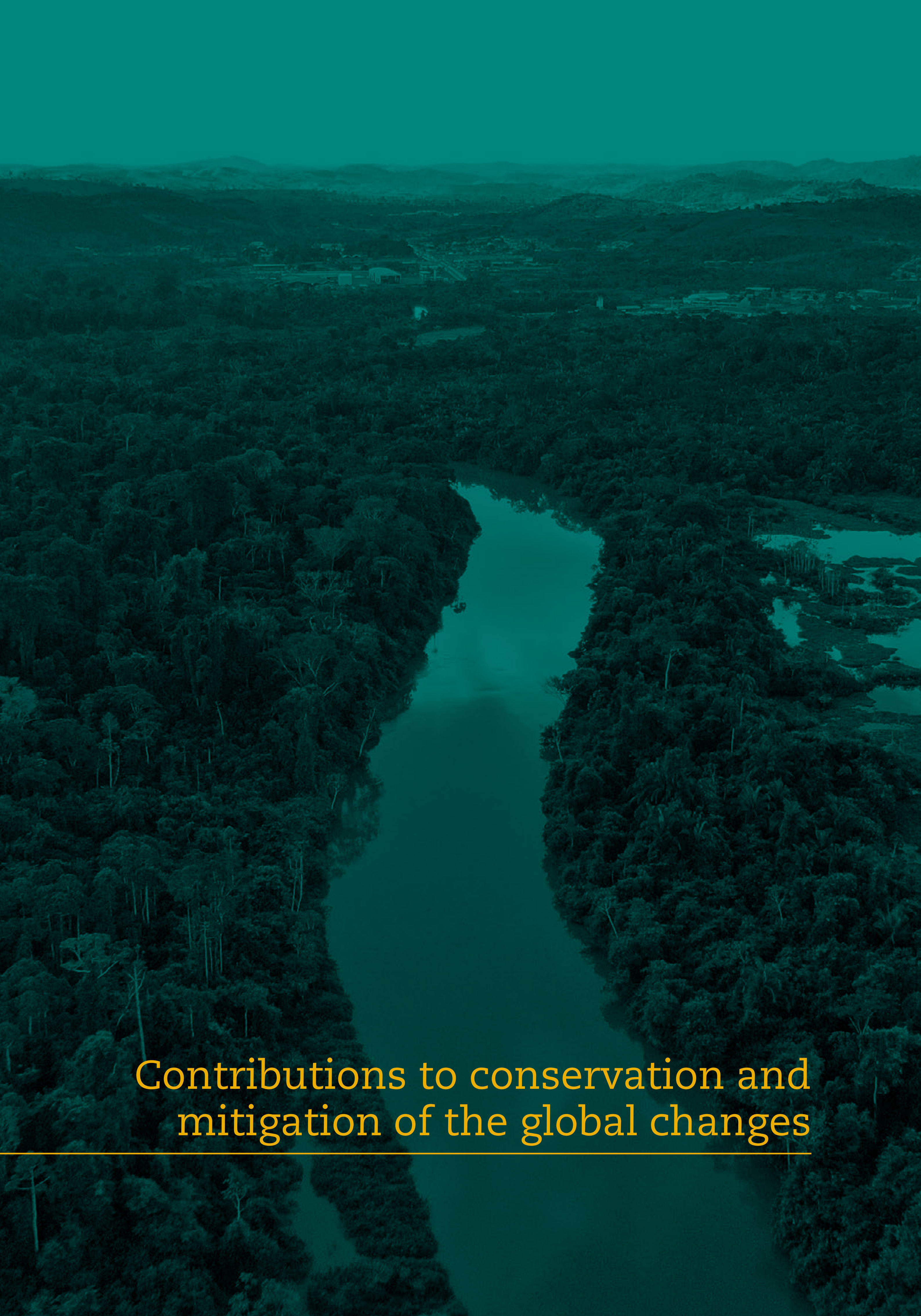

Contributions to conservation and mitigation of the global changes

16

Genetic resources and conservation of biodiversity

Michele Molina, Alexandre Aleixo, Guilherme Oliveira, Santelmo Vasconcelos

Genetic resources in conservation

The region of the Carajás National Forest (Flona) is recognized as an area of high biodiversity, highlighting the strategic importance of the region for the conservation of species from the Amazon biome. A broad characterization of biodiversity is necessary and urgent to understand this ecosystem. However, the survey of species involves the challenging task of identification and taxonomic description, which depends on a meticulous morphological analysis by specialist taxonomists. Such professionals are often scarce and are not evenly distributed to cover the entire biological diversity.

In this context, molecular biology tools have been successfully used to access the composition of the diversity of natural populations quickly and robustly, and to genetically characterize critical species for the maintenance of the ecosystem services. Furthermore, the use of genetic information overcomes some problems imposed by the traditional morphological identification, such as the occurrence of adaptive convergence, which can result in the incorrect interpretation of homoplasies (Hebert & Barrett, 2005), in addition to the phenotypic plasticity of characters used to identify species (Kress & Erickson, 2007).

DNA barcodes and the characterization of biodiversity

Although there is a wide variety of components of genetic material used to determine the identity of the eukaryotic species, the small accessory genomes in mitochondria (mitogenomes) and in chloroplasts (plastomes) have been widely used for plant genetic characterization. Mitogenomes can vary significantly in size and

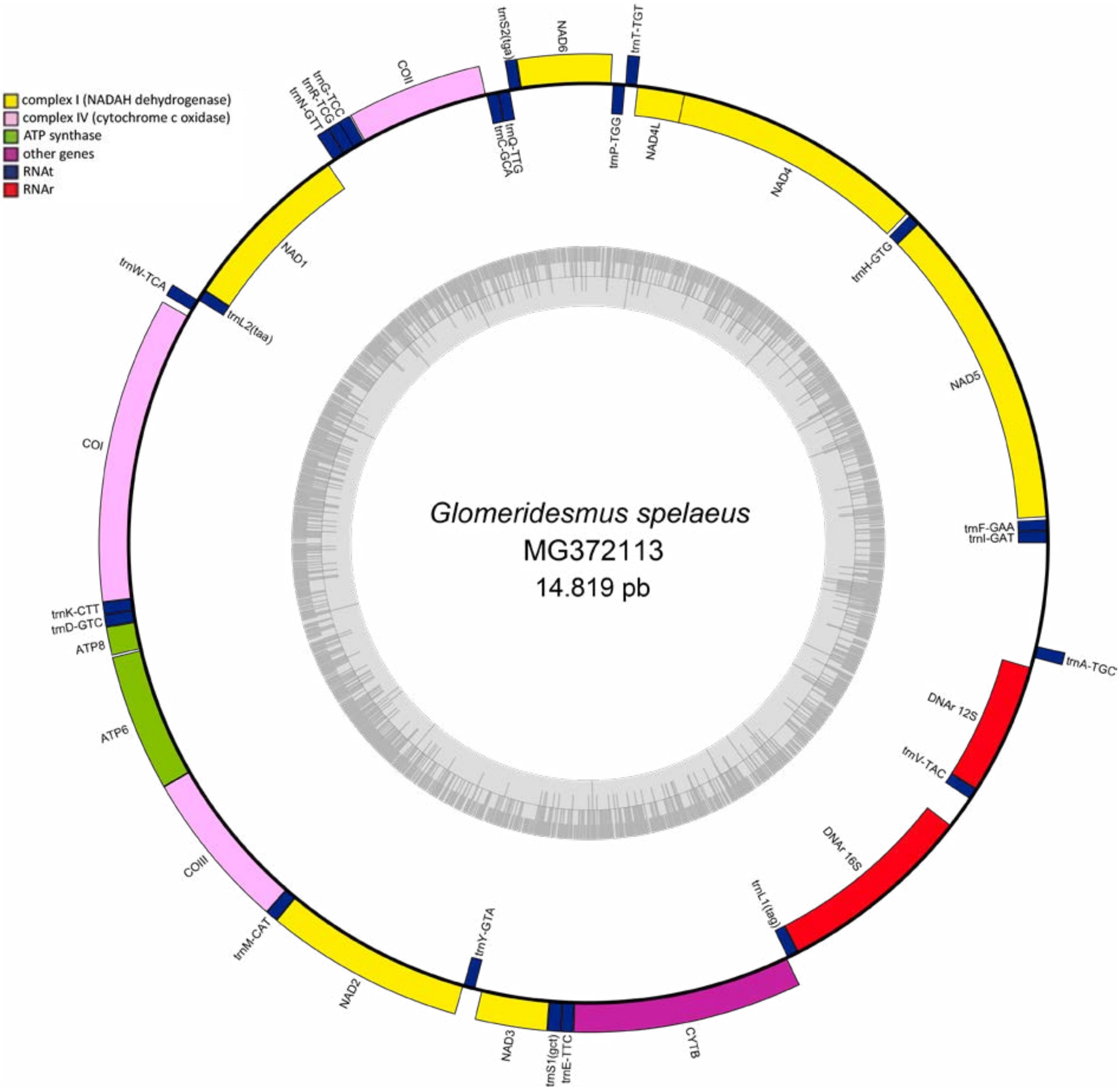

Figure 1. Map of the mitochondrial genome of *Glomeridesmus spelaeus* (Diplopoda, Glomeridesmida, Glomeridesmidae), a cave millipede endemic to the Serra dos Carajás region, adapted from Nunes et al. (2020).

gene content among different biological groups, exhibiting more conserved patterns in animal species, which range from 13 to 20 thousand base pairs (bp) (Figure 1) on average. Meanwhile, the mitochondrial genomes of fungi and plants can easily reach more than 10-20 times this size (Bock & Knoop, 2012). On the other hand, the mutational rates presented by animal mitochondrial DNA are approximately 100 times higher and can therefore be widely used in species delimitation and even population studies (Hebert et al., 2003; Bock & Knoop, 2012). In fact, only a part of the mitochondrial gene for subunit 1 of the enzyme cytochrome c oxidase (COI), measuring about 700 bp, has been most frequently used as DNA barcodes for animal taxa.

However, mitogenomes are not informative for identification of fungi and plants, considering the reduced mutational rates in both groups. Therefore, other parts of DNA have been tested and validated as barcodes for these groups of organisms. In case of fungi, the internal transcribed spacer region (ITS) of the 45S rDNA of the nuclear genome presents satisfactory levels of variation between species and is universally used for taxonomic characterization (Schoch et al., 2012). For plants, the process of selection, validation, and widely applying universal barcodes has been significantly hindered by the lack of a general pattern of nucleotide diversification in equivalent genomic regions among species, or even at higher taxonomic levels. In fact, plastomes (Figure 2) present higher mutational rates than plant mitogenomes, with several genes and non-coding regions of plastid genomes are used in analyses of evolutionary relationships between plant taxa. The genes of the large subunit of the ribulose-1,5-bisphosphate carboxylase oxygenase enzyme (rbcL) and the maturase K (matK) are more frequently used, with the nuclear ITS playing an important role as a complementary plant barcode. Nonetheless, it is worth pointing out that the broad acceptance of "official" barcodes has been more difficult among botanists, precisely due to the difficulty in standardizing genetic markers and analytical protocols (Hollingsworth et al., 2011, Vasconcelos et al., 2021).

In 2011, the International Barcode of Life consortium (https://www.ibol.org) implemented a broad genetic database on the diversity of eukaryotic species from all over the planet, the Barcode of Life Data (BOLD) Systems (https://www.boldsystems.org), seeking a wide range of information and the standardization of procedures to obtain high-quality data. Several national and international institutions have contributed significantly to the production of DNA barcodes since the implementation of the BOLD Systems, with the database currently containing over 13 million specimens from approximately 350 thousand species with deposited and validated sequences. However, the proportion of taxonomic coverage of available data is widely uneven, especially when considering the most diverse taxa in tropical regions (Table 1). Among the animal groups, Chordata have the highest proportion of coverage, with 36.24% of the 122,224 species with genetic data available, while Brachiopoda show the worst representation, with only 0.30% of the species with

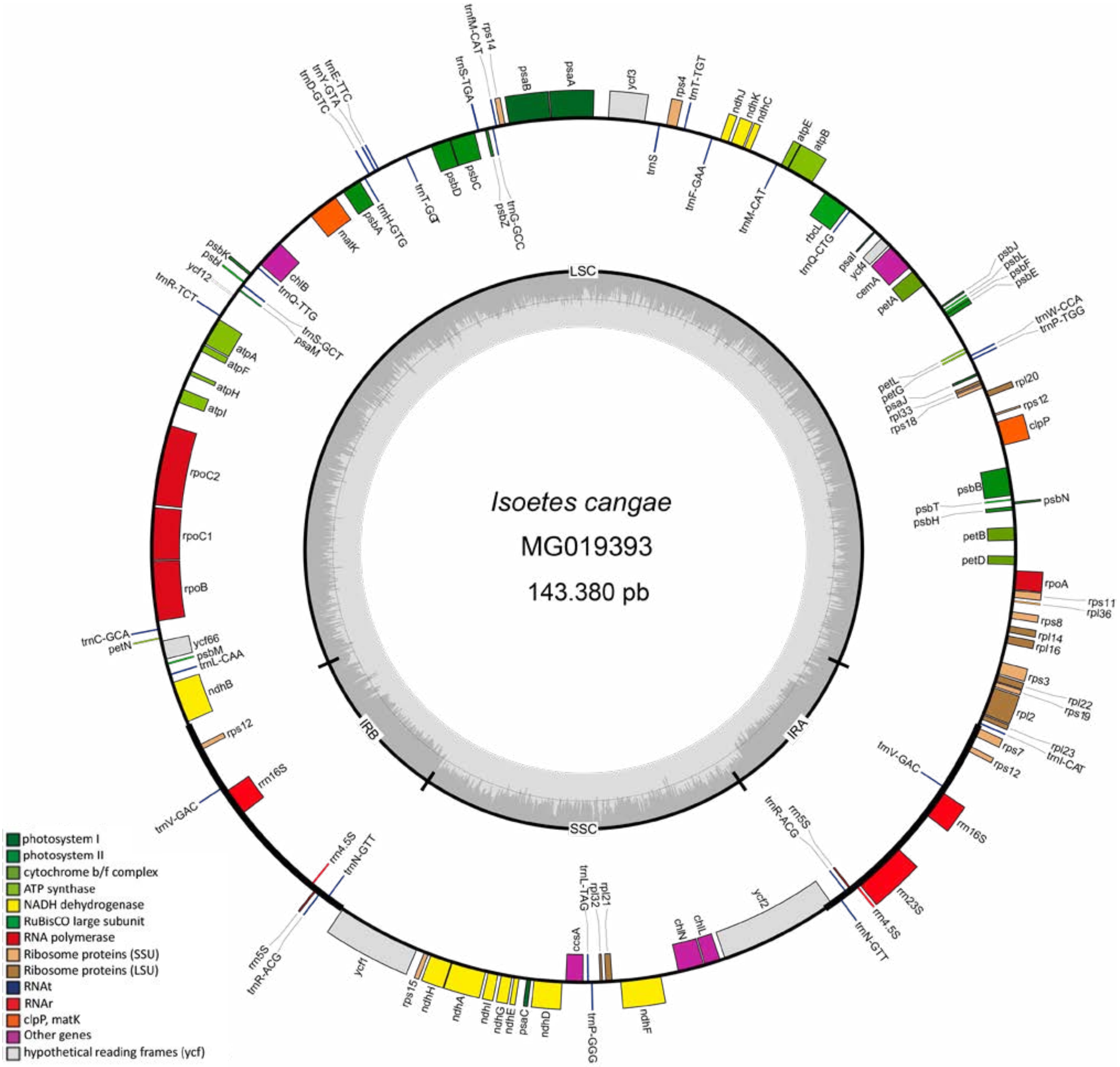

Figure 2. Map of the plastid genome of *Isoetes cangae* (Lycopodiopsida, Isoetales, Isoetaceae), an aquatic lycophyte microendemic from the Serra dos Carajás region, adapted from Nunes et al. (2017).

barcodes. For Arthropoda, the most diverse phylum among eukaryotes, reference sequences are available for 283,540 of the 1,343,184 described species (21.11%). The scenario is no different for the groups of fungi and plants, the groups with the greatest species diversity appear among the worst in terms of representation on the barcode base (Table 1).

Table 1. Groups of eukaryotes with DNA barcodes deposited in the BOLD Systems database (https://www.boldsystems.org). Only phyla of animals, fungi and plants with at least a thousand valid described species were listed, considering the data available in GBIF (https://www.gbif.org).

Group	**N. species**	**Species with barcodes**	**% species with barcodes**	**Specimens with barcodes**
Animalia				
Acanthocephala	1.498	108	7,21%	1.903
Annelida	25.003	6.908	27,63%	90.821
Arthropoda	1.343.184	283.540	21,11%	11.296.372
Brachiopoda	13.559	40	0,30%	241
Bryozoa	23.606	524	2,22%	3.126
Chordata	122.224	44.299	36,24%	744.370
Cnidaria	23.989	3.527	14,70%	23.146
Echinodermata	16.206	2.827	17,44%	43.487
Mollusca	174.204	20.426	11,73%	224.081
Nematoda	21.130	1.760	8,33%	17.772
Nemertea	1.535	559	36,42%	5.849
Platyhelminthes	26.942	1.110	4,12%	11.542
Porifera	12.623	1.680	13,31%	6.364
Rotifera	2.282	612	26,82%	10.698
Tardigrada	1.425	375	26,32%	2.375
Fungi				
Ascomycota	109.860	17.536	15,96%	84.978
Basidiomycota	55.508	13.619	24,54%	62.147
Chytridiomycota	1.123	76	6,77%	231
Myxomycota	1.184	158	13,34%	223
Zygomycota	1.192	521	43,71%	3.173
Plantae				
Bryophyta *s.l.**	38.678	1.866	4,82%	7.194
Charophyta + Chlorophyta	5.792	1.847	31,89%	5.891
Rhodophyta	4.184	3.384	80,88%	28.229
Tracheophyta	489.843	74.317	15,17%	268.324

*Bryophyta *s.l.* is a non-monophyletic group comprising three phyla of avascular land plants, Anthocerophyta (hornworts), Bryophyta (mosses) and Marchantiophyta (liverworts).

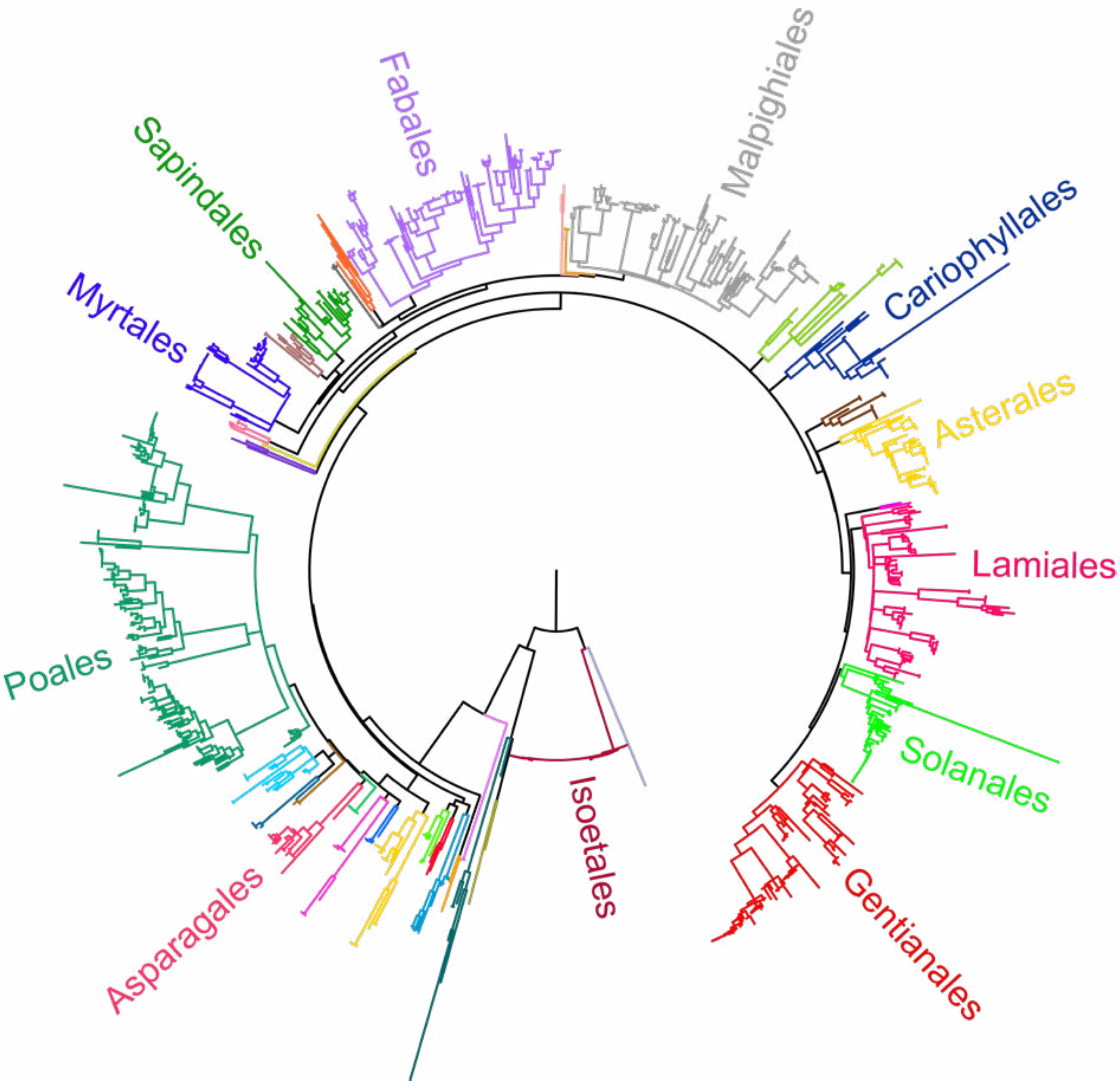

Figure 3. Phylogenetic reconstruction based on DNA barcode data from the flora of the cangas of Serra dos Carajás, highlighting the main groups of vascular plants observed in the region, adapted from Vasconcelos et al. (2021).

Vascular plants (Tracheophyta) exhibit immense ecological diversity, representing major components in terms of biomass in tropical forest ecosystems. However, only a very small fraction of this floristic diversity has been properly studied and cataloged, especially in biomes with broader geographical distribution, as is the case in the Amazon basin. As mentioned earlier, the genetic diversity of these environments is even less known, reflecting the very limited availability of comprehensive taxonomic treatments for local floras.

Diversity of the Carajás National Forest

In the Amazon, the canga region of the Carajás National Forest is the only one with a complete floristic survey available, with taxonomic treatments aimed at all families of the described vascular plants (Mota et al., 2018; Salino et al., 2018). It also includes the description and the implementation of a comprehensive library of genetic references based on DNA barcodes for flora (Figure 3), with coverage of almost 80% of endemic species of vascular flora with genetic information generated and deposited in public databases. (Vasconcelos et al., 2021). Thus, the availability of this wide range of information collected about the flora in the region has shown to be essential for the directing of the species conservation measures and maintenance of the ecosystem services, especially considering the high rates of endemism described for Serra dos Carajás (Giulietti et al., 2019). Additionally, with the validation of the application of DNA meta-barcoding to survey plant diversity through composite sampling (Vasconcelos et al., 2021) or indirect sampling with environmental DNA (Martins et al., 2021), access to the plant composition of monitoring areas in Serra dos Carajás could be obtained more quickly and efficiently, using massive DNA sequencing approaches and targeted analyses made possible by the availability of a library of genetic references for the region. Finally, in the context of the Natural Capital project, we collected samples of the bark of 2 thousand specimens of forest trees (350 species – see Chapter 2 on flora) which will be analyzed using DNA barcoding to increase the coverage of the knowledge about the flora of the Carajás forest.

In this context, in addition to consolidating the broad database of genetic references for the flora of the Carajás National Forest, there is also a growing effort to build a similar library for the arthropods in the region, given the high importance of this animal group for fundamental ecosystem services, such as pollination, seed dispersal and decomposition (see Chapter 3). The effort has initially been made for species of bees and butterflies from Flona de Carajás, also aiming to expand the knowledge related to the species of invertebrate pollinators in the region and further enabling studies of the interaction between species, in addition to the application of DNA meta-barcoding to monitor the diversity of invertebrates. Totally, 90 species of insects (54 of bees and 36 of butterflies) have already been genetically referenced with the purpose to expand not only the list of species of these orders included in the barcode library, but also contemplate other orders of invertebrates, for example, Araneae, Coleoptera and Diptera, in the coming years.

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17

The mitigation hierarchy as a principle for the sustainable use of the forest and its natural resources

Priscila Sanjuan, Taise Pinheiro, Markus Gastauer

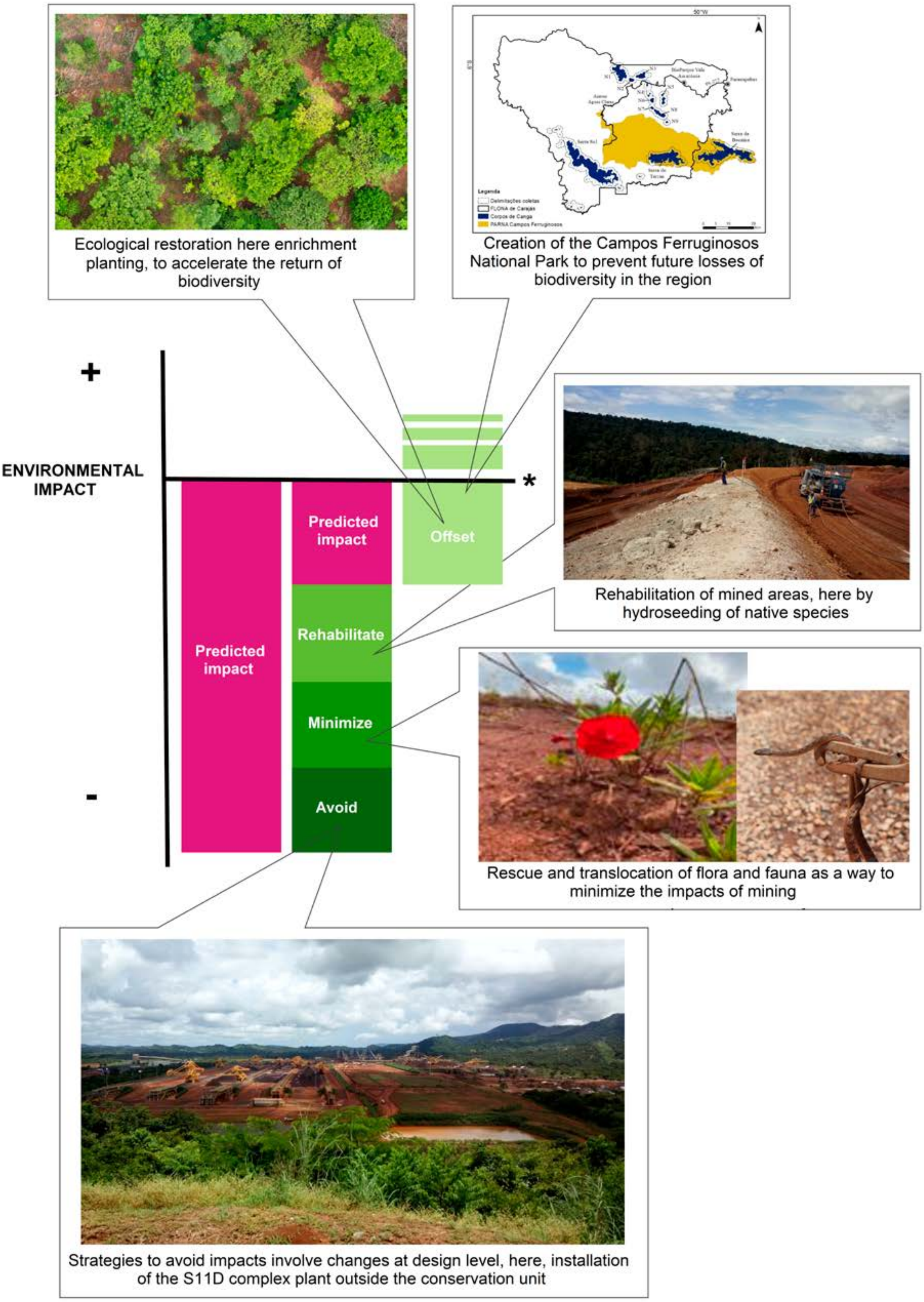
Conceptualization

Issues involving environmental sustainability have been a recurring concern throughout the history of humanity, present in different cultures and traditions. Although the philosophy of balance between man and nature had already been widely discussed in Ancient Greece, the term "sustainability" became popular in 1987, with the publication of the report Our Common Future, produced by the United Nations Environment Committee. In this document, the concept of sustainable development was defined as "development that meets the needs of the present without impairing the capacity of the future generations to meet their own needs".

Sustainability encompasses economic, social and environmental issues, and is incorporated into public policies, business practices and individual decisions around the world. The popularization of the concept also increases the society's perception of the need to reconcile socioeconomic development with the protection of the natural capital in planning a more sustainable future. Today, addressing issues such as hunger, poverty, inequality, climate change, natural resource scarcity, and biodiversity loss requires not only quick and effective solutions but also proper management of the natural capital to ensure its preservation and the balanced and fair utilization of resources.

The principle of impact mitigation hierarchy

Although the use of renewable energy, waste reduction, recycling and investments in cleaner and more efficient technologies are essential tools to make our



Ecological restoration here enrichment planting, to accelerate the return of biodiversity

Creation of the Campos Ferruginosos National Park to prevent future losses of biodiversity in the region

Rehabilitation of mined areas, here by hydroseeding of native species

Rescue and translocation of flora and fauna as a way to minimize the impacts of mining

Strategies to avoid impacts involve changes at design level, here, installation of the S11D complex plant outside the conservation unit

Figure 1. Principle of the impact mitigation hierarchy with some examples from the S11D iron mining complex within the Carajás National Forest to guide the sustainable use of the natural capital. (Photos: André Luiz de Rezende Cardoso, Markus Gastauer).

future increasingly more sustainable, mineral exploration still needs to advance over natural ecosystems to provide the raw materials necessary for the decarbonization of the industry (Sonter et al. 2020). To ensure this occurs in an organized manner, the International Council on Mining and Metals (ICMM) has published recommendations for mitigating the impacts on biodiversity and natural capital. This framework, called Impact Mitigation Hierarchy (IMH), establishes a logical sequence of actions to mitigate negative environmental impacts, supported by the following pillars (Figure 1):

1. Avoid environmental impacts, by seeking alternatives that cause the least possible environmental harm;
2. Minimize environmental impacts during project execution through rest periods for hunting or fishing populations, rescue of fauna and flora during clearing, dust and sediment control programs to protect water resources, among others;
3. Remediate damages to ecosystems through the restoration of degraded areas; and
4. Compensate for residual impacts when reduction is not possible; compensatory actions may involve ecological restoration or the creation of conservation programs.

In this way, the rigorous application of the HMI ensures the reduction of negative environmental impacts in all phases of different economic activities, assuring the continuity of the ecosystem services provided by nature.

Residual impact compensation

The residual impact of the projects needs to be compensated when it is not possible to avoid, mitigate and rehabilitate environmental damages. Compensation is a mechanism that seeks to balance environmental losses caused by an economic activity and can be achieved through protection or restoration of natural areas, the creation of species conservation programs, or the implementation of measures to reduce the impacts of other similar activities. As a result, the compensation creates direct gains for biodiversity (restoration) or prevents future habitat degradation through its protection. The idea is that by preventing future environmental degradation, ecosystem functions and services are preserved.

For the compensation to be effective, it is important to comply with three basic principles (Damiens et al., 2021). First, Equivalence, which ensures that the compensation is proportional to the impacts generated by the project or activity. In other words, the environmental compensation must be capable of restoring or preserving the affected natural resources in a similar or equivalent manner to the damage caused, considering species, habitats and spatial proximity. Second, the compensation actions must be planned to ensure their permanence in long term. It is important that the areas designated for environmental compensation are adequately protected and maintained so that the generated benefits are enduring. Finally, the environmental compensation must be additional to existing conservation and protection efforts, ensuring that compensation measures go beyond existing legal obligations.

To assure that these principles are met, it is paramount that environmental compensation is carefully planned and monitored by professionals specialized in the rehabilitation and the conservation of the environment. Furthermore, it is important for society to be involved in the process of defining compensation measures and assessing the achieved results.

Quantify gains and losses for biodiversity

Methodologies that quantify the environmental impact must provide information about the magnitude and the severity of the environmental impacts generated by an activity, using appropriate indicators. The analysis of changes in land use and cover, for example, is an important tool, as it enables assessing the changes on the Earth's surface. Through this analysis, it is possible to detect areas where there has been loss of native vegetation and increased forest fragmentation, identifying where conservation and restoration activities generate benefits and gains for biodiversity and the ecosystem services. Often, the stakeholders work with counterfactual scenarios to capture avoided deforestation or degradation, seeking to identify what the landscape would be like without implementing the specific project.

There is consensus that the value of an area for biodiversity is determined by its size, the importance of the habitats it contains, and its ecological conditions, such as richness, diversity, presence of rare or threatened species, or performance of ecosystem services (Gastauer et al. 2013). Thus, we can define the environmental impact of a project as the product of (i) Area, (ii) Importance and (iii) Conditions, summed over all involved habitats, and compare the sum before, during and after the project's completion. If this sum, called biotic value, is negative, the project would cause losses to biodiversity and the natural capital, and positive values would indicate gains.

Researchers of Instituto Tecnológico Vale (ITV) developed a methodology to determine the importance and the conditions for given habitat (Gastauer et al. 2024). The importance is measured through four criteria: (i) naturalness, (ii) rarity, (iii) substitutability and (iv) importance for ecosystem structure (Table 1). Each criterion is independently evaluated with scores ranging from zero (minimum value) to five (maximum value) for each habitat. The importance is the sum of the scores divided by 20, ranging from zero to one.

To assess the conditions of a habitat, indicators related to vegetation structure, community diversity (vegetation and fauna) and ecological processes are necessary (Gastauer et al. 2021). A multivariate analysis of principal coordinates is used to integrate all indicators collected in the field into a single measure of environmental quality; after the ordination, the environmental quality of a given habitat corresponds to the actual distance between the habitat and the natural reference ecosystem in multivariate space, compared to the overall distance between the most degraded state that exists or existed within the project to the natural reference ecosystem (Figure 2).

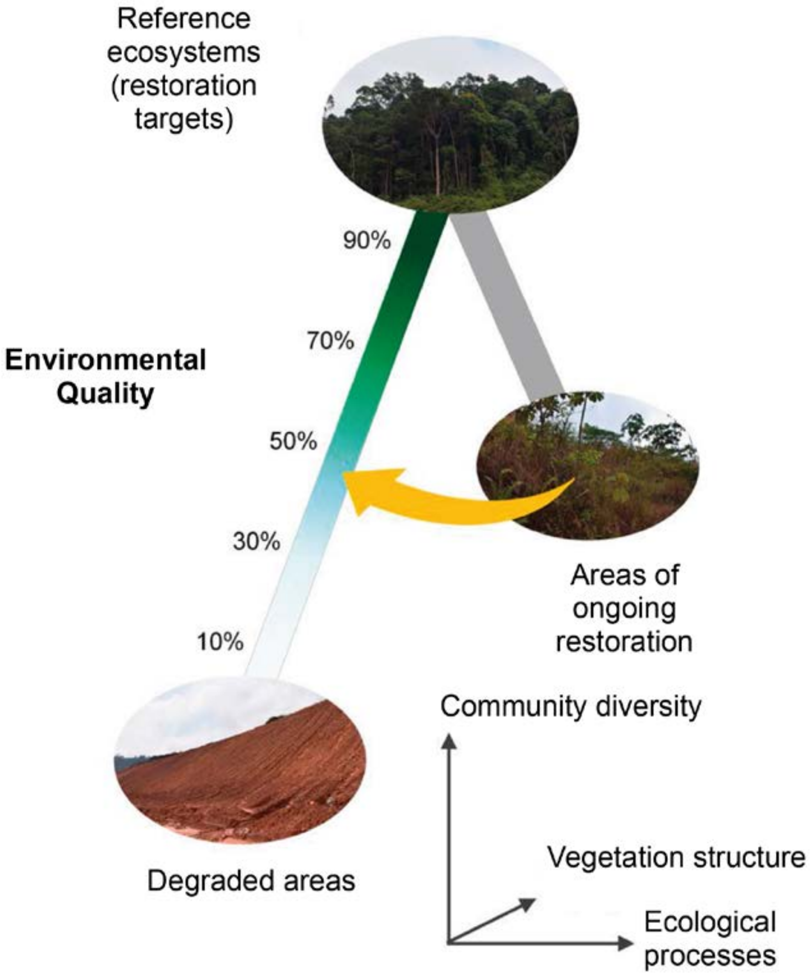


Figure 2. Detection of environmental quality by integrating different environmental indicators by means of multivariate analysis of principal coordinates.

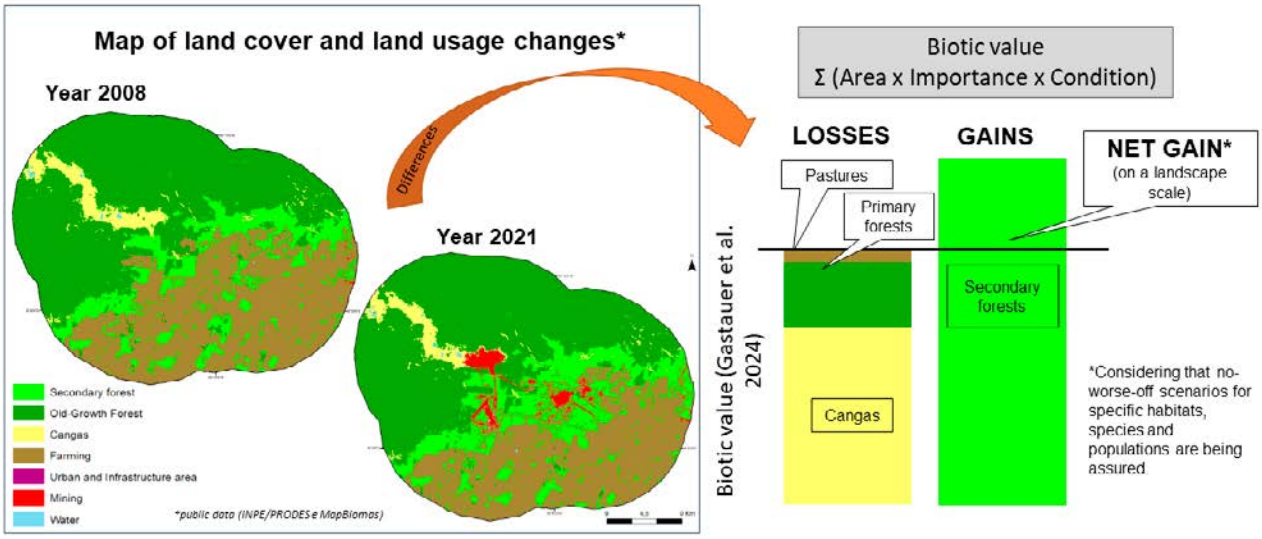
Table 1. Definition of the criteria used, accompanied by some examples to detect the importance of habitats.

Definition	**Scores**	**Canga**	**Primary forest**	**Secondary forest**	**Agriculture**	**Mined area**
Naturalness – degree of human interventions on site, i.e., inputs and extractions of energy and matter, or their residues, on site	Destroyed areas free of vegetation; 1: Planted areas without native vegetation; 2: Semi-natural areas, such as agro-forestry systems or slash-and-burn agriculture; 3: Near-natural areas with altered communities; 4: Natural ecosystems in their representative composition	4	4	3	1	0
Substitutability – spatial and time dimension to replace similar types of habitat in the region	Common habitats in the surroundings: 0: Biocenosis replaceable within 1 to 3 years; 1: 3-30 years; 2: 30-150 years ; 3: 150-300 years; 4: >300 years Unusual or rare habitats in the surroundings: 1: 1-3 years; 2: 3-30 years ; 3: 30-150 years; 4: >150 years	4	4	1	0	0
Rarity/Endangerment – spatial availability of similar habitats and their suitability for rare, endemic species and populations or endangered	Widespread habitats and species; 1: Common vegetation formations and species; 2: Declining vegetation formations or species; 3: Threatened habitats and species; 4: Large remnants of natural vegetation and their rare communities in the regional context	4	3	3	0	0
Importance for the ecosystem structure - (a) importance for migratory species and gene flow among separate populations, (b) buffer functions, for example for conservation units, and (c) importance for animals with large territories or that use different habitats or ecosystems for hiding, breeding, feeding or hibernation	The area does not meet any of the three sub-criteria; 1: The area meets one of the three sub-criteria; 2: The area meets two of the three sub-criteria; 3: The area meets all the three sub-criteria; 4: The area meets all the three sub-criteria above the average	4	4	3	1	0

Mining in Flona de Carajás: the role of forest restoration in HMI

With the methodology presented in the previous section, researchers from ITV analyzed, on a landscape scale, the impact of the installation of Mineral Complex Eliezer Batista S11D – Canaã dos Carajás on the biodiversity in the region. The study area was defined by a range of 11 km around the mine and the plant (extensions in 2021) and covers part of the Carajás National Forest. Between 2008, that is the beginning of Environmental Impact Assessment to obtain the installation and operation license, and 2021, the researchers detected significant changes in the land use and cover (Figure 3). Around 700 hectares of canga were logged for the extraction of iron ore. On the other hand, with the installation of the plant outside the boundaries of the conservation unit, the impact on the natural resources was avoided. Additionally, extensive areas (around 3,500 hectares) of pastures were transformed into secondary forests with restoration projects. As a result, there were gains for biodiversity that exceeded the losses due to the mining activity (Figure 3).

While effective management plans for specific biological features are essential to ensure 'no net loss' (NNL), our results show that the forest restoration activities can compensate for the impacts on biodiversity and ecosystem services promoted by the mining (Figure 4). Considering other compensation strategies, as well as mine rehabilitation planned by the mitigation hierarchy, it is possible that the responsible implementation of the S11D mining complex could generate net gains in biodiversity in the mega-diverse Amazon in medium and long term.



*Considering that no-worse-off scenarios for specific habitats, species and populations are being assured

Figure 3. Methodology developed by researchers from ITV to quantify losses and gains for biodiversity, based on analysis of changes in land use and cover.

Figure 4. Aerial photo of a restored area of approximately 7 years.

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18

Contributions to conservation and mitigation of the global changes

Sâmia Nunes, Markus Gastauer

Context

Ecosystem conservation is recommended as the first strategy for maintenance of biodiversity and natural capital, but the Amazon alone has already lost 12% (44 million hectares) of its native vegetation in the last 37 years, mainly due to agriculture (MapBiomas, 2022). Restoration, that is, the process of restoring biodiversity and ecosystem services, helps maintain plant formations in different biomes and, thus, generates benefits for the environment and human development, in addition to helping to mitigate changes climate (Nunes et al., 2020a). Today, we are in the Decade of Ecosystem Restoration (2021-2030) (UNEP, 2021) initiated by the United Nations (UN), in a global effort to scale up restoration. This movement aligns with the UN's Sustainable Development Goals (SDGs) to eradicate poverty, protect the environment, and address climate issues (UN, 2023). Brazil is a signatory to the Paris Agreement (UNFCCC, 2018), an international treaty adopted in 2015 for measures to reduce carbon dioxide emissions from 2020. During the 26th Conference of the Parties (COP 26) in 2021, the country committed to restoring and reforesting 18 million hectares of forests by 2030 and eliminating illegal deforestation by 2028. However, large-scale restoration is complex, with various challenges in implementation, technical aspects, politics, economics, and social factors (Nunes et al., 2020a).

Historically, after deforestation (complete removal of forest cover), three main pathways are observed: (i) continuation of land use in the deforested state; (ii) abandonment of the area, leading to the formation of secondary vegetation; (iii) intentional restoration of vegetation. In the Amazon, the primary restoration strategies applied include assisted natural regeneration (ANR) (passive restoration), complete planting of seeds and seedlings (active restoration), or a combination of both methods (e.g., densification or enrichment) (Figure 1). The

Figure 1. Seedling nursery in Carajás.

decision on the best method depends on the time of land use, the intensity of degradation, the potential for natural regeneration (NR) of the site (presence of a seed bank and forest fragments in the surroundings), and the objective of the restoration (e.g., conservation or economic production) (Brancalion et al., 2015). Simplistically, ANR is recommended for areas with low degradation intensity, with some level of seed bank and forest remnants nearby. On the other hand, areas compacted due to high land use intensity and lacking significantly expression of NR require active restoration strategies.

Environmental suitability of private rural properties and the Native Vegetation Protection Law

Most of the native vegetation in Brazil is in private areas or in public areas without destination (Soares-Filho, 2013). Thus, the strategies of conservation and

Figure 2. Rural property with different land uses and the preserved Flona de Carajás in the background.

restoration need to cover both public and private areas to assure the maintenance of the forest ecosystem services. Environmental adequacy aims to address environmental irregularities on private rural properties (Figure 2). In Brazil, the conservation of native vegetation on private lands – regulated by the Native Vegetation Protection Law (NVPL – Law no. 12,651, dated May 25, 2012) – is divided into two main categories: (i) legal reserve areas (LR), created to promote the sustainable use of natural resources and biodiversity conservation; and (ii) permanent preservation areas (PPA), created to protect particularly sensitive areas, such as riparian vegetation, river sources, steep areas (> 45º) and mangroves.

Ten years of its last review, Brazil has yet to make significant progress in implementation this law on two main fronts: curbing deforestation and promoting large-scale restoration of the native vegetation. Studies in Brazil have shown that the protection of PPA and LR is not proving effective, and the forest debt in these areas is not being recovered over time (Nunes et al., 2016, 2019a). Situated in the southeast of Pará, in the deforestation arc, The Itacaiúnas River Basin (IRB) has an area of approximately 41,300 km2 – equivalent to the size of Switzerland – and has already lost 50% of its forests. A study by Instituto Tecnológico Vale (ITV) indicated a total debt (PPA+RL) of 5,700 km2, 58% of which must be recovered and 42% could be compensated through the "rental" of forest on another property in the same biome (this is the LR compensation mechanism) (Nunes et al., 2019b). These numbers demonstrate that the implementation of NVPL in Brazil is a significant opportunity to scale up restoration in the country and meet the national commitments regarding restoration. However, legal obligation alone is not enough to incentivize landowners. Additional measures and incentives are necessary, such as Payment for ecosystem services (PES) mechanisms, reduced interest rates, easier access to credit, and technical support.

Secondary vegetation

The economic land use model practiced in the Amazon is high dynamic, with several cycles of cut-regeneration-cut, which enables growth of secondary vegetation (SV) (Figure 3) – which grows in the abandoned area after deforesting – at different stages of development (Nelson et al., 2000; Vieira et al., 2014). In 2014, almost a quarter (22%) of the total deforested area in the Amazon was under some kind of regeneration (TerraClass, 2014), and almost half of SV mapped in 2017 in the Amazon (> 5 Mha) was up to five years old – due to the practice of fallowing, in which the soil is left unused to restore part of the nutrients – while only 13% were over 20 years old

Figure 3. Secondary vegetation on a private rural property.

(1.5 Mha) (Nunes et al., 2020b). The same study reaffirmed the ephemeral nature of SV in the Amazon, with 72% of deforestation in SV up to five years old and less than 10% of deforestation in SV between 11 and 32 years old, during the entire analysis period. Nonetheless, SV proved to be a carbon sink in the Amazon, accumulating on average of 8.9 Tg C per year.

The extensive area of SV, coupled with high deforestation rates in the initial years, weakens its effectiveness as an alternative to combat climate change. There are significant implications for the low coverage of more mature SV in the Amazon, such as negative impacts on the provision of ecosystem services and biodiversity recovery. Furthermore, SV is crucial in the context of implementing environmental legislation to reduce areas of liability and pressure for deforestation in primary forests. Additionally, monitoring of the age, gain and loss of these areas helps scientists and decision-makers measure the net carbon balance and its impacts on climate change. Studies indicate that the current deforested area is sufficient for food production without the need to encroach on new forest areas (Griscom et al., 2017).

Therefore, we believe that SV has high potential for carbon sequestration, biodiversity restoration and provision of ecosystem services, provided that: (i) a portion of it is protected from deforestation, especially by the states (the state of Pará being the only one with specific legislation protecting SV outside of PPA and LR); (ii) inspection/monitoring is more efficient, incorporating SV dynamics into official and unofficial annual and alert systems; (iii) PES programs are expanded and regulated as an incentive to maintaining these areas on a large scale; (iv) landowners apply technology in agricultural areas to increase efficiency, reducing the pressure for new deforestation, and prioritize areas with low agricultural suitability for restoration.

Technical challenges for large-scale restoration

Several institutions have discussed opportunities, challenges (Aliança pela Restauração na Amazônia, 2020; Nunes et al., 2020a) and barriers (Gastauer et al., 2020) to promote large-scale forest restoration in the country, such as:

- Stimulating productive arrangements with economic return and connecting demand and supply to establish the value chain and facilitate product distribution. Açaí, cocoa and cupuaçu are examples for new bioeconomy in the Amazon, but other species have commercial potential, either for PES, emerging carbon markets, pharmaceutical and cosmetic industry, or as sources of fiber and cellulose.
- Promoting ANR when possible to reduce implementation costs of restoration and increase net returns.

Figure 4. Agroforestry systems amid secondary vegetation.

Figure 5. Production arrangement within a deforested area.

- Developing local communities and nurseries to increase the availability of seeds and seedlings and labor to meet the demand for large-scale restoration.
- Investing in research and development of native species for greater efficiency (e.g., plant nutrition, soil management, genetic improvement) and increasing returns from the plantings.
- Adequate selection of species with specific adaptations for the planting locations to reduce failures during implementation.
- Reducing competition with agriculture by selecting areas of low agricultural suitability for environmental adaptation.
- Implementing effective monitoring systems, preferably remote, to verify, at low cost, the maintenance of SV, especially in cases involving PES or sequestered carbon.

Recommendations for public policies

To enable large-scale forest restoration, public policies need to be created and intensified to stimulate the sustainable economic use of native and frestored forests, promoting the production chain, the bioeconomy and investing in productive arrangements such as agroforestry systems. Effective incentives, such as PES, carbon market regulation, and access to credit are necessary, as well as SV protection to stimulate restoration on private properties, reduce environmental liabilities and increase carbon sequestration (Figures 4-5). These incentives need to be combined with actions that strengthen command and control and with the implementation of existing laws, policies and commitments (e.g., rural environmental registry, environmental regularization program, Brazilian commitments at COPs, National Policy for Recovery of Native Vegetation), including the private sector in partnerships with governments, communities, and education and research institutions. Large-scale forest restoration can benefit and contribute to the maintenance of biodiversity and ecosystem services, the mitigation of climate change and sustainable development.

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Species of trees for restoration, considering plant-bee interaction networks

Luiza de Araújo Romeiro, Rafael Cabral Borges, Edilson Freitas da Silva, José Tasso Felix Guimarães, Tereza Cristina Giannini

Introduction

Interactions between species act as the driving force behind ecological dynamics within communities (Berlow et al., 2009). Especially in tropical regions, the plant dependence on pollinators is high (Ollerton et al., 2011). The interaction between plants and their pollinators generates benefits for both, and is called mutualism. This type of interaction is particularly important for conservation and restoration programs, as threats that affect the interacting species can potentially lead to risk to the reproduction and evolution of the plants, as well as the long-term maintenance of the biodiversity of pollinators (Mendes, 2018). However, the interaction data is still scarce (Hortal et al., 2015), especially in high-canopy tropical forests, as the plants produce their flowers approximately 30 meters above the ground (Ferreira et al., 2020)..

Bees are the main group of pollinators of flowering plants, and knowing bee--plant interactions enables comprehending their habits of food resource collection. This information is essential for the planning of sustainable management strategies, restoration and conservation of species in degraded areas. Furthermore, from interactions we can comprehend the dependence of native and cultivated plants on the pollination services (Bommarco et al., 2010).

The Carajás National Forest is part of an isolated set of protected areas in the eastern Amazon. The region surrounding this set of areas is highly impacted by human activities and could benefit from restoration projects. However, one of the most challenging stages in the restoration process is the selection of native plant species that contribute to increasing the resilience of the ecosystem (Hallett et al., 2013). Plant species that offer floral resources to the bees can be prioritized to support the restoration of the interaction networks (Campbell et al., 2019). Furthermore, pollination increases the chances of reproduction of plant species, supporting the success of the restoration strategies. Therefore, the identification and the prioritization of plant species that participate in bee-plant interactions can bring important benefits to the restored communities (Aguiar et al., 2013).

Bee-plant interactions in Carajás

In this chapter, pollen analysis is used to describe the interactions between bees and plants in the Carajás National Forest and the surrounding areas. Aiming to fill the gap in existing knowledge about bee-plant interactions in the tree canopy, pollen adhered to specific body structures was collected in bees from the Carajás region which are deposited in museums (Figure 1). The pollen was analyzed using a microscope and, as it presented unique characteristics for each plant species, it was possible to identify the collected species. In this study, bee pollen samples deposited at Museu Paraense Emilio Goeldi (MPEG, Belém, Pará) and Universidade Federal de Minas Gerais (UFMG, Belo Horizonte, Minas Gerais) were used.

To expose the structure of pollen grains, pollen loads were submitted to the acetolysis process (Erdtman, 1960). For each sample, three pollen slides were mounted so that approximately 500 pollen grains could be counted per sample, and the percentages of occurrence were established (Sniderman et al., 2018). The pollen grains were identified according to their pollen type according to their morphology and compared with reference pollen grains to identify the species deposited in the Palinotheque of Instituto Tecnológico Vale (PaliITV).

Figure 1. Left: bee *Paratrigona sp*, highlighting the pollen loads on the hind legs (in dark yellow) (Fototeca Cristiano Menezes, FCM). Right: photos of pollen grains under an optical microscope of two mentioned plant species: a, b) *Myrcia splendens* (Sw.) DC and c, d): *Tachigali vulgaris* L.G.Silva & H.C.Lima (Photos: Luiza Romeiro) Scala: 10 µm.

Figure 2. Flower of *Callisthene microphylla Warn*.

From the identification of pollen grains, the bee-plant interaction network was built (Dormann, 2008). To determine the potential use in restoration strategies, the identified plant species were compared with literature data for Brazil (Campbell et al., 2019).

Overall, 72 pollen loads of the 252 specimens sampled belonging to 51 bee species were found (Figure 2). The pollen loads came from bees belonging to two families (Apidae and Megachilidae) and 16 genera. The genera with the highest number of species were Centris Fabricius, 1804 (11 species), *Trigona* Jurine, 1807 (10) and *Melipona* Illiger, 1806, *Epicharis* Klug, 1807 and *Megachile* Latreille, 1802 (4 species each). The identified pollen material consisted of 82 pollen types distributed in 28 plant families, 54 genera, 43 species and three indeterminate types (types 1, 2 and 3). The most representative families, i.e., with the greatest number of species or taxa, were Fabaceae (18), Malpighiaceae (9) and Solanaceae (7). In total, 158 interactions between plants and bees were obtained (Figure 3).

Highlighted plant species

Of the species identified, 18 (43%) are trees, 14 (33%) are shrubs and the remainder are herbaceous plants and lianas (5 species each; 12%). The majority (74%) occur in forests, 21% occur in open areas (cangas), and for 5%, there is no habitat information.

The interaction data obtained herein can assist in the selection of species for the restoration of degraded areas, which is important, considering the location of Carajás and its surroundings within the arc of deforestation in the Amazon. The analysis of multiple bee-plant networks in Brazil showed that families Solanaceae, Fabaceae, Euphorbiaceae, Melastomataceae, Asteraceae and Malpighiaceae can be selected as priorities for restoration programs aimed at supporting the bee maintenance, once the species from these families provide resources for several species of bees (Campbell et al., 2019). Families Malpighiaceae and Solanaceae also had great prominence in the analysis of interaction networks in the present study in Carajás.

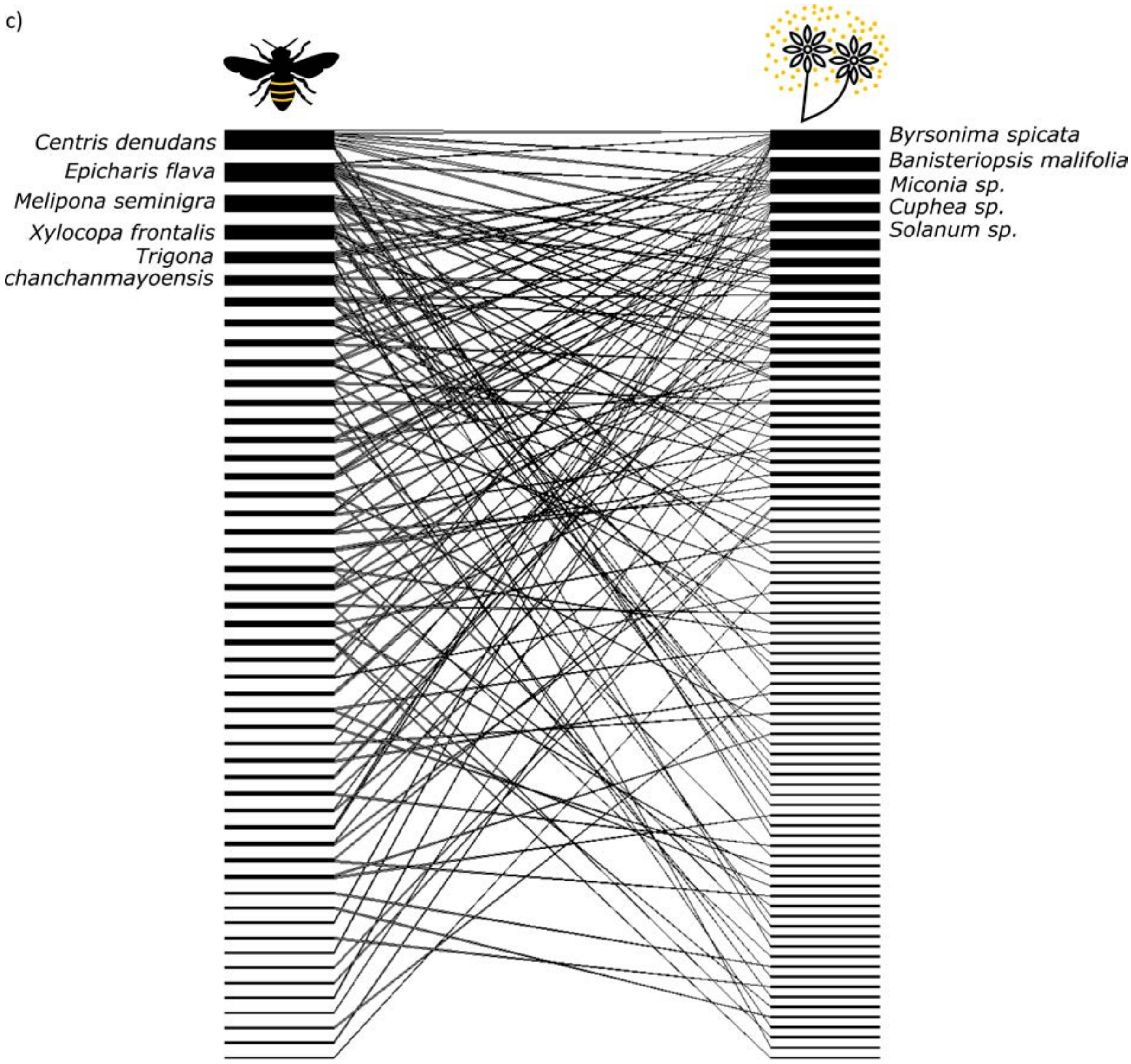

Figure 3. Bee-plant interaction network built from the analysis of pollen grains attached to bee specimens sampled in the Carajás National Forest and deposited in biological collections. The five most generalist species of bees and plants (with the largest number of species) are indicated.

The genera with the largest number of species were *Solanum* (8), *Banisteriopsis* (5) and *Borreria* (4). The pollen grains with the highest frequency in pollen loads belonged to genus *Solanum*, present in samples from 14 species of bees. Among the pollen types identified, *Byrsonima spicata* (Cav.) Rich. ex Kunth and *Banisteriopsis malifolia* (Nees & Mart.) were the plant species with the highest number of interactions with bees, the first have arboreal habit. In addition thereto, other tree species stood out due to the number of interactions found, for example: *Apuleia leiocarpa* (Vogel) J.F.Macbr., *Byrsonima crassifolia* (Cav.) Rich. ex Kunth, *Callisthene microphylla* Warn., *Mimosa acutistipula* var. *ferrea* Barneby, *Myrcia splendens* (Sw.) DC., *Roupala montana* Aubl., *Sacoglottis mattogrossensis* Malme, *Solanum crinitum* Lam., *Tachigali vulgaris* L.G.Silva & H.C.Lima. These are important species for recovery areas, especially when it comes to recovering ecological interactions in long terms, once tree species remain in the environment for long periods.

Pollen load analyses significantly increased the amount of available data when compared to field observations alone; therefore, it is necessary to highlight the importance of including this type of analysis in the study of the plant-bee interactions (Fisogni et al., 2017). One of the main causes of the global decline of bees is the loss of floral resources. The loss of bee diversity, in turn, can interfere with the spread and the genetic flow of the plants (Maia-Silva et al., 2014). These factors have to be considered if we are to produce pollinator-friendly conservation and restoration planning.

This study enabled expanding the knowledge about the interactions between bees and plants and the floral preferences of the bee species in and around the Carajás National Forest, including interactions with arboreal plants. This is the first research to investigate the network of interactions between bees and plants in the Amazon using pollen analysis. This data is extremely important to guide restoration projects, especially in the southeast of the biome, highly impacted by human activities. This data is also fundamental to guide decision-making processes involving the conservation of bee species, important pollinators of the local flora. This investigation also offered a significant advance in the visitors' knowledge of tree plant species, once the collections using traditional methods are unfeasible due to the height of the canopy. Therefore, herein it is suggested this approach be further explored to identify interactions.

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Climate change: the meteorological basis and scenarios for Carajás

Renata Gonçalves Tedeschi, Claudia Wanzeler da Costa, Antônio Vasconcelos Nogueira Neto

The meteorological base

The most discussed topic nowadays, especially when it comes to meteorology (Figure 1), are the climate changes. They are often mentioned when natural disasters related to climate extremes occur, such as the landslide in São Sebastião in February 2023, floods in Petrópolis in February 2022 and in southern Bahia in December 2021. There is also news about climate extremes themselves, such as the snow in Curitiba in 2013 or in Texas in 2021, the heat waves in Europe in 2019 or the record temperature in the Arctic Circle in 2020.

There is evidence that climate change has always occurred on the planet Earth, both as global warming and ice ages. Marcott et al. (2013) show, by means of reconstruction of the global temperature, how this happened over the last 11,300 years. However, the current warming cycle has a very important component, the strong warming trend in a few years. Paleoclimatic data indicate that achieving a 5°C increase in the global average temperature took around 5,000 years, while the current climate models indicate that this variation could occur within just one century, i.e., 100 years.

In 2021, the Intergovernmental Panel on Climate Change (IPCC) released its sixth report (IPCC, 2021), in which it made some emphatic statements. The scientists who compiled the report show that the current climate change occurs across the globe and is intensifying every year. Furthermore, for the first time since the creation of IPCC in the 1990s, the scientists affirm that the human activities play an important role in these changes. Finally, if there are no reductions in the emissions (immediate, quick and on a large scale) of greenhouse gases, it will be impossible to limit average global warming to 1.5°C as suggested in the Paris Agreement, made in 2015 ("The Paris Agreement | UNFCCC" n.d.).

Figure 1. Rain over the river.

The greenhouse effect and life

The greenhouse effect is a physical process without which there would be no life on Earth. Without it, the global average temperature would be -18ºC instead of 15ºC, i.e., this phenomenon increases the global average temperature by 33ºC.

This effect occurs as follows: solar radiation reaches the Earth atmosphere, part of which is reflected back to space and part of which is absorbed by the Earth. Subsequently, the Earth emits this energy through infrared radiation. The energy at this wavelength is absorbed by some chemical molecules (carbon dioxide, methane, water vapor, among others). After absorbing this energy, it can be emitted into space or re-emitted to the Earth surface. The re-emitted part heats the atmosphere and the surface, and is therefore responsible for maintaining life on Earth. The problem occurs when the concentration of these gases (known as greenhouse gases – GHG) increases, because the greater their amount in the atmosphere, the more energy is re-emitted to the surface, which causes greater global warming.

Scenarios for Carajás

Climate patterns in the Itacaiúnas River Basin

The Carajás National Forest is within the Itacaiúnas River Water Basin (BHRI) (Figure 1 Chapter 10). The average patterns of the main atmospheric variables (rainfall and

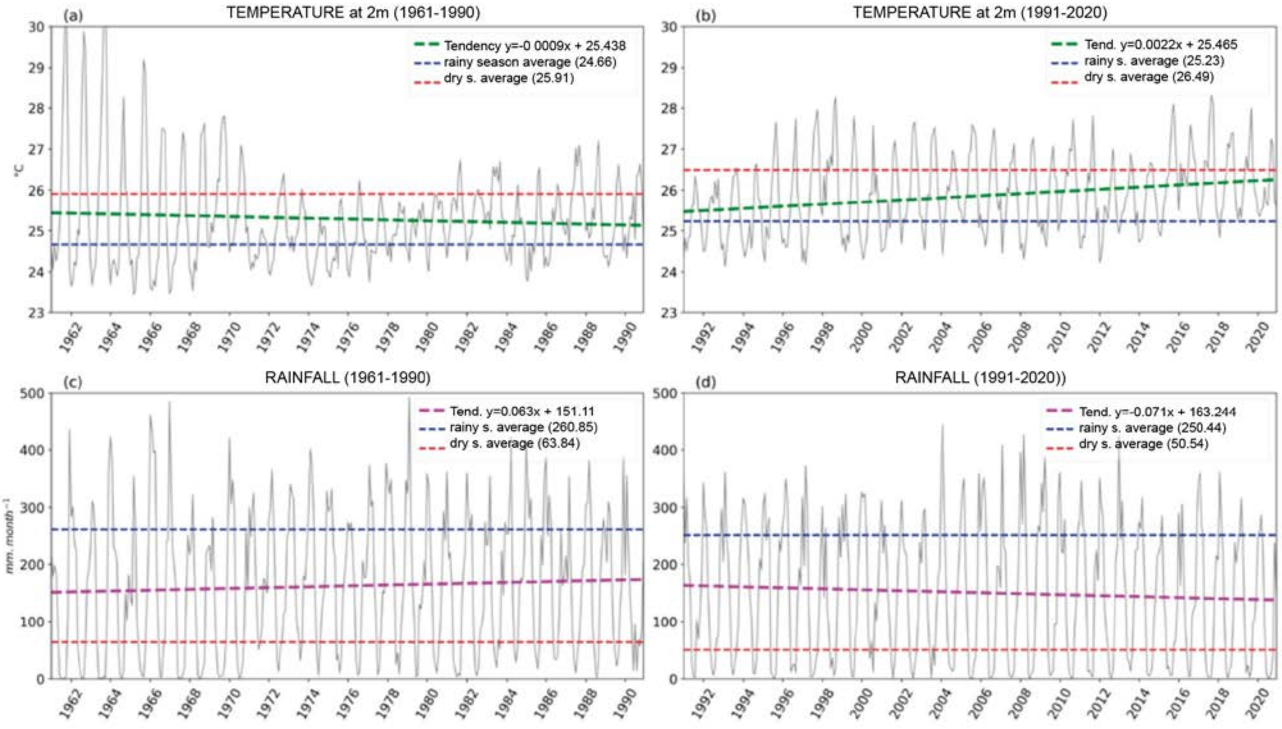

Figure 2. Time series of the average air temperatures at two meters (a and b) and rainfall (c and d) in BHRI in two different periods: 1961-1990 (a and c) and 1991-2020 (b and d).

temperature) for this basin between 1961 to 1990 and 1991 to 2020 will be shown here, as well as the trend of these periods.

As the density of the meteorological stations (observed data) in BHRI is low, it was decided to use reanalysis data (Hersbach et al. 2020) to create patterns of atmospheric variables (rainfall and temperature at two meters from the surface) for this region.

The temperature analysis (Figure 2, first line) shows a decreasing trend for this variable over the period from 1961 to 1990, mainly due to the strong temperatures observed in the 1960s. However, the most recent period (1991 to 2020) showed a sharp increase in the average temperature in the basin. Another important piece of information is the increase in the average temperature in the most recent period compared to the period from 1961 to 1990, both in the rainy season (blue line) and in the dry season (red line). For the average rainfall time series of BHRI (Figure 2, second row), there is no a trend as pronounced as the average air temperature series. Even so, when comparing the two trend lines, it is possible to see that there was an increasing trend in the period from 1961 to 1990, while, in the current period, the trend is towards decrease in the rainfall in the basin.

Figures 3 and 4 show the spatial patterns and the differences between the two periods in relation to the annual average of the same variables, in addition to the

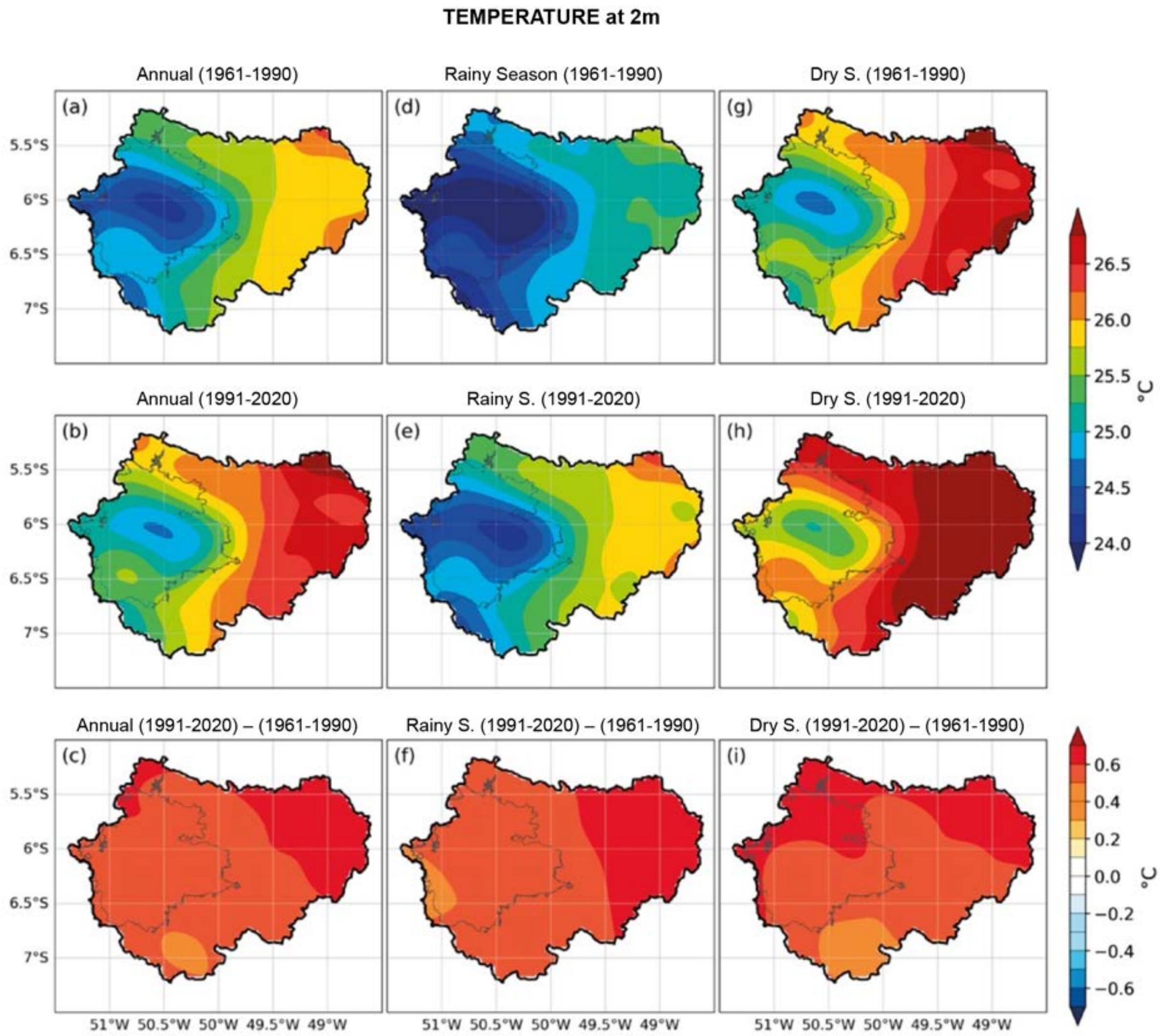

Figure 3. Spatial patterns of average air temperature in BHRI in different periods: 1961-1990 (first line), 1991- 2020 (second line) and the difference of the two periods (third line), in different periods of the year: annual, rainy season (November to April) and dry season (May to October). Gray line identifies the protected forest areas.

patterns for the rainy and dry seasons. From Figure 3, it can be seen that lower temperatures occur in the region of the Carajás National Forest and higher temperatures west of BHRI, in all analyzed periods and seasons. The difference between periods shows increase in the temperature throughout the basin, as indicated in the time series, with increase above 0.6°C mainly to the east of BHRI and in some areas to the west when considering the average annual and the dry season.

Conversely, the rainfall patterns (Figure 4) show that the highest rates occur over the protected forest area and that BHRI suffered decrease in the rainfall between the two periods, with the Carajás National Forest area being the most affected. Furthermore, the results indicate that, in the current period (1991-2020), the rainy season has become less rainy and the dry season even drier.

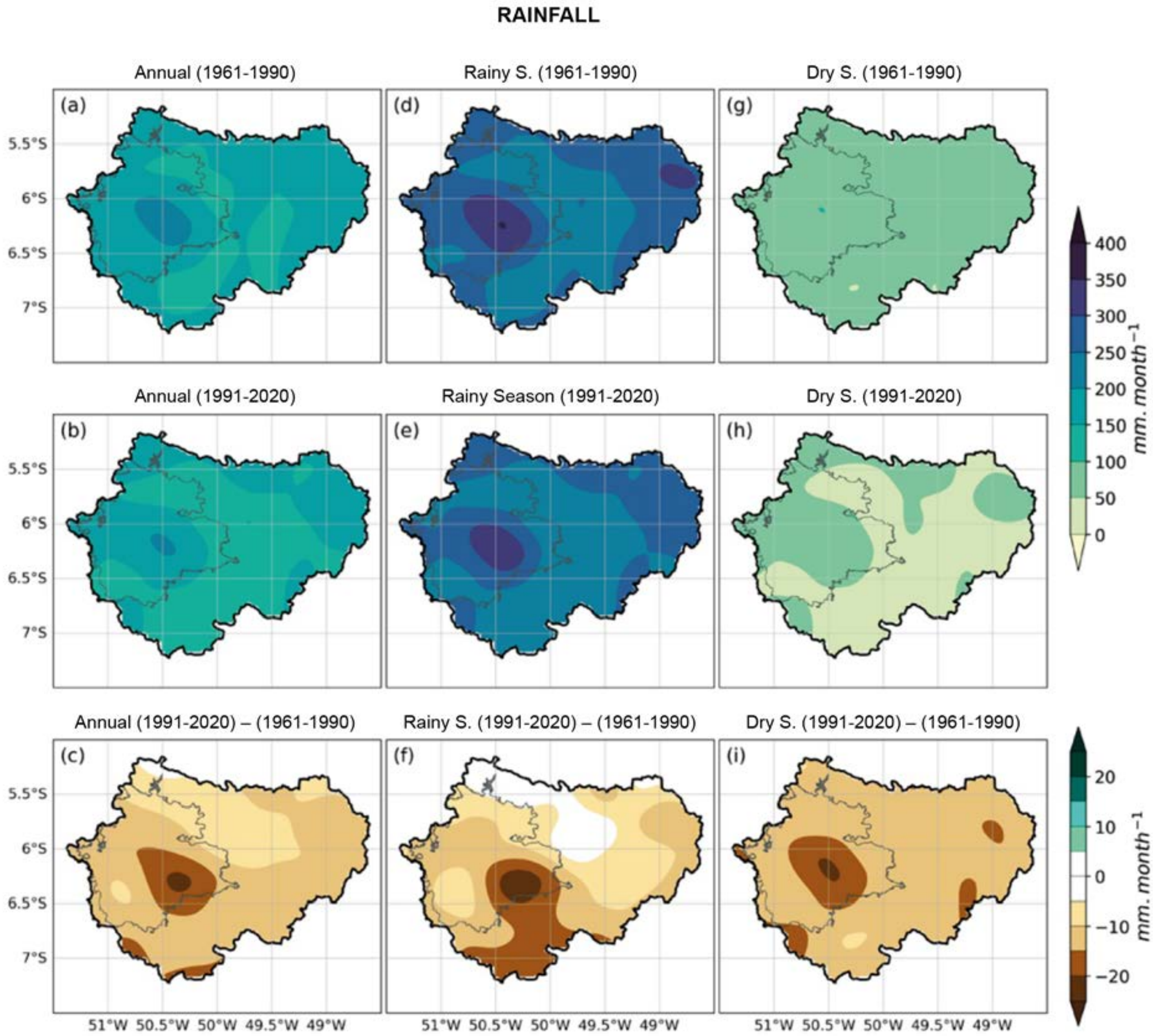

Figure 4. Spatial patterns of rainfall in BHRI in different periods: 1961-1990 (first line), 1991-2020 (second line) and the difference of the two periods (third line), in different periods of the year: annual, rainy season (November to April) and dry season (May to October). Gray line identifies the protected forest areas.

The presented results give indications of the general scenario that could occur if global warming, due to increase in GHG emissions and changes in land use, continues at the current rates.

Climate forecasting in the BHRI

Along with its sixth report (IPCC, 2021), IPCC provided a website (https://interactive-atlas.ipcc.ch/regional-information) where it is possible to check changes in several variables, in some predefined regions, in different global warming scenarios, and download global data in a grid of 1° latitude by 1° longitude. Currently, the assessments are made by warming levels (1.5°C, 2.0°C, 3.0°C and 4.0°C) and specific scenarios which consider radiative forcing and socioeconomic scenarios (known by the acronyms SSP – Riahi et al. 2017), and no longer the radioactive forcing scenarios known by the acronym RCPs. In the fifth IPCC report (2014), the assessment is also made by periods of the year.

Table 1 shows what the variation in temperature and rainfall should be, according to different IPCC scenarios, throughout the year, in the rainy season (November to April) and in the dry season (May to October), in relation to 1961-1990 period, in BHRI. IPCC has five different scenarios and temperature increase levels of 1.5°C, 2.0°C, 3.0°C and 4.0°C. The scenarios chosen to exemplify the changes in this basin were global average warming of 1.5°C in scenario SSP1-2.6 (optimistic scenario, called sustainable development), the same warming in scenario SSP5-8.5 (pessimistic scenario, called fossil fuel-based development) and 4.0°C warming in scenario SSP5-8.5. Remembering that for the pessimistic scenario, warming of 1.5°C would be reached sooner than in the sustainable development scenario.

Figure 5. Fog over the forest.

The temperature variations in the region of interest indicate increases of 1.5°C (optimistic scenario) to 5.1°C in the annual average. However, when assessing the dry and rainy seasons separately, it is noted that the temperature increase can reach 5.5°C in the region of interest. This means that the average annual temperature in this region will be 30.5°C, compared to the current 25.7°C.

Table 1. Variations in temperature and average rainfall in the South American monsoon region under different CMIP6 warming scenarios, compared to the average temperature in the period 1961 to 1990.

Scenario	Heating	Temperature (°C)			Rainfall (mm/month)		
		Annual	Rainy Season	Dry S.	Annual	Rainy S.	Dry S.
SSP1-2.6	1.5°C	+1.5	+1.3	+1.7	-6.8	-7.8	-6.3
SSP5-8.5	1.5°C	+2.0	+1.8	+2.3	-9.7	-9.5	-9.8
	4.0°C	+5.1	+4.7	+5.5	-21.2	-29.9	-13.9

Source: https://interactive-atlas.ipcc.ch/regional-information

When the values of change in total rainfall are verified in future projections, the result is given as a percentage; so, the variation calculation must be made. The climatology values (1961 to 1990) for BHRI are: 154.3 mm/month annual mean, 256.7 mm/month in the rainy season (November to April) and 50.0 mm/month in the dry season (May to October). Table 1 shows the variation in the rainfall, in mm/month, in the different scenarios mentioned above.

The most optimistic scenario shows that there could be decrease of 6.8 mm/month in the average rainfall in this region, while for the pessimistic, this variation is 21.2 mm/month less than in the period from 1961 to 1990. This means 254.4 mm/year less annual rainfall. When separating the year into rainy and dry seasons, it is noted that, for the SSP1-2.6 (with warming of 1.5°C) and for SSP5-8.5 (with warming of 4.0°C) scenarios, the greatest reduction in the rainfall is in the rainy season (Figures 5 and 6).

Conclusions

The rainfall and temperature patterns shown in this chapter, both for the present (1991-2020) and in the future (1.5°C and 4.0°C warming scenarios), are in accordance with that shown in the sixth IPCC report: if there are no reductions in the emissions (immediate, quick and on a large scale) of the greenhouse gases, it will be impossible to limit the warming to 1.5°C (consistent with the SSP1-2.6 scenario) as suggested in the Paris Agreement. For the region of interest, this warming could reach 5.1°C annual mean (4.0°C warming scenario and SSP5-8.5). In addition, there will also be decrease in the accumulated rainfall.

Figure 6. Rain over the Carajás forest.

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Selection of plant species for restoration based on climate change scenarios

Victoria Teresawa, Vitor Gomes, Markus Gastauer

Restoration in a context of climate change

Ecological restoration is the process of assisting the recovery of an ecosystem which has been degraded, damaged, or destroyed (Gann et al., 2019). For this purpose, different strategies are used: while natural regeneration or assisted natural regeneration take advantage of the spontaneous arrival of seeds, active restoration introduces seeds or seedlings to accelerate the return of the ecosystem functions (see also Chapter 18). In this case, the selection of suitable species is a key factor for the return of the healthy conditions and the successful restoration of the forest environments (Elliott et al., 2003), which basically depends on the set of native species available and their characteristics, as well as its management potential (Brancalion & Holl, 2020). The practice of forest restoration has sought to prioritize the selection of species with uses for the management of local populations, contributing to the engagement of these actors in the success of the process (Meli et al., 2014). To be successful, the selection of species must also focus on those that will have greater chances of adapting to biotic and abiotic environmental factors in the planting area, especially those that may limit the habitat colonization process (Bochet & García- Fayos, 2015).

In the last decades, the climate change induced by humanity has affected the forest habitats (Feeley & Rehm, 2012), impacting all ecosystems. The lack of adaptation of the species to the future climate can lead to serious threats of extinction, as the speed at which climate changes are occurring today is much greater than the ability of the species to adapt to the new conditions (Gomes et al., 2019). The changes can impact the forest restoration, and the main impact factor is due to the possible lack of adaptation of the selected species to the future climate conditions (MacKenzie & Mahony, 2021). Consequently, the selection of species with greater resilience to climate change can contribute to the success of the forest restoration in future climate change scenarios (Thomas et al., 2017).

Estimates indicate that half of the Amazon could be impacted by 2050 due to climate change and deforestation, with loss of up to 65% of suitable habitat for tree species, with 53% of all known species threatened with extinction (Gomes et al., 2019). Currently, it is estimated that deforestation is the main source of impact on the Amazon forest, but future climate changes may exceed the impacts caused by deforestation, as they will continue to affect the entire region, while deforestation will advance gradually, mainly depending on the opening of roads. Giannini et al. (2021) investigated the impacts of climate change on the vegetation of the Carajás National Forest, analyzing 608 species. Approximately half of the analyzed species are in open canga areas, and half, in forest or *capões florestais*. It was observed that 42% of the studied plant species may potentially not find suitable habitat in the future due to the climate change, and that this effect will equally affect species in these two types of habitat.

In the present work, the objective was to use the species distribution modeling technique, a widely applicable computational tool, to assess the distribution of the tree species used in the forest restoration process in climate change scenarios, considering the Itacaiúnas River Water Basin (BHRI). This tool enables estimating areas where the species have greater probability of finding suitable habitats under different climate scenarios. The work hypothesis is that, among the species commonly selected for BHRI forest restoration, there are those that may be strongly affected by

Figure 1. *Dipterix odorata* in the Carajás forest.

Figure 2. *Simarouba amara* in the Carajás Flona.

climate change in future scenarios. This assessment can contribute to the construction of a list of species recommended for forest restoration, highlighting options with greater potential for adapting to future climate change scenarios.

Selecting species for restoration

The potential distribution of species was estimated for an original climate scenario (period between 1970-2000), presenting areas where the species were commonly distributed before the pressures of modern climate change promoted by human activities; and for two future scenarios for 2050 (pessimistic and optimistic), presenting areas where the species can be distributed in the future under climate change scenarios.

The modeled species were defined based on the most recent list of tree species for the Amazon (see Steege et al., 2019), and on a list of species used in forest restoration projects in the region, such as those presented by the work of Gastauer et al. (2020) and Rodrigues et al. (2019). From the models generated for known tree species and the crossing with those used in restoration projects, we sought to define which ones have the greatest potential to contribute to forest restoration in the region under conditions of future climate change. From the distribution models, the

Figure 3. *Parkia multijuga* in the Carajás Flona.

species richness and compositional variations were also estimated, which can contribute to the assessment of strategies for restoration of BHRI.

Based on the list of Amazonian species and the occurrence records available in the Global Biodiversity Information Facility (GBIF; www.gbif.orf), 464 tree species were found with at least one occurrence record in BHRI. Of these, 457 presented a sufficient number of occurrence records required for the modeling process, which resulted in statistically valid distribution models. Among the species with valid models, 214 have been used in forest restoration projects. The most frequently mentioned were *Hymenaea courbaril* L. (Fabaceae), *Dipteryx odorata* Forsyth f. (Fabaceae) (Figure 1), *Eschweilera coriacea* S.A. Mori (Lecythidaceae), *Handroanthus serratifolius* (Vahl) S.O. Grose (Bignoniaceae), *Simarouba amara* Aubl. (Simaroubaceae) (Figura 2), *Trema micrantha* (L.) Blume (Cannabaceae), *Cecropia palmata* Willd. (Urticaceae), *Cenostigma*

Figure 4. One of the factors for high mortality in plantations may be due to the fact that local adaptations to current and future conditions of species used for forest restoration were not considered.

tocantinum Ducke (Fabaceae), *Euterpe oleracea* Mart. (Arecaceae), *Jacaranda copaia* (Aubl.) D. Don (Bignoniaceae), *Parkia multijuga* Benth. (Fabaceae) (Figure 3), *Parkia platycephala* Benth. (Fabaceae) and *Tapirira guianensis* Aubl (Anacardiaceae). Of these, 196 (91%) are used by the local populations, a relevant factor for the success of restoration through the engagement of local people in the process. Only 162 species showed potential for use in restoration projects given their resilience to the assessed future climate scenarios.

Among the most frequently mentioned, *Eschweilera coriacea* S.A. Mori, *Trema micranta* (L.) Blume, *Euterpe oleracea* Mart., *Jacaranda copaia* (Aubl.) D. Don and *Parkia multijuga* Benth will not find adequate habitat in the future. *Eschweilera coriacea* S.A. Mori is one of the most abundant hyper-dominant species in the Amazon (see Steege et al., 2013), very frequently used in restoration projects. However, it will find few suitable habitats under the future climate conditions projected for the region. The list of 162 species with potential resilience to climate change represents 35% of those with suitable habitat in BHRI and can contribute to the selection of species for restoration in the region, considering the effects of climate change.

The average loss of suitable habitat for the 162 species was just 4% for both future climate change scenarios, highlighting the great resilience of these species. Half of them did not show any habitat losses, and 92% have some type of potential use by the local communities. A total of 33% of the species on the list had suitable habitat throughout the entire basin, including in future scenarios (approximately 41 thousand km2). These species have demonstrated extreme resilience to future change scenarios.

Species selection efforts, for example, those of Salomão et al. (2012), Giannini et al. (2017), Gastauer et al. (2020) and Rodrigues et al. (2019), investigated the contribution of factors, such as biomass values, commercial value of the wood, quantity of forest products, abundance, frequency of distribution, colonization and functional characteristics, in order to determine the potential contribution of the selected species for the forest restoration process. However, these methodologies do not include analyses which can predict the potential impacts of climate change on the selected species. The assessment of the effects of climate change on the potential distribution of the species can further contribute to refining the species selection process, avoiding that selected species show low resilience to the effects of the climate in the future (Figure 4).

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22

Impacts of the climate change on the benefits generated by the forest

Vitor Gomes, Tereza Cristina Giannini

The conservation of tropical forests has been a challenge in the face of the global changes induced by humanity, affecting life on Earth in several aspects, with deforestation and climate change having a greater role (Feeley & Silman, 2016, see Steege et al. , 2015). Estimates show that the Amazon has been impacted by these changes and could be even more so by the middle of the century (Gomes et al., 2019). Even small losses of biodiversity can reduce the capacity of the ecosystems to adjust to the global changes (Kremen, 2005). As a result, the diversity and the distribution of species can be severely reduced, threatening them with extinction. Therefore, diversity has been considered an essential component of the ecosystem resistance and resilience to the environmental changes (Walker et al., 1999), since, under given impact, it is expected that, in biodiverse native areas, the remaining species can compensate the services of the lost species (Díaz et al., 2005). Costanza et al. (2014) estimated the total monetary value of the global ecosystem services at US$125 trillion/year by 2011. In valuation studies, the service components often present higher values than those of the forest products linked to biodiversity (Costanza et al., 1997). Although the impacts of the global changes have been debated, estimates are still scarce (Binder et al., 2017; Foley et al., 2007).

The biodiversity of tropical forests is expressed in the richness and the composition of species in their different areas (Brown, 2014). Such richness corresponds to the total number of species in given region and can be estimated using different data collection methods. It is also possible to compare the composition of these species in different areas using similarity indexes (Steinitz et al., 2005), a particularly useful analysis when one wants to compare changes in species due to the impacts of the global change, as proposed in the present study. The analysis of these two aspects (richness and similarity of the species composition) is of great relevance for the provision and maintenance of the ecosystem functions and services (Mace et al., 2012). Since tropical forests are mega-diverse, the conservation of these spaces and their different subsets of species are essential activities to guarantee the provision of ecosystem services in their entire complexity and diversity (Brockerhoff et al., 2017). The sustainable use of natural resources can promote economic and environmental benefits, reducing the pressure on the natural areas and assuring the survival of threatened species (Gavin et al., 2018; Kremen & Merenlender, 2018).

In this study, the effects of climate change and deforestation on the richness and similarity of the species composition were assessed, also calculating the change in monetary value of nine ecosystem services provided by trees. The method used was species distribution modeling, aiming to assess the extent of the effects of the global changes on the ecosystem services in the Amazon. The base was a list with more than 10 thousand species described for the Amazon (see Steege et al., 2019).

Assessment of the plant species richness under climate change scenarios

Four different scenarios were used to assess the effects of the global changes: (1) historical (period between 1970-2000); (2) modern (year 2018); and (3 and 4) future

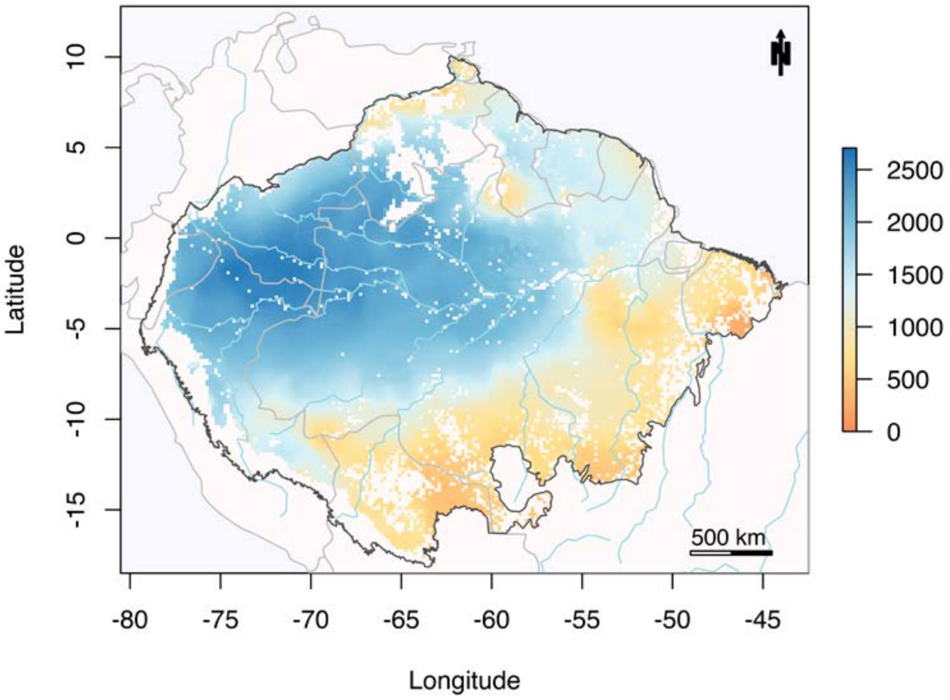

Figure 1. Estimated richness of plant species in the Amazon (values on the scale correspond to the number of species).

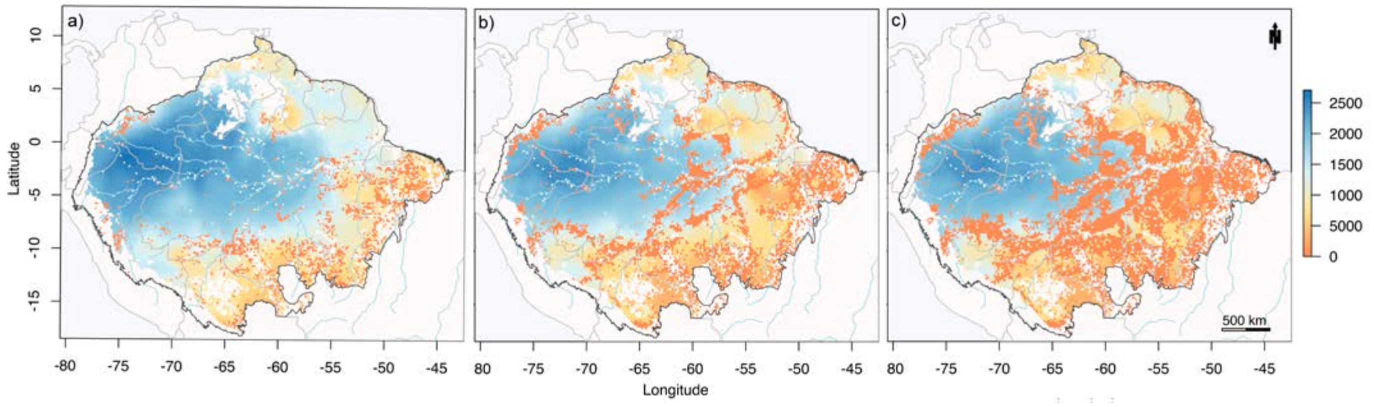

Figure 2. Species richness estimate, considering a) 2018, and future projections for 2050, considering b) optimistic and c) pessimistic scenarios.

scenarios (2050; optimistic with governance and pessimistic without governance). Of the almost 10 thousand reported species, it was possible to produce distribution models for 5,104 with sufficient occurrence records and statistically valid results, representing a total of 125 families and 828 genera.

The average species richness was 1,540 species per map cell at spatial resolution of 0.16 arc degrees (approximately 18 x 18 km) (Figure 1). The richness varied between 251 and 2,640 species across the map cells. The western and central parts of the Amazon presented the highest species richness values, while the eastern and southern parts presented the lowest values.

Between 2001 and 2018, deforestation increased in an area corresponding to 485,805 km2, approximately 9% of the total area of the Amazon (Figure 2). Deforestation projected for the optimistic scenario for 2050 doubled the total amount of forest loss, reaching 1,253,261 km2 (22%); the pessimistic scenario almost quadrupled the deforestation, reaching 2,195,443 km2 (39%) (Figure 2). In 2018, the average species richness dropped to 1,453 (approximately 5%).

The species richness estimated for future projections for 2050 showed the upper limit of the species richness varying between 2,519 (optimistic scenario) and 2,462 (pessimistic scenario). The average values for estimated species richness decreased abruptly based on the projected changes for 2050, ranging between 1,097 (optimistic scenario) and 896 plant species (pessimistic scenario). The effects of deforestation severely impacted the east and south of the forest. The pessimistic scenario presented a big drop in the estimated richness in the central part of the forest due to deforestation.

Previous studies have already demonstrated that the effects of the global changes can widely impact the Amazon Rainforest, contributing to severe decrease in the diversity and the distribution of the species (Bellard et al., 2012; see Steege et al., 2015), their combination could halve the tropical forest by the middle of the century (Gomes et al., 2019).

Assessment of the similarity of the plant species composition under climate change scenarios

The species composition was represented by the Jaccard similarity index (where 0 represents total dissimilarity and 1 total similarity), considering the species shared in each square analyzed on the map. Each climate scenario (present and future) was considered a different community, where beta diversity between the areas was assessed by dividing the number of species shared between the two scenarios (e.g. historical and 2018) by the total number of species of both scenarios. The similarity between the historical and the modern scenarios varied by average drop of 20% (Figure 3). For future projection scenarios, the drop variation was even bigger, reaching 35% (optimistic) and 50% (pessimistic), respectively (Figure 3). The species composition showed higher similarity values for the western and central parts of the Amazon in all assessed scenarios. In the optimistic and pessimistic scenarios for 2050, the species composition showed bigger variation in decline in the eastern part of the Amazon.

The species composition is recognized as a metric of great importance, as it is associated with ecosystem services and species identity (Díaz et al., 2006). The results of this study demonstrate that composition may also be more sensitive to the effects of climate change, presenting greater losses than the species richness.

Variation in the value of the ecosystem services provided by the plant species

A sharp reduction was observed in the monetary value of the ecosystem services, considering the results obtained from the modeling of the impact scenarios

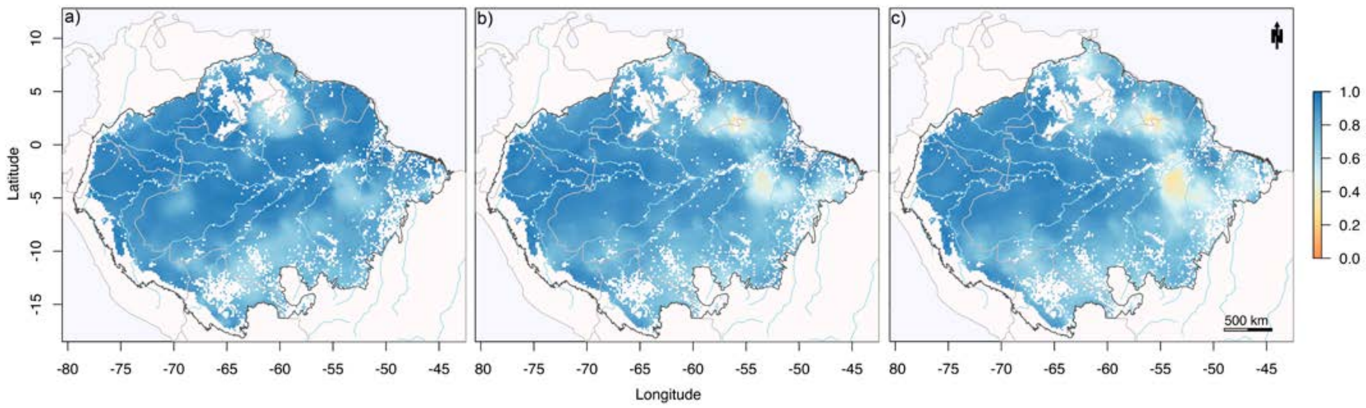

Figure 3. Change in the species composition based on the Jaccard similarity index, considering a) 2018, and future projections for 2050, considering b) optimistic and c) pessimistic scenarios.

mentioned above (Table 1). Between the historical and the modern scenarios, the reduction was 8.7%, varying between 22.4% and 40% when considering the optimistic and pessimistic future projection scenarios, respectively. By using species richness and composition reduction as a multiplier, and by measuring the effect on the ecosystem services, the reduction in the value of the ecosystem services is even greater than considering only the potential distribution loss (areas in km^2) estimated by the models.

Table 1. Estimation of the values of the ecosystem services related to the trees based on Costanza et al. (2014) and according to four global change scenarios (values presented in billions of dollars), considering the reduction in potential area due to global changes

Ecosystem service (in billion dollars)	**History 1970-2000**	**2018 modern**	**2050 optimist**	**2050 pessimist**
Forest area	$3,017.66	$2,754.88	$2,341.33	$1,809.93
Climate regulation	$1,146.06	$1,046.26	$889.20	$687.38
Disorder regulation*	$37.01	$33.78	$28.71	$22.20
Nutrient cycling	$1.12	$1.02	$0.87	$0.67
Pollination	$22.43	$20.47	$17.40	$13.45
Habitat/refuge	$347.07	$316.85	$269.28	$208.17
Food production	$151.39	$138.20	$117.46	$90.80
Raw material	$85.23	$77.80	$66.12	$51.12
Genetic resources	$251.19	$229.32	$194.89	$150.66
Total	$5,059.14	$4,618.60	$3,925.28	$3,034.38

* Storm protection, flood control, drought recovery, and other aspects of habitat response to environmental variability controlled primarily by the vegetation structure.

In 2018, the reduction reached 30.7%, and, in 2050, the values could vary between 64.2% and 82.5%. Changes in the composition alone contributed more than changes in the species richness to the reduction in the value of the ecosystem services. The total reduction reached 27.3% by 2018 (compared to 13% considering only the reduction in the species richness) and varied between 49.7% and 69.9% until 2050 (compared to 44.7% and 65.1% considering only the reduction of the species richness).

The connection between biodiversity and ecosystem services has been investigated (Balvanera et al., 2014; Costanza et al., 2007). Despite the efforts made to deepen the knowledge about the link between biodiversity and the ecosystem services, it is difficult to define a direct relationship or the proportion in which different aspects of biodiversity can impact the ecosystem services (Figure 4). When using a direct ratio between biodiversity and ecosystem services, very sharp reduction in the values of these services is obtained, with implications for human well-being which have to be urgently assessed.

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Figure 4. One of the factors for tree mortality could be the ongoing climate change.

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The importance of the scientific collections as evidence of biodiversity

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Actions for protection and conservation of biodiversity and the Vale Amazônia Biopark

Cesar de Sá Carvalho Neto, Lourival Tyski, Paulo Rogério Oliveira, André L.R. Cardoso, Nereston Camargo

Environmental protection actions are important tools for the conservation of the natural capital of Flona de Carajás, and in this context, the conservation actions of the Carajás Biodiversity Management Plan (PGBIO) (Figure 1), of Bioparque Vale Amazônia (BVA) and the Carajás Herbarium (HCJS) are highlighted..

PGBIO has developed actions to add sustainability to the iron ore extraction operations in the mosaic of the Carajás Conservation Unit and the surrounding areas. One of them aims to encourage the generation of knowledge for the conservation of biodiversity and natural capital, providing the necessary guidelines for the adoption of responsible practices in biodiversity management throughout the life cycle of the enterprises, reconciling conservation needs with development priorities. It focuses on identifying and managing the risks of the company's activities in relation to the biological diversity, in addition to sustaining results that reflect lower risk for the planning, implementation and operation of projects, adding reliability and competitiveness in the market (Vale, 2021). The development and the implementation of PGBio made it possible to identify risks related to biodiversity and propose measures to resolve them through mapping and support for research applied to sustainable biodiversity solutions for mining. This has fostered conservation combined with sustainable production, reducing the impacts as much as possible, or even aiming at positive impacts through science-based decisions for the projects to avoid, minimize, recover and restore nature in mined areas.

Figure 1. Members of PGBIO. From left to right: André L. R. Cardoso, Lourival Tyski and Cesar de Sá Carvalho Neto.

Bioparque Vale Amazônia (BVA)

Bioparque Vale Amazônia (BVA) is 37 years old. It occupies an area of 30ha completely immersed in the natural environment and is one of the few in the country to have this possibility of integration with the forest (Figure 2). There are approximately 360 animals part of the herd, distributed across 70 species, all from the Amazon biome (Figure 3). The Biopark is a member of the Association of Zoos and Aquariums of Brazil (AZAB) and is consequently part of the Technical Cooperation Agreement, signed by Instituto Chico Mendes de Conservação de Biodiversidade (ICMBio) and the Ministry of the Environment (MMA), for the management ex situ of 25 species of Brazilian fauna threatened with extinction. Among these species,

Figure 2. Visitors observing nature at BioParque.

Biopark declared the responsibility and institutional commitment to establishment and *ex situ* management of safe populations of the species *Amazona farinosa* (southern mealy parrot); *Ateles marginatus* (white-cheeked spider monkey); *Guaruba guarouba* (golden parakeet); *Harpia harpyja* (harpy eagle); *Panthera onca* (jaguar); *Saguinus bicolor* (pied tamarin); *Speothos venaticus* (bush dog) and *Pteronura brasiliensis* (giant otter), with genetic and demographic viability, in long terms, for conservation purposes. Also with the main objective of conservation in accordance with the signed agreement, the Biopark meets what is indicated as the best destination for the animal, considering the priority management recommendations made by the Studbook Keepers, and the capacity of the different institutions to receive, maintain and apply these recommendations. The studbook

Figure 3. Above, woolly monkey and scarlet ibis. Below, harpy and jaguar.

keepers are responsible to assure the populations and the individuals in captivity (Pelletier et al. 2009) (Figure 4).

With this purpose, today, in the Biopark, there are 18 adult individuals of *Guaruba guarouba* (golden parakeet) in its breeding stock and through pairing of couples and reproduction management, three puppies have already been born, which in 2019 were sent to Parque Estadual do Utinga in Belém/PA (reintroduction program into nature). There are three more puppies also born in the Biopark awaiting recommendations from the studbook keepers specialists. In the Biopark, there are also eight adult individuals of *Panthera onca* (jaguar) and one young one, born in the Biopark, five females, three males and the young female. The reproductive success of jaguars in the Biopark highlights the important role of the institution in the reproductive management of threatened species. In the last 10 years, there have been more than six births of jaguars in the Biopark, with emphasis on the most recent ones which were destined in accordance with the recommendations from the studbook keepers: a female melanic jaguar destined to the Zoo in Americana/SP in July 2021; another female melanic jaguar destined to the Zoo of Gramado/RS in August 2021; and a male jaguar born in the BioPark to Animalia Park in São Paulo in January 2023 (Figure 5).

In the breeding stock of the BioPark, there are also two males of *Speothos venaticus* (bush dog), four adult individuals of *Amazona farinosa* (southern mealy parrot)

Figure 4. Spectacled owl (*Pulsatrix perspicillata*), vulnerable species.

Figure 5. Jaguar or puma (*Puma concolor*) in BioPaque.

in the breeding sector, a couple of *Saguinus bicolor* (pied tamarin) in exhibition, a couple of *Harpia harpyja* (harpy eagle) in exhibition and a female in the extra sector, addition to four adult individuals of *Ateles marginatus* (white-cheeked spider monkey), three of which are females and one is male.

The Biopark is also recognized in the Amazon region due to the quality of its premises and the employees, in addition to being located in the middle of the forest (see also Chapter 14). With this recognition, the park became one of the main

Figure 6. Analyzing a specimen of the flora in the Carajás Herbarium.

institutions in the Amazon to receive and shelter seized animals, a result of the fight against animal trafficking and mistreatment. Highlighting the importance of conservation and management programs ex situ, in 2019, the Biopark received from Naturatins (environmental agency of the state of Tocantis) a baby *Pteronura brasiliensis* (otter), approximately 3 weeks old, who was under the parental care of the Biopark team. Following recommendations from the studbook keeper, in October 2022, the animal was sent to the São Paulo Aquarium to couple with a female.

Carajás Herbarium (HCJS)

The Biopark also shelters the Carajás Herbarium, established in 1987 (Figure 5). The Herbarium is a collection indexed by The New York Botanical Garden, integrating an international route of research into flora. It is part of the Brazilian Herbaria Network with acronym HCJS and is also the headquarters of the Carajás Biodiversity Management Plan. Currently, the collection is made up of more than 14,000 exsiccates distributed in 180 botanical families, predominantly angiosperms, with 151 families; pteridophytes, with 28 and gymnosperms, represented in the region solely


Macaco barrigudo
Humboldt's Woolly Monkey
Lagothrix lagothricha
Ordem: Primates
Família: Atelidae
Alimentação:
Distribuição geográfica:

by genus *Gnetum*, from the Gnetaceae family. Among the angiosperms, ten families represent 50% of the collection: Leguminosae 12%, Poaceae 8%, Cyperaceae 7%, Rubiaceae 7%, Melastomataceae 4%, Asteraceae 3%, Convolvulaceae 3%, Myrtaceae 2%, Eriocaulaceae 2%, Euphorbiaceae 2%. It is currently considered the largest collection of floristic diversity in the southeast region of Pará, mainly for species from ferruginous outcrops, consolidating knowledge about the present and/or past occurrence of several species and their distribution data.

The public-private partnership for the development of actions to protect FLONA de Carajás, research work to generate knowledge for conservation and management actions *ex situ* with the purpose to assure safe populations are important tools for the maintenance of the natural capital of this territory and to leave a legacy for future generations (Figure 7).

Figure 7. The legacy of nature, present in the BioPark, for future generations.

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24

The role of the botanical collections in the discovery of the flora of Carajás

Pedro Lage Viana, Eline Tainá Garcia, Tirza Teixeira Brito, Caroline Oliveira Andrino, Rafael Gomes Barbosa-Silva

History of the flora collections in Carajás

Biological collections are primary sources of information about biodiversity. The pioneer studies on the flora in the Carajás region took place long before the creation of the Carajás National Forest (Flona) in 1998. The botanist Paulo Cavalcante, a researcher at Museu Paraense Emílio Goeldi (MPEG) at that time, carried out the first expedition to collect botanical specimens in the region in May 1969 (Viana et al. 2016), bringing to the Herbarium collection of Museu Goeldi (MG) just over 100 samples from different botanical groups, all of them collected in cangas (vegetation on hilltops with ferruginous soil) in the region. Most of these collections were different from anything else already existing in this herbarium. So, to obtain taxonomic identifications, duplicates of these samples were sent as donations to herbaria in different parts of the world, so that the botanists specializing in specific groups of plants could study them in detail.

As a result of the study of these samples collected in the region, several plant species, previously unknown to science, were discovered and given a new scientific name, such as the iconic Carajás flower (Ipomoea cavalcantei D.Austin), described by the American botanist Daniel Austin in honor of the collector Paulo Cavalcante (Austin, 1981). The flora of the Carajás region then began to be known not only regionally, but throughout the international botanical community (Figures 1 and 2).

The interest of the scientists in knowing and unveiling the peculiar diversity of the plants in Carajás led to more expeditions to study this flora. The Goeldi Museum continued its botanical research in the region, carrying out several collection expeditions in the 1980s which increased the botanical collection in herbaria, especially in the MG herbarium. Some of these expeditions included the participation of foreign botanists, such as Calvin R. Sperling, responsible for a important set of

Figure 1. Record of a pioneer scientific expedition to Serra Sul, in the early 1970s, carried out by the team of the Goeldi Museum.

collections from Carajás, today spread across several herbaria. Thus, the MG herbarium collection subsidized the publication of the first list of plant species occurring in canga areas in Serra Norte (Secco & Mesquita, 1983).

The studies on the plant diversity in the region continued in the 1990s under the coordination of Dr. Manuela Silva, also from MPEG. The researcher continued carrying out botanical collections, mainly in the canga areas, and as a result, another significant number of samples were incorporated into the MG Herbarium collection.

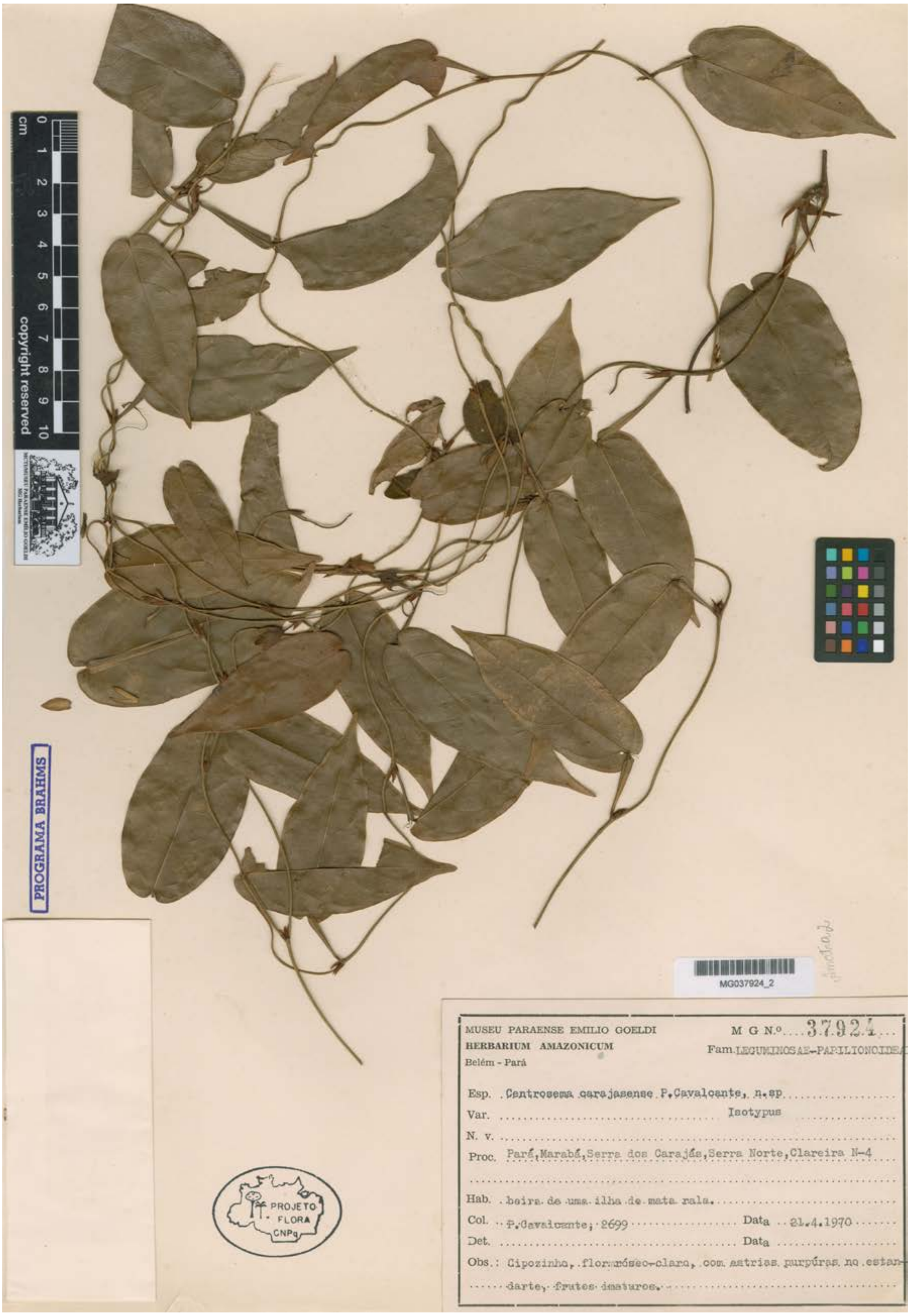
In the 2000s, studies intensified in the Carajás region related to environmental licensing processes, which required botanical collections to be deposited in herbaria. At that time, botanists hired by consulting companies contributed greatly to the knowledge of the flora in the region, enriching herbarium collections with more specimens from the region, including the MG herbarium, the main reference collection on the flora of Carajás.

This entire volume of specimens from Carajás and distributed in several herbaria, but mainly in the Goeldi Museum, was the starting point for the idealization of a big project with the purpose to systematize the knowledge about the flora in the cangas of the region of Carajás. Then, the Goeldi Museum and Instituto Tecnológico Vale entered into a partnership to carry out the audacious project Flora das Cangas da Serra dos Carajás, with involvement of more than 400 taxonomists from Brazil and abroad (Mota et al., 2018).

In the context of the project, several botanical collection expeditions were carried out, which, together with the historical records available in several herbaria, formed an excellent and representative reference collection for the intended studies. Based on this collection, taxonomic monographs were created and published for all botanical families in the Carajás canga areas, in addition to an updated compilation of species in the region. These taxonomic monographs include morphological descriptions of the species, keys to assist in the botanical identification, illustrations and a list of exsiccates corresponding to each species available in herbaria. Reaching this important level of knowledge about the flora of the Carajás cangas was possible only due to the countless exsiccates deposited and protected in herbaria, storing the knowledge about the important and threatened habitat of the cangas.

After all, what is an exsiccate exactly? An exsiccate is a sample of a plant collected in the field, which is pressed, dehydrated, cataloged and preserved in a herbarium. Each exsiccate has a label which contains information about the taxonomy of the species, what its botanical identification is, the date and place of collection (country, state, municipality, geographic coordinates), the name of the responsible collector, description of the environment where the plant was collected and other relevant information (Bridson & Forman, 2013).

An exsiccate deposited and listed in a herbarium is the only document, widely accepted by the scientists, which attests to the occurrence of a specific species in a specific location. Furthermore, for each species of plant known in the world, there is at



MUSEU PARAENSE EMILIO GOELDI
HERBARIUM AMAZONICUM
Belém - Pará

M G N.º 37924

Fam. LEGUMINOSAE-PAPILIONOIDE

Esp. Centrosema carajasense P.Cavalcante, n.sp

Var. Isotypus

N. v.

Proc. Pará,Marabá,Serra dos Carajás,Serra Norte,Clareira N-4

Hab. beira de uma ilha de mata rala.

Col. P.Cavalcante; 2699 Data 21.4.1970

Det. Data

Obs.: Cipozinho, flor róseo-claro, com estrias purpúras no estandarte, frutos imaturos.

Figure 2. An exsiccate from the first collection of the species *Centrosema carajasense* (Leguminosae), deposited in the Goeldi Museum herbarium and described for the Carajás region.

least one exsiccate deposited in some herbarium, which is the main reference about its identity. This material is called nomenclature "type". We can, therefore, say that the exsiccates distributed in herbaria around the world are the documentary base of all scientific knowledge about the richness and the distribution of flora in the world.

These specimens are not only studied by taxonomist botanists – those who identify and classify plants. Exsiccates are true sources of knowledge about biodiversity, fundamental pieces in different studies in plant biology and related areas, such as evolution, ecology, anatomy, conservation, genetics, biogeography, phytochemistry.

They are also important historical documents, which report the occurrence of species in given area over time, the characteristics of the environment and the history of efforts and exploratory trajectory of the researchers in their fieldwork. In times of increasing rates of deforestation and alteration of the landscape due to human activities, the set of exsiccates deposited in herbaria provides precious information to support reforestation and area recovery strategies, using species which originally occurred in the degraded areas.

Currently, the Herbarium of Museu Paraense Emílio Goeldi comprises the largest botanical collection from the Carajás region (Figure 3). Currently, there are records of 9,594 exsiccates collected in the region. Most samples of this total (at least 6,500) come from areas of ferruginous outcrops, known as canga, which occupy only a small part of the total area of the Carajás Flona. Just over 3 thousand specimens from this set were collected in other types of environments in the region, mainly forest formations. This entire collection has been meticulously studied over the last four years and is in the process of digitalization (Figure 4), with the purpose to obtain precise systematization of the knowledge about the flora in the region.

This qualification of the collection includes detailed examination of the morphology of the specimen to check or update its taxonomic identity (attribution of the correct scientific name), based on check in specialized literature, as well as update and checkout of information from the database of the herbarium.

The digitization task consists of obtaining a high-resolution image of the exsiccate, associating this image with its record in the collection database, and subsequently, making the information available in on-line databases for broad access by the scientific community. Of the total number of specimens from Flona de Carajás in the MG herbarium collection, 4,921 specimens were photographed and included in the institutional repository of biological databases.

At the end of this process, this information will be made available in the databases of the Brazilian Diversity Information System – SIBBr (https://www.sibbr. gov. br/), Global Biodiversity Information Facility – GIBIF (https://www .gbif.org/) and Reflora (https://reflora.jbrj.gov.br/), according to policy and activity schedule of the management of Herbário MG.

HCJS herbaria (BioParque Vale Amazônia), with approximately 7 thousand specimens collected in the region, BHCB (Federal University of Minas Gerais), with more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L

than 4,700 exsiccates from Carajás, and NY (New York Botanical Garden) also shelter a big part of the exsiccate collection already collected in the Carajás region.

Figure 3. Exsiccates stored and organized in cabinets in the Goeldi Museum Herbarium.

Flora of the forest

The historical botanical collection efforts in the Carajás region are concentrated in the canga formations. Therefore, today, the flora of the cangas in the Carajás region is very well known. On the other hand, the very rich forests that surround the canga formations and represent most of the area of the Carajás National Forest were not the target of recent research in the area, and therefore, there was little systematized botanical knowledge about the forest areas until the beginning of the Natural Capital project, in 2019, which also gets collaboration from Museu Paraense Emílio Goeldi (see Chapter 2).

Fieldwork in forest environments can often be quite challenging. In addition to the difficulties in getting around to access different areas within the forest, obtaining

Figure 4. Pedro Lage Viana in the Goeldi Museum Herbarium.

a botanical sample from a big tree can be a huge challenge. Often, the help of professional climbers is indispensable to access the parts of the plant necessary to compose an exsiccate. Furthermore, the specialized tools normally used for collection from trees, such as telescopic pruners and buckets, are difficult to handle and extremely limited for collection from very tall trees, which are so common in the Amazon Rainforest. Investment in the creation of new technologies to assist in the collection from trees could be an important ally in the knowledge of the forests in the region and the entire Amazon.

In this aspect, advance in the knowledge of the species in the Carajás forests have been made in the recent years, with field expeditions focused on these forest areas between 2019 and 2023. In addition, permanent plots for forest monitoring were installed, and the collected materials were deposited in the MG Herbarium, with duplicates sent to several herbaria in Brazil. These collections, as well as all those already carried out in the forest area of the Carajás region, are being compiled, cataloged and analyzed with the purpose to generate knowledge about the species present in the Carajás forest. This type of listing is rare in the Amazon in general, largely due to the huge challenges it represents. Therefore, it will hardly be possible to have exhaustive knowledge about the flora of a region like the Carajás forest. Although knowledge about the biodiversity of the Carajás region has been boosted in the recent decades, there are still gaps, especially in the forest habitats, which justify a greater concentration of investigation efforts. This knowledge becomes even more urgent considering the global climate change and the acceleration of the conversion of forests into different land uses.

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Entomological collections of Carajás at Museu Paraense Emílio Goeldi (MPEG) and considerations about the fauna

Orlando Tobias Silveira

Biological collections are pillars of disciplines, such as systematics and biogeography and important support for ecology and conservation biology. They are systematized repositories of specimens and information, including taxonomic identity and collection sites and environments (Bradley et al., 2014). They keep type specimens that support the correct application of the scientific names of the species. The development of the digitization of specimen data and images and their storage in computer bases has multiplied the potential use of the collections. Ecology and conservation projects can quickly access collection databases looking for spatial (and time) patterns of occurrences of species and characteristics. They are, therefore, fundamental in studies of species distribution modeling and indispensable in the assessment of the impacts of regional and global changes (Meineke et al., 2018).

Museu Paraense Emílio Goeldi (MPEG) is a pioneer in collections in the Brazilian Amazon, having started this activity between the 19th and 20th centuries. Adolfo Ducke was one of the founders of the entomological collection, having described a high number of genera and species of bees and wasps. Few Brazilian museums have such ancient and diverse collections of Amazonian insects, totaling close to 1 million specimens, including primary and secondary types of just over 490 species. The origin of most of the material is Amazonian, especially from the eastern part and along the Amazon River.

Carajás insects as represented in the MPEG collection

Of the regional faunas represented in MPEG, that of Serra dos Carajás (or more specifically Serra Norte), in Pará, has the largest and most diverse collection. The inventory carried out by the museum between 1983 and 1986 adopted traditional fauna survey methods to obtain collections of most of the big insect taxa. Although MPEG probably holds the largest collections of insects in Carajás (Figure 1), other institutions also keep important collections. Information from report Diagnosis of the state-of-the-art of the knowledge of the Serra de Carajás fauna (MPEG, 2005) is summarized herein and updated with information from the collection databases. Quantitative differences in relation to that work are due to digitalization deficits, loans and methodological issues (we counted only identified species here).

Table 1 presents numbers of already digitized specimens from Carajás deposited in MPEG and information about identification. There are no collections of entognathous hexapoda (Collembola, Protura and Diplura), although they were treated by M.L. J. Macambira (in MPEG, 2005) in a study on the soil mesofauna of Carajás. Nor are there collections of Thysanura (Archaeognatha and Zygentoma), except a recent specimen from order Zygentoma. There are specimens of most orders of winged insects in the collection. Of those with primitive wing articulation and aquatic immatures (paleopterans), only Odonata has a larger collection of Carajás. "Neopterans" (capable of folding their wings longitudinally over the body) comprise most insects, with 23 orders in Brazil (Rafael et al., 2012). Fifteen orders are represented in the Carajás collections and the lack of the remaining eight does not necessarily indicate rarity, but rather failure to use adequate collection and preparation techniques (Table 1).

Of the insects with a body type similar to "grasshoppers and cockroaches" (Polyneoptera), the largest collections at Carajás are cockroaches, but the collection of grasshoppers and crickets (Orthoptera) is more diverse and better taxonomically studied.

There is a very diverse collection of Hemiptera (bedbugs and cicadas) with emphasis on specimens of aquatic and semi-aquatic taxa, which correspond to 30% of the total.

Of the large Holometabola group, there are collections of Carajás from the four "megadiverse" orders (Hymenoptera, Coleoptera, Diptera and Lepidoptera), and small collections of Neuroptera, Megaloptera and Trichoptera. In Hymenoptera, ants, bees and wasps are the largest collections, totaling more than 20 thousand specimens from 30 families. There was a recent significant addition of hymenoptera, collected by teams from Instituto Tecnológico Vale (ITV) and by consulting companies operating in the Carajás National Forest (Flona) and the surrounding areas (Figure 2).

The already digitized collection of Coleoptera de Carajás covers 4,309 specimens from 20 families (Table 1). However, the total number of beetles is higher, as already presented by Valente (in MPEG, 2005), who mentioned 10,325 specimens from 58 families. Of the Carajás diptera, 7,409 specimens from 23 families are digitized, with predominance of the Tabanidae family. The Carajás digitized collection of Lepidoptera contains 2,444 specimens, from 17 families. Specimens of Nymphalidae butterflies represent 30% of the material.

Table 1. Numbers of insect specimens from Carajás in MPEG, by orders (and some families of Hymenoptera), from already digitized collections and by numbers of identified families, genera and species (not counting morphospecies).

TÁXON	N. specimens	N. families	N. genera	N. species
ZYGENTOMA	1	–	–	–
ARCHAEOGNATHA	–	–	–	–
ODONATA	484	11	21	5
EPHEMEROPTERA	30	4	–	–
ZORAPTERA	–	–	–	–
EMBIOPTERA	7	1	–	–
PLECOPTERA	28	1	1	3
ORTHOPTERA	456	15	60	44
DERMAPTERA	131	3	3	3
PHASMATODEA	12	3	5	3
MANTODEA	89	3	5	7
BLATTARIA	665	3	21	19
ISOPTERA	609	2	32	53
HEMIPTERA	4,863	47	214	162
THYSANOPTERA	–	–	–	–
PHTHIRAPTERA	–	–	–	–
PSOCOPTERA	31	3	–	–
HYMENOPTERA	20,336	30	177	377
Formicidae	11,674	–	60	94
Apidae	5,417	–	33	122*
Megachilidae	114	–	2	1
Halictidae	117	–	6	5
Andrenidae	11	–	1	2
Vespidae	2,450	–	22	106
NEUROPTERA	218	7	9	8
MEGALOPTERA	4	1	1	0
COLEOPTERA	4,309	20	221	248
STREPSIPTERA	–	–	–	–
DIPTERA	7,409	23	63	118
MECOPTERA	–	–	–	–
SIPHONAPTERA	–	–	–	–
TRICHOPTERA	147	5	3	–
LEPIDOPTERA	2,444	17	182	279
Totais	62,056	199	1,142	1,537

* the number of bee species from Carajás including morphospecies and considered other Brazilian collections is currently 222 (ITV data).

Taxonomic development of the collection

Figure 2 shows proportions of Carajás specimens identified at the genus and species levels. In most taxa, 50% or more are identified at least to the genus level. The percentages identified in species are lower, as expected, but close to 50% in most collections with more than 500 specimens. Higher identification rates on the far right of Figure 1 are due to small collections, with less than 150 specimens.

A few dozens of species have already been described based on type material from Carajás, with 13 holotypes (and 46 paratypes) of beetles in the MPEG collection, especially from Cerambycidae, Curculionidae, Elateridae, Histeridae, Passalidae and Scarabaeidae; 12 holotypes (and 22 paratypes) of hymenoptera, seven species of Bethylidae, five species of Vespidae and one species of Meliponini (paratype of *Lestrimelitta ciliata*); six holotypes (and 236 paratypes) of diptera from the families Tabanidae, Ctenostylidae and Sarcophagidae; two holotypes (and three paratypes) of five species of bedbugs and five paratypes of one species of leafhopper; a holotype (and a paratype) of a species of mantises; and a paratype of a termite species.

Distribution of the effort by environment and recent collections

In Figure 3, showing insect collection sites in Flonas Carajás and Tapirapé-Aquiri, white circles indicate approximate locations of insect collection points in expeditions in the 1980s, all of them in Serra Norte, and most associated with the roads, and in forest areas. However, considerable collection effort was dedicated to the canga areas, especially the old N1 core. Regarding water environments, considerable effort was spent on the collection of hemiptera, beetles, trichoptera, dragonflies and other groups associated with bodies of water at some stage of development.

Regarding explorations of new areas, recent collections by ITV teams in the surroundings of Serra Sul should be highlighted, covering mainly butterflies and bees, but also wasps (Figure 3, yellow circles and black diamonds). Recent deposits of bees and ants from areas in Flona Carajás (Granite-Sandstone project) and the surrounding areas, such as Serra Leste (blue circles), were made by environmental consulting companies.

Highlights about the collections

General numbers of the Carajás computerized collection in MPEG (Table 1) suggest there is potential for studies and discoveries. Greater limitations on the older part of these data arise from the non-use of a defined sampling design at the time that would allow precise characterization of the collection effort. Most of the authors in MPEG (2005) resented the lack of methods that would have allowed better sampling of taxa

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Figure 1. Orlando Tobias Silveira in the entomological collection of the Goeldi Museum.

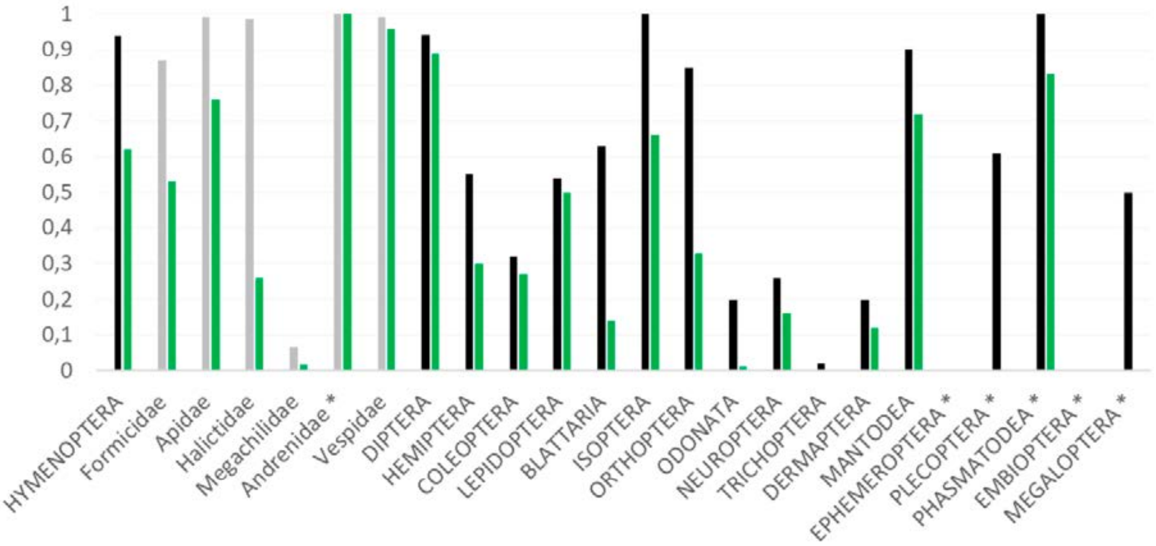

Figure 2. Bar graph with proportions of specimens identified at the level of genus (black, or gray for families of Hymenoptera) and species (green), for insect orders from Carajás represented in the MPEG collection (ordered from left to right according to number of specimens; * indicates less than 50).

insufficiently represented in the collections (Figures 4 and 5). Despite that, by means of approximations of the locations of the collection points of the first inventories, and with the more intensive taxonomic study of some groups, it is possible to make reasonably accurate generalizations about some of these faunas (see Silveira, in MPEG, 2005).

In the Vespidae family, for example, the almost 120 species and morphospecies of social species (Polistinae) are found only similarly in a few areas of the Neotropics which have undergone more intensive and systematic sampling (Caxianã, PA), or long-term surveys (Belém, PA). Based on the frequency of the species at the collection points, the table of the most common species (of the genera *Agelaia* and *Angiopolybia*) is very similar to the findings in recent inventories using more systematized methods (Silveira et al., 2012). In addition to the richness (and new species), this fauna has elements not found in the Amazon lowlands, such as *Polybia ruficeps*, *Mischocyttarus omicron* and three species of this genus described by Borges and Silveira (2019). Still in Vespidae, Silveira (2015) described the solitary species *Paramasaris fernandae* from Carajás, a unique record of wasps from the subfamily Masarinae in Amazonian forests, whose species feed the larvae with pollen, a unique habit in a group in which all the rest is from predators. Of the bees collected in the 1980s, there is predominance of Meliponini (stingless bees), with just over 60 species from 17 genera. Most species belong to genera *Trigona*, *Melipona* and *Partamona*. Seventeen most common species occurred in more than 30% of the collection points (53% of *Trigona*). In addition to the three genera above, *Ptilotrigona* and *Tetragona* also had representatives among more common species.

For the butterflies, there is still no published list of species for the Carajás National Forest, but recent studies for the Natural Capital project in 2019 and 2022 resulted in

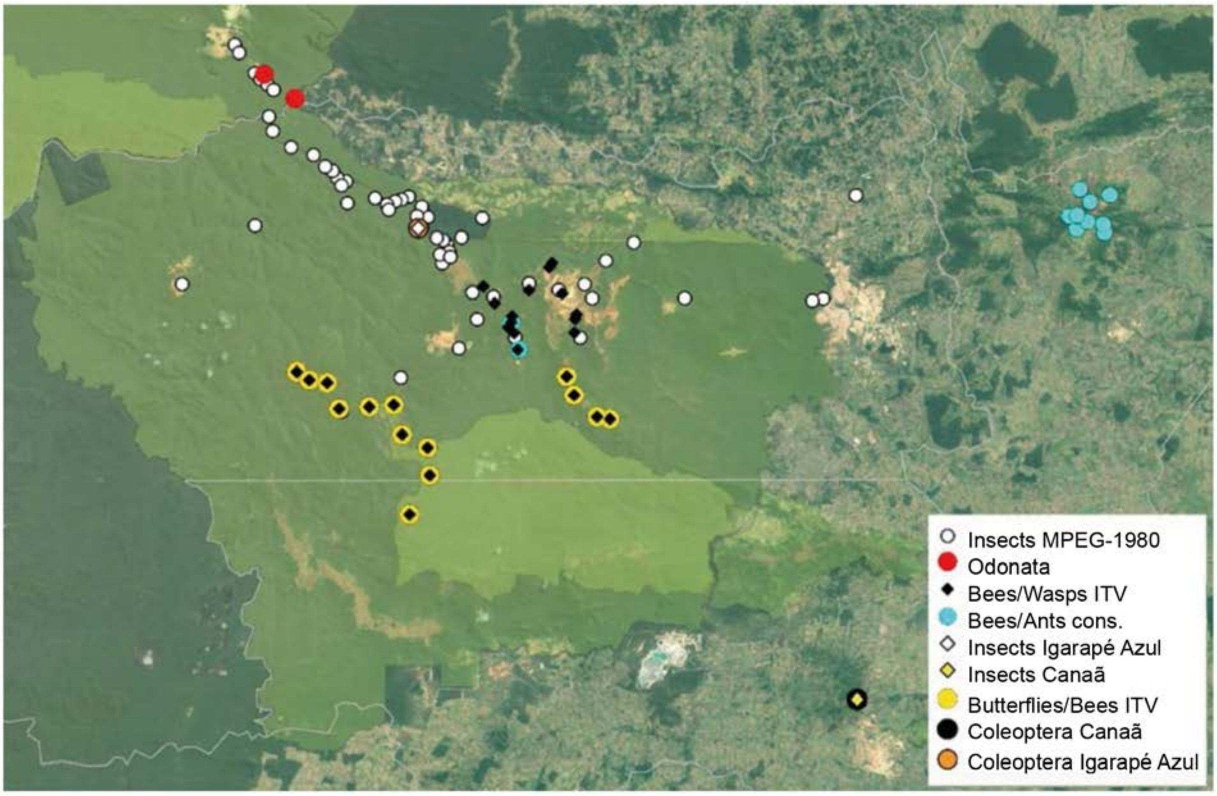

Figure 3. Distribution of insect collections in the Carajás and Tapirapé-Aquiri Flonas (part) and the surrounding areas, according to material in MPEG. White circles indicate approximate MPEG collection points in the 1980s; for other sites, see the legend.

the recognition of 182 species. All six butterfly families are represented (Hesperiidae, Lycaenidae, Nymphalidae, Papilionidae, Pieridae and Riodinidae), with remarkable predominance of Nymphalidae, which gathers 129 species or 71% of the sampled fauna (80% of the collected individuals). This big proportion of Nymphalidae is due to the easier sampling using Van Someren-Rydon traps with fermented fruit baits. Butterflies from other families have been captured only with entomological nets.

Recommendations

Despite the considerable amount of entomological material from Carajás already deposited in collections, the unquestionable natural richness of the region requires recognizing the need for greater effort to have a satisfactory record of biodiversity. For several reasons, including logistical ones, Flona Carajás represents a unique opportunity for more detailed knowledge of the fauna in Amazonian areas. Furthermore, the great importance of the insects, from different perspectives, scientific and practices, combined with recent publications on the decline of their populations (Wagner et al., 2021), only increases the urgency for more studies. The recent trend has been to favor

Figure 4. Butterfly species collected in Carajás and deposited at the Museu Goeldi.

Above:

A- *Phocides thermus*;

B- *Pyrrhopygopsis socrates*;

C- *Urbanus esmeraldus*;

D- *Yanguna cometes*.

Below:

A- *Astraptes alardus*;

B- *Phoebis argante*;

C- *Parides eurimedes*;

D- *Morpho menelaus*.

Figure 5. Collection cabinet of the Goeldi Museum entomological collection. In the drawers, we can see blue butterflies (*Morpho* sp. Fabricius, 1807).


Nymphalidae
Satyrinae
Morphini
Em estudo
Nymphalidae
Satyrinae
Em estudo

some indicator taxa, normally collected by traps. At least for special areas, it would be important to increase the taxonomic coverage of these inventories. Table 1 shows that the number of insect orders underrepresented in Carajás collections is still considerable. Even in Hymenoptera, the order with the biggest collection, most specimens are from relatively few taxa that contain social species (ants, wasps and bees). It is possible to diversify the listed taxa without giving up sampling designs that allow comparative studies of diversity.

In Carajás, it will also be important to expand the sampled area. It can be seen in Figure 3 that most insect collections occurred in the northern region of Carajás, and that studies have recently been advancing only in Serra Sul. Finally, it will be important to encourage the study of the entomological material which has already been deposited, especially hyperdiversified groups with greater identification deficit in the collections, such as beetles and moths, among others.

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Bees from Carajás deposited at Universidade Federal de Minas Gerais – the contributions of professor Fernando Amaral da Silveira

José Eustáquio dos Santos Júnior, Roderic Breno Martines, Roselaini Mendes do Carmo da Silveira

The importance of the bees

Bees, belonging to order Hymenoptera, have approximately 20 thousand species worldwide (Michener, 2007; Alexander et al., 2023). In Brazil, 1,965 species of bees were cataloged (Moure et al. 2022), but the estimate is approximately 3 thousand species (Silveira et al., 2002). The Brazilian species belong to five of the seven existing families, Andrenidae, Apidae, Coletidae, Halictidae and Megachilidae (Michener, 2007).

Native bees, as well as other pollinators, are of great interest to the scientific research and the economy (Kearns et al. 1998). In recent decades, the importance of these insects, considered to maintain biodiversity thanks to the services provided by pollination, has been measured in billions of dollars annually. In Brazil, this value is around 12 billion dollars per year for agriculture (Wolowski et al., 2019). The importance of the bees goes beyond pollination, as some species can be used as bioindicators of the environmental quality (Ruiz et al., 2013, Gonçalves & Faria, 2021), and/or even in the recovery of degraded areas (Williams, 2011). In addition to the benefits as insect pollinators and bioindicators, the bees are a source of products with added economic value, such as honey, pollen, wax and propolis (e.g. meliponines and *Apis mellifera* – Michener, 2007); and as a source of microorganisms with economic potential (e.g. yeasts for the production of fermentation-based products – Rosa et al., 2003; Teixeira et al., 2003).

Although the bees are among the most studied groups of insects in the world, there is lack of ecology, systematics and taxonomy works (Silveira et al., 2002; Michener, 2007). The lack of these studies can be identified in the lists of species of scientific works (e.g. Maia et al., 2020), where there are morphospecies specimens (not identified to the lowest taxonomic level of specificity). Some genera have only morphospecies taxa because they do not have keys available for identification or due to the lack of identified material available for comparison in taxonomic collections. Only increasing taxonomic review work will it be possible to link the names available in the literature to currently unidentifiable taxa, check synonymies, and when necessary, describe possible new species.

The bees are among the organisms historically used to monitor the Carajás National Forest. The use of bees as bioindicator organisms was encouraged and proposed by Professor Fernando Amaral da Silveira, a researcher who lived to develop knowledge about the Brazilian bees. Many of the bee collections since the 1980s were carried out by this researcher. The collected specimens are deposited at the Taxonomic Collections Center of Universidade Federal de Minas Gerais (CCT-UFMG), constituting an important collection about the diversity of bees in the region.

This chapter aims to pay tribute to Professor Fernando, recently deceased, reporting his academic and professional history, with his important contributions to the development of melitology in Brazil (i.e. study of bees in all their biological and systematic aspects) and to understand the bee fauna of Carajás.

A summary of Fernando Amaral da Silveira’s academic career

Professor Fernando's enthusiasm and dedication to the studies of bees can be seen since his academic qualification. He graduated as an agronomist from Universidade Federal de Viçosa (UFV) in 1985 when he started his first work with bees. In 1988, he became a master in Entomology at UFV, where he studied bees and their food sources at the Paraopeba Forest Experimentation Station, Minas Gerais. In 1995, he received a Ph. D. degree in Entomology from the University of Kansas, where he developed research about the phylogenetic relationships and classification of Exomalopsini (Insecta: Apidae). After defending his thesis, he became a professor at Universidade Federal de Minas Gerais (UFMG), where he taught subjects in the area of systematics and invertebrate zoology. The emphasis of his research projects was on systematics and conservation of bees, working mainly on the following topics: bees, fauna, systematics, conservation and biodiversity.

Upon joining the faculty at UFMG, Fernando founded the Laboratory of Systematics and Ecology of Bees – LSEA, today the Laboratory of Insect Systematics of the Department of Zoology at UFMG, where he helped create the Postgraduate Program in Zoology (PgZoo-UFMG). With the foundation of LSEA, the bee collection of UFMG was born, which would later become CCT-UFMG. The beginning of the collection included specimens collected in two projects started in 1995, both with connection to the areas of the Metallurgical Zone and/or the high altitude fields of eastern Brazil (V&M Florestal Ltda and CNPq).

Throughout his academic life, Fernando wrote several articles (e.g. Silveira & Cure, 1993, Santos Júnior et al., 2015, Freitas et al. 2019) and a book (Silveira et al., 2002) on bee systematics and biogeography. He was also of great importance in the qualification of many professionals, having guided undergraduate (Biological Sciences), master's and Ph. D. degree students, the latter in the Postgraduate Programs in Zoology and Ecology and Wildlife Management, both at UFMG. Fernando always drew attention to the enormous diversity of bees, considering their ways of life, the ecological services they provide and the threats we pose to their survival.

The project started in 2002 with the publication of Brazilian Bees — systematics and identification (Silveira et al. 2002) was just the first part of a bigger book, which covered all aspects of the biology of the Brazilian bees. However, the incipience of the state-of-the-art up to the date of that publication and the activities in other projects meant that the authors put aside the "big book" project, which was taken up by Professor Fernando intensively in the last years of his life. The work had great importance in the evolution of the knowledge about the bees in Brazil over the last two decades, facilitating the identification of the Brazilian species, and thus, enabling other studies that would be compiled in his second book.

Throughout his career, Professor Fernando directly supervised 46 students (i.e. scientific initiation, course completion work, master's degree, Ph. D. and post-doctoral degree supervision), among them, there are professors, technicians and environmental analysts who continue today passing on lessons about the importance (i.e. ecosystem services – pollination), diversity (e.g. taxonomy, systematics, inventory and monitoring), conservation (e.g. assistance to the environmental bodies in the composition of the lists of species threatened with extinction, members of national action plans – PAN for species conservation and environmental education) and mitigation of environmental impacts on the bee populations.

Inventories in Carajás and UFMG collection

At the beginning of 2008, Fernando started to participate in inventories of bees with known occurrence in Flona de Carajás (Figures 1 and 2), among them, there are the study of similarity of metallophilic savanna landscapes in the region of Carajás, PA and the biodiversity survey and conservation status of Serra da Bocaina, PA. These studies added more knowledge about the bees of Serra dos Carajás and increased the collection of bees in the insect collection of CCT-UFMG. The identification keys made available by Professor Fernando and the collection of specimens started by him, which became the insect collection of CCT-UFMG, made it possible to carry out other works. For example, Borges and collaborators

(2020) cataloged 222 species of bees in the municipalities where Flona de Carajás is located, compiling the available data in taxonomic collections and identifying the specimens deposited by a specialist.

The collection started by Professor Fernando currently contains approximately 200 thousand specimens of insects deposited, 20 thousand of which approximately distributed in hundreds of species, were sampled in the Carajás National Forest. The precise number of bee specimens and species from Serra de Carajás deposited in the insect collection of CCT-UFMG is difficult to estimate, as many specimens are awaiting the process of listing, digitalization of the identifications in the database and checkout of the identifications. Furthermore, some species are waiting to be described (new species), such as the species *Scaura amazonica*

Figure 1. Fernando Amaral da Silveira (in the foreground) on a visit to BioParque Vale Amazônia (Flona de Carajás, in Pará) in 2008.

Figure 2. Members of the project team *Survey of biodiversity and conservation status of Serra da Bocaina, PA* during a visit to Pedra da Harpia (Flona de Carajás), with detail for the presence of professor Fernando Amaral da Silveira (second, from right to to the left).

Nogueira, Oliveira & Oliveira, 2019 (five paratypes from Canaã dos Carajás deposited at CCT-UFMG) and *Neocorynura rubicunda* Gonçalves, 2019 (holotype from Canaã dos Carajás deposited at CCT-UFMG).

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List of authors

Alexandre Aleixo – **Instituto Tecnológico Vale**

Amanda Paracampo – **Instituto Tecnológico Vale**

André Luiz de Rezende Cardoso – **Vale S. A.**

Antônio Vasconcelos Nogueira Neto – **Instituto Tecnológico Vale**

Bruno Garcia Luize – **Universidade Estadual de Campinas**

Caio Yoshiura – **Instituto Tecnológico Vale**

Caroline Oliveira Andrino – **Universidade Nacional de Brasília**

Cesar de Sá Carvalho Neto – **Vale S. A.**

Claudia Wanzeler da Costa – **Instituto Tecnológico Vale**

Daniela C. Zappi – **Universidade Nacional de Brasília**

Edilson Freitas da Silva – **Instituto Tecnológico Vale**

Edivaldo Afonso de Oliveira Serrão – **Instituto Tecnológico Vale**

Eline Tainá Garcia – **Museu Paraense Emílio Goeldi**

Emily Ane Dionizio – **Instituto Tecnológico Vale**

Everaldo Barreiros de Souza – **Universidade Federal do Pará**

Felipe Costa Trindade – **Instituto Tecnológico Vale**

Felipe Martello – **Instituto Tecnológico Vale**

Gabriel Caixeta Martins – **Instituto Tecnológico Vale**

Guilherme Oliveira – **Instituto Tecnológico Vale**

Isa Rebecca Chagas da Costa – **Instituto Tecnológico Vale**

José Augusto Bitencourt – **Instituto Tecnológico Vale**

José Eustáquio dos Santos Júnior – **Universidade Federal de Minas Gerais**

José Tasso Felix Guimarães – **Instituto Tecnológico Vale**

Juliana Lovo – **Universidade Federal da Paraíba**

Leandro Argolo – **Instituto Tecnológico Vale**

Leonardo de Sousa Miranda – **University of Lancaster**

Leonardo Trevelin – **Instituto Tecnológico Vale**
Lourival Tyski – **Vale S.A.**
Luciana Patrícia Silvestre de Souza – **Instituto Tecnológico Vale**
Luiza de Araújo Romeiro – **Universidade Federal do Pará**
Markus Gastauer – **Instituto Tecnológico Vale**
Michele Molina – **Instituto Tecnológico Vale**
Nereston Camargo – **Vale S.A.**
Nikolas Jorge Carneiro – **Instituto Tecnológico Vale**
Orlando Tobias Silveira – **Museu Paraense Emílio Goeldi**
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Paulo Rogério Oliveira – **Vale S.A.**
Pedro Lage Viana – **Museu Paraense Emílio Goeldi**
Priscila Sanjuan – **Hydro**
Rafael Borges da Silva Valadares – **Instituto Tecnológico Vale**
Rafael Cabral Borges – **Instituto Tecnológico Vale**
Rafael Gomes Barbosa-Silva – **Instituto Tecnológico Vale**
Rafael Melo de Brito – **Department of Environment and Sustainability of the State of Pará**
Renata Gonçalves Tedeschi – **Instituto Tecnológico Vale**
Roderic Breno Martines – **Biobrasilis Consultoria Ambiental Ltda**
Ronnie Alves – **Instituto Tecnológico Vale**
Rosane Barbosa Lopes Cavalcante – **Instituto Tecnológico Vale**
Roselaini Mendes do Carmo da Silveira – **Biobrasilis Consultoria Ambiental Ltda**
Sâmia Nunes – **Instituto Tecnológico Vale**
Santelmo Vasconcelos – **Instituto Tecnológico Vale**
Sidnei de Melo Dantas – **Instituto Tecnológico Vale**
Silvio Ramos – **Instituto Tecnológico Vale**
Taise Pinheiro – **Instituto Tecnológico Vale**
Tereza Cristina Giannini – **Instituto Tecnológico Vale**
Tirza Teixeira Brito – **Museu Paraense Emílio Goeldi**
Ulysses Madureira Maia – **Instituto Tecnológico Vale**
Victoria Teresawa – **Universidade Federal Rural da Amazônia**
Vitor Gomes – **Instituto Tecnológico Vale**
Wendel Valter da Silveira Pereira – **Instituto Tecnológico Vale**

Acknowledgments

We would like to thank the creators of project Capital Natural das Florestas de Carajás at Instituto Tecnológico Vale (ITV), José Oswaldo Siqueira and Vera Lucia Imperatriz-Fonseca, who recognized the importance of the topic and supported the performance of the research. We also thank Guilherme Oliveira, current Scientific Knowledge Manager at ITV, for all his support in the development of the research activities related to the project.

We thank for the support of the partners of Vale's Carajás Biodiversity Management Plan (PGBIO), especially, Cesar Neto, Lourival Tyski and André L. R. Cardoso, whose knowledge of the local fauna and flora has always been fundamental at all stages of the process. They were important sources of inspiration, and contributed greatly throughout all stages of the research.

We are also deeply thankful to the partners from Museu Paraense Emílio Goeldi (MPEG), the depository of biological collections in the state of Pará, especially Pedro Viana and Orlando Silveira. We would also like to thank our partners from Universidade Federal de Minas Gerais (UFMG), especially the late Fernando Silveira, former curator of the bee collection at that institution, who has always supported and accompanied us in the grateful task of deepening our knowledge about the Brazilians bees.

We would also like to thank the partners who made their photos and images available to illustrate the book. Especially, we would like to thank Miguel Aun, whose look brought multiple perspectives to the concept of natural capital through the art of photography, and Rosivan Nascimento, who accompanied us in the field operating a drone for aerial images, helping us to give an idea of the size of the area where the forest extends.

Finally, we would like to thank the partners of ITV, who embraced the project activities with satisfaction and supported each stage, generously sharing their knowledge and expertise. Thank you very much for all your enthusiasm to participate in the project and for the fruitful exchange of ideas, which helped a lot in the development of the research.

The number of authors of this book and their diverse backgrounds is clear demonstration of a joint activity of great value in the search for deepening the knowledge about the Amazon in a multidisciplinary way, an attitude, in fact, increasingly necessary and urgent under the present scenario of quick global changes.

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Dados Internacionais de Catalogação na Publicação (CIP)

N285 Natural Capital of the Carajás forests. / Organization: Tereza Cristina Giannini.
Belém: ITV, 2024.
272 p. : il. color.

ISBN (eletrônico) 978-85-94365-24-8
DOI 10.29223/BOOK.ITV.DS.2024.01.Giannini

1. Carajás National Forest – Brazil. 2. FLONA Carajás. 3. Biome – Amazon.
4. Natural Capital – Pará. I. Giannini, Tereza Cristina, org. II. Instituto Tecnológico Vale (Belém, PA). III. Museu Paraense Emílio Goeldi. IV. Título.
CDD 23. ed. 577

Eddie Saraiva – Bibliotecário – CRB 2/1843

INSTITUTO TECNOLÓGICO VALE

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ISBN 978-85-94365-24-8

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