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POVOS INDÍGENAS, PRODUÇÃO DO CONHECIMENTO E BIODIVERSIDADE AQUÁTICA NA AMAZÔNIA: UMA ABORDAGEM BIBLIOMÉTRICA E ECOLÓGICA

Belém – Pará
2026

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Dissertação apresentada ao Programa de Pós-Graduação em Ecologia da Universidade Federal do Pará, como requisito para obtenção do título de doutor em Ecologia.
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A minha família (meu pai, mãe e minha irmã) que sempre
apoiaram os meus sonhos. Dedico esta dissertação

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POVOS INDÍGENAS, PRODUÇÃO DO CONHECIMENTO E BIODIVERSIDADE AQUÁTICA NA AMAZÔNIA: UMA ABORDAGEM BIBLIOMÉTRICA E ECOLÓGICA

RESUMO

A Amazônia abriga uma das maiores biodiversidades do planeta e desempenha papel fundamental na regulação de processos ecossistêmicos. No entanto, mudanças impulsionadas por atividades antrópicas têm intensificado a fragmentação e a destruição de habitats naturais. Essas alterações também impactam sobre a sociobiodiversidade, uma vez que a Amazônia é lar de diferentes populações indígenas, cujo seus modos de vida estão intrinsecamente associados as práticas diretas da conservação e a sustentabilidade do ambiente. Nesse contexto, esta dissertação integra abordagens bibliométrica e ecológica para compreender padrões de produção científica e respostas da biodiversidade aquática às alterações ambientais na Amazônia. No primeiro capítulo, uma análise bibliométrica da literatura científica (1997–2025) evidenciou crescimento recente das publicações sobre povos indígenas e a conservação da biodiversidade, porém marcado por assimetrias geográficas e epistemológicas. A produção científica é majoritariamente liderada por instituições do Norte Global, embora países amazônicos como Brasil, Equador e Peru concentrem a maior parte dos estudos. Além disso, observamos a baixa representatividade de coautoria indígena. Apesar do reconhecimento dos povos indígenas como atores-chave na conservação, sua participação efetiva na produção do conhecimento científico permanece ainda limitada. No segundo capítulo, observamos que a diversidade beta taxonômica de insetos aquáticos foi predominantemente estruturada pela substituição de gêneros e associada a variáveis limnológicas, características do habitat físico e componentes espaciais. Em contraste, a diversidade beta funcional foi dominada pelo componente de diferença de riqueza e explicada principalmente por variáveis ambientais locais, corroborando nossas hipóteses. Esse padrão revela um desacoplamento entre as dimensões taxonômica e funcional da biodiversidade, indicando que mecanismos distintos governam a composição de gêneros e a distribuição de atributos funcionais em ecossistemas lóticos tropicais. Os resultados obtidos poderão subsidiar estratégias mais eficazes para a preservação dos ecossistemas aquáticos, ressaltando a relevância da integração entre a ciência indígena e cientifica na gestão e manutenção dos ecossistemas em territórios indígenas.

Palavras-chave: Povos indígenas, organismos bentônicos; bibliometria; biomonitoramento; lacunas de conhecimento; Amazônia.

INDIGENOUS PEOPLES, KNOWLEDGE PRODUCTION, AND AQUATIC BIODIVERSITY IN THE AMAZON: A BIBLIOMETRIC AND ECOLOGICAL APPROACH

ABSTRACT

The Amazon harbors one of the greatest biodiversities on the planet and plays a fundamental role in regulating ecosystem processes. However, changes driven by anthropogenic activities have intensified the fragmentation and destruction of natural habitats. These transformations also affect sociobiodiversity, as the Amazon is home to diverse Indigenous populations whose ways of life are intrinsically linked to conservation practices and environmental sustainability. In this context, this dissertation integrates bibliometric and ecological approaches to understand patterns in scientific production and the responses of aquatic biodiversity to environmental changes in the Amazon. In the first chapter, a bibliometric analysis of the scientific literature (1997–2025) revealed a recent increase in publications on Indigenous peoples and biodiversity conservation, although marked by geographic and epistemic asymmetries. Scientific production is predominantly led by institutions from the Global North, while Amazonian countries such as Brazil, Ecuador, and Peru concentrate most of the studies. In addition, we observed low representation of Indigenous co-authorship. Despite the recognition of Indigenous peoples as key actors in conservation, their effective participation in scientific knowledge production remains limited. In the second chapter, we found that the taxonomic beta diversity of EPT was predominantly structured by genus turnover and associated with limnological variables, physical habitat characteristics, and spatial components. In contrast, functional beta diversity was dominated by the richness difference component and was mainly explained by local environmental variables, supporting our hypotheses. This pattern reveals a decoupling between the taxonomic and functional dimensions of biodiversity, indicating that distinct mechanisms govern genus composition and the distribution of functional traits in tropical lotic ecosystems. Overall, the results provide important insights to support more effective strategies for the conservation of aquatic ecosystems, highlighting the relevance of integrating Indigenous and scientific knowledge in the management and maintenance of ecosystems within Indigenous territories.

Keywords: Indigenous peoples, Benthic macroinvertebrates, Bibliometric analysis, Knowledge gaps, Amazon

SUMÁRIO

1. INTRODUÇÃO GERAL

A Amazônia é uma das regiões mais biodiversas do planeta e abriga a maior floresta tropical do mundo, a qual desempenha um papel crucial na regulação climática e na oferta de serviços ecossistêmicos essenciais para o bem-estar humano (Mena et al.,2020). No entanto, apesar da sua importância, a região enfrenta ameaças devido ao avanço das atividades antrópicas, que promovem a fragmentação e a destruição de habitats naturais, comprometendo a biodiversidade e colocando em risco o equilíbrio dos ecossistemas. Essas alterações também impactam a sociobiodiversidade, uma vez que a Amazônia é lar de diferentes populações indígenas cujo seus modos de vida estão intrinsecamente associados as práticas diretas da conservação e a sustentabilidade do ambiente (Schmink et al., 2019; Levis et al., 2024; Marentes et al.,2022). Em seus territórios, os povos indígenas cultivam e se beneficiam dos recursos locais por meio de práticas sustentáveis, fundamentadas em conhecimentos ancestrais transmitidos ao longo de gerações (Perez et al.,2019).

Por essa razão, os territórios indígenas são amplamente reconhecidos pela sua contribuição à conservação da biodiversidade (Garnett et al., 2018; Esbach et al., 2024). Essas áreas desempenham um papel fundamental na redução do desmatamento e na manutenção da integridade ecológica, muitas vezes superando a proteção oferecida por outras áreas protegidas (Sze & Carrasco, 2020; Fernàndez-Llamazares et al., 2021; Figel et al., 2022; Osborne et al., 2024). No entanto, apesar do reconhecimento formal da importância da participação dos povos indígenas em políticas globais de proteção ambiental, como a Convenção sobre a Diversidade Biológica (CDB, 2019) e marcos nacionais como a Política Nacional de Gestão Territorial e Ambiental de Terras Indígenas (PNGATI), sua contribuição nas estratégias formais de proteção de seus territórios e na tomada de decisão é menos frequente (Amir et al., 2019).

Além disso, os desafios associados ao diálogo intercultural entre os sistemas de conhecimento indígenas e a ciência acadêmica refletem-se na limitada quantidade de estudos voltados ao conhecimento de estudos ecológico em territórios indígenas (Carvalho et al., 2023), frequentemente negligenciado em favor da ciência ocidental, que não prioriza a inclusão de vozes locais nos trabalhos (Turner et al., 2024; Weaver et al., 2023). Mesmo quando esses estudos são realizados nesses territórios, observa-se uma lacuna da representação de investigações direcionadas aos ecossistemas aquáticos, com predominância de estudos em ambientes terrestres (Athayde et al., 2025). Essa sub-representação limita a compreensão dos processos ecológicos que estruturam a biodiversidade nesses ambientes, dificultando a avaliação do papel dos territórios indígenas na manutenção da integridade ecológica dos ecossistemas aquáticos. A compreensão dos fatores que organizam as comunidades aquáticas é central para a interpretação do funcionamento dos processos ecológicos e para o desenvolvimento de estratégias de conservação (Perez et al.,2018).

Compreender a variação na composição biológica entre ambientes aquáticos dentro de áreas protegidas, como os territórios indígenas, contribui para o entendimento do funcionamento dos ecossistemas e para planejar medidas de conservação (Heino et al.,2015). Dentre as métricas de diversidade utilizada em estratégias de conservação, está a diversidade beta. A diversidade beta pode ser mensurada tanto pela variação das espécies (taxonômica) quanto pela variação de características das espécies (funcional), o que auxilia na compreensão dos processos ecossistêmicos. Dessa forma, abordagens integrativas considerando tanto a diversidade taxonômica quanto a funcional é fundamental na avaliação de estudos ecológicos, possibilitando entender melhor as dinâmicas das comunidades aquáticas e dos fatores que as moldam.

A biota aquática reflete a integridade ecológica desses ecossistemas e são excelentes instrumentos para estudos ecológicos (Shimano et al.,2015). E dentre da fauna aquática, os macroinvertebrados aquáticos das ordens Ephemeroptera, Plecoptera e Trichoptera (EPT) são modelos importantes na avaliação da integridade ambiental (Rosemberg & Resh, 1993). Esses organismos desempenham papéis essenciais nos processos de fragmentação da matéria orgânica, ciclagem de nutrientes e produtividade primária, além de serem importantes recursos na rede trófica para a manutenção dos ecossistemas aquáticos (Callisto et al.,2020; Maneechan et al., 2015). Nesse sentido, embora a diversidade beta tenha avançado como uma importante abordagem em ecossistemas lóticos, porém ainda são limitados os estudos que consideram de forma integrada, as dimensões taxonômica e funcional, sobretudo em ambientes com alta integridade ecológica, como os territórios indígenas amazônicos.

Portanto, essa dissertação foi estrutura em dois capítulos: No primeiro capítulo, realizamos uma análise bibliométrica sobre a sociobiodiversidade em territórios indígenas na Amazônia. Essa análise buscou mapear como a literatura cientifica tem vinculado a conservação da biodiversidade ao conhecimento tradicional dos povos indígenas e como os povos indígenas são representados nos estudos, identificando padrões, tendências temporais e lacunas na literatura. Com isso, as perguntas centrais que orientaram o primeiro capítulo foram: (i) como a produção científica sobre esse tema mudou ao longo do tempo? (ii) quais áreas geográficas e territórios indígenas foram estudados com mais frequência? (iii) quais países e instituições lideram essa pesquisa? (iv) Como as afiliações institucionais e a coautoria indígena são representadas em estudos sobre conservação da biodiversidade na Amazônia? (v) que tipos de contribuições são atribuídas a comunidades indígenas? (vi) quais ecossistemas, táxons e métodos foram priorizados?

No segundo capítulo, avaliamos a diversidade beta taxonômica e funcional de macroinvertebrados aquáticos das ordens Ephemeroptera, Plecoptera e Trichoptera (EPT) no território indígena Panará. O objetivo principal foi compreender como esses organismos respondem à contribuição relativa de variáveis ambientais locais, de paisagem e espaciais na estruturação desses padrões, bem como contribuir para o preenchimento da lacuna associada à sub-representação de estudos em ecossistemas aquáticos e à limitada inclusão indígena em estudos ecológicos. Para isso, testamos duas hipóteses centrais do estudo: a primeira, de que a diversidade beta taxonômica é estruturada conjuntamente por variáveis ambientais e componentes espaciais, enquanto a diversidade beta funcional é predominantemente explicada por variáveis ambientais locais; e a segunda, de que a diversidade beta taxonômica é dominada pelo componente de substituição de espécies, enquanto a diversidade beta funcional apresenta maior contribuição do componente de diferença de riqueza, sugerindo um desacoplamento parcial entre essas dimensões da biodiversidade.

Ao integrar uma análise ampla da produção científica com um estudo ecológico detalhado, esta dissertação busca oferecer uma perspectiva abrangente sobre a conservação da biodiversidade nos territórios indígenas da Amazônia. Os resultados obtidos poderão subsidiar estratégias mais eficazes para a preservação dos ecossistemas aquáticos, ressaltando a relevância da integração entre a ciência indígena e cientifica na gestão e manutenção dos ecossistemas em territórios indígenas.

2. Sessão I

Mapping research on Indigenous peoples, traditional knowledge, and biodiversity conservation in the Amazon: gaps and Indigenous knowledge co-production

A primeira sessão desta dissertação foi elaborada e formatada conforme as normas da publicação científica *Biodiversity and Conservation*, disponível em: https://link.springer.com/journal/10531

Mapping research on Indigenous peoples, traditional knowledge, and biodiversity conservation in the Amazon: gaps and Indigenous knowledge co-production

Abstract

Indigenous peoples play a central role in biodiversity knowledge and conservation, yet their participation in scientific research remains limited. Understanding how Indigenous peoples, traditional knowledge, and Indigenous territories are represented in the scientific literature is essential for developing more equitable and culturally grounded conservation strategies. We conducted a bibliometric analysis of 94 articles on biodiversity conservation in the Amazon, published between 1997 and 2025 and indexed in Scopus and Web of Science, that explicitly examined Indigenous participation. We analyzed temporal trends, geographic distribution, institutional leadership, Indigenous co-authorship, focal ecosystems and taxa, and the contributions attributed to Indigenous peoples. Indigenous perspectives were incorporated through a participatory approach. Scientific production increased after 2010. Research leadership remained concentrated in institutions from the Global North, although Brazil, Ecuador, and Peru were the most frequently studied countries. Indigenous co-authorship was identified in only 6.4% of the studies. Most research focused on plants, mammals, and birds, whereas aquatic environments and taxa such as insects, amphibians, and reptiles received comparatively less attention. The contributions most frequently documented in the literature were community-based monitoring and management (41.48%) and cultural practices and traditional ecological knowledge (38.19%). Our findings indicate that Indigenous peoples are widely recognized in the literature as knowledge holders and conservation actors, yet remain underrepresented as authors and research partners. This study highlights persistent geographic, epistemic, and collaborative asymmetries in Amazonian biodiversity research. Conservation science and policy can become more effective and equitable by moving beyond documenting Indigenous knowledge toward supporting Indigenous leadership, equitable partnerships, and inclusive co-production of knowledge.

Keywords: Bibliometric analysis; Community-based monitoring; Epistemic justice; Indigenous participation; Indigenous territories.

Introduction

Biodiversity loss is one of the most critical environmental challenges of our time, accelerating species decline, reducing essential ecosystem services, and undermining human well-being (Hogue and Breon 2022; Díaz et al. 2019; Ceballos et al. 2010). In megadiverse regions such as the Amazon, these threats are intensified by deforestation, agricultural expansion, and mining, which accelerate habitat degradation and loss while weakening communities that depend directly on natural resources for their livelihoods and sociocultural reproduction (Fearnside 2017; Silva Junior et al. 2021; Joly et al. 2020; Da Silva et al. 2024; Brandão et al. 2022).

In this context, Indigenous peoples play a crucial role in conserving natural resources. Their ways of life, grounded in the multiple use of nature, are closely linked to ecological integrity and supported by knowledge systems deeply rooted in territory and biodiversity management, transmitted across generations, and reflecting integrated understandings of environmental dynamics and society-land relationships (Schmink et al. 2019; Levis et al. 2024; Da Silva et al. 2024; Berkes et al. 2000; Gadgil et al. 1993). These knowledge systems provide a foundation for participatory biodiversity management and conservation strategies in local communities and can also inform broader conservation models (Leret-Câmara et al. 2019; Batista et al. 2020; Varese et al. 2021).

Cultural practices, traditional farming systems, and ecological perceptions help maintain essential ecological processes, support ecosystem services, enhance socioecological resilience, and sustain evolutionary processes (Levis et al. 2024; Folhes et al. 2025). A substantial share of global biodiversity occurs in lands traditionally managed by Indigenous peoples, and preserved Amazonian habitats, including primary forests, have been shaped and managed by these populations over centuries (Garnett et al. 2018; Barlow et al. 2012; Nascimento et al. 2024).

Despite this recognition, reinforced by frameworks such as Brazil's National Policy for Territorial and Environmental Management of Indigenous Lands (PNGATI), a persistent gap remains between institutional discourse and conservation practice (Guimarães et al. 2014; Gannon et al. 2019; Witter and Satterfield 2019; Dawson et al. 2023). Although these initiatives emphasize incorporating traditional knowledge and the active participation of Indigenous communities in conservation policy, this recognition has yet to translate into effective inclusion in scientific research and decision-making (Corrigan et al. 2018; Osborne et al. 2024; Berkes et al. 2000). The challenge of intercultural dialogue between Indigenous sciences and academic science is reflected in the scarcity of studies on ecological knowledge in Indigenous territories and in the limited participation of Indigenous peoples in research processes (Carvalho et al. 2023). As a result, approaches that privilege Western science alone often overlook the equitable inclusion of traditional knowledge and produce conservation policies that are poorly aligned with local realities (Levis et al. 2024; Da Silva et al. 2024).

Although recent initiatives have demonstrated the success of community-based ecological monitoring and Indigenous leadership in conservation, relationships between knowledge systems remain shaped by power asymmetries (Constantino et al. 2008; Freitas et al. 2019; Moraes et al. 2024; Juruna et al. 2025; Sheil et al. 2015). These examples show that Indigenous participation is essential for Amazon conservation, as ecological perceptions, sustainable practices, and deep connections with forests are fundamental to maintaining biodiversity and ecological functioning (Levis et al. 2024; Santos et al. 2024).

Although dialogue between traditional and scientific knowledge is frequently invoked in international agreements, these encounters remain shaped by historically entrenched power relations rooted in epistemic inequalities and the hierarchical positioning of Western science (Martinelli et al. 2022; Lunetta et al. 2025). Concrete actions that value Indigenous leadership and respect Indigenous sciences are therefore essential, alongside public policies that safeguard Indigenous rights and strengthen conservation through collaboration between knowledge systems (Berkes 2017; Díaz et al. 2019).

Against this backdrop, this study uses a bibliometric approach to examine how the scientific literature has linked biodiversity conservation to the traditional knowledge of Indigenous peoples in the Amazon and how Indigenous peoples are represented in the production of scientific knowledge on biodiversity conservation. We identify patterns, temporal trends, and gaps in the literature to map the thematic development, recognize emerging directions, and inform evidence-based research agendas and public policies (Guerrero-Moreno et al. 2024; Da Silva et al. 2024; Oliveira-Junior et al. 2022).

Specifically, we ask: (i) How has scientific production on this topic changed over time? (ii) Which geographic areas and Indigenous territories have been most frequently studied? (iii) Which countries and institutions lead that research? (iv) How are institutional affiliations and Indigenous co-authorship represented in studies on biodiversity conservation in the Amazon? (v) What kinds of contributions are attributed to Indigenous communities? Furthermore, (vi) which ecosystems, taxa, and methods have been prioritized? By answering these questions, we aim to identify advances, inequalities, and opportunities to strengthen Indigenous leadership in global biodiversity conservation agendas.

Materials and Methods

Study scope and database construction

This study focused on the Pan-Amazon region, which encompasses the world's largest tropical forest and one of its richest centers of biodiversity (Góes et al. 2025). This geographical region is an important reservoir of ancestral knowledge held by Indigenous peoples whose ways of life are closely linked to the conservation of local ecosystems. We used a bibliometric approach to analyze the international scientific literature, allowing the identification of publication trends, authorship profiles, geographic distribution, and contributions attributed to Indigenous peoples over time. Literature searches were conducted in Scopus and Web of Science, which were selected for their broad, multidisciplinary coverage and representation of global scientific production (Da Silva et al. 2024).

In both databases, we applied the search string (Indigenous AND Biodiversity AND Conservation AND Amazon*) to the titles, abstracts, and keywords. The truncation operator (*) was used to capture variations such as "Amazonia" and "Amazonian", and the Boolean operator AND ensured the inclusion of all thematic components.

Inclusion and exclusion criteria

To ensure consistency, we included only original research articles published in peer-reviewed journals that explicitly examined Indigenous participation, Indigenous knowledge systems, Indigenous-led management, co-management practices, community-based monitoring, or other direct contributions of Indigenous peoples to biodiversity conservation. We excluded reviews, book chapters, conference abstracts, notes, theses, and 284 studies that merely mentioned Indigenous peoples or Indigenous territories without analyzing their role in conservation.

The temporal scope ranged from 1997 to 2025, corresponding to the earliest record identified. Searches were conducted on 28 August 2025. No language restrictions were applied to include diverse regional and cultural perspectives (Walpole et al. 2019; Guerrero-Moreno et al. 2024) (Fig. 1). Although the search string was intentionally broad to maximize retrieval, only studies that explicitly examined Indigenous participation, Indigenous knowledge, Indigenous-led management, co-management, or other direct contributions of Indigenous peoples to biodiversity conservation were retained for analysis. Studies in which Indigenous peoples were mentioned only incidentally, without substantive engagement with conservation processes, were excluded during full-text screening.

>> Fig. 1

Data organization and categorization

We screened titles, abstracts, keywords, and methods to assess the study objectives (Costa et al. 2025). Based on this screening, we extracted structured information across five analytical axes:

I. Indigenous participation: Whether Indigenous peoples were involved in conservation-related actions and strategies.

II. Types of contribution: classified into four main categories, adapted from Da Silva et al. (2024): (i) cultural practices and traditional ecological knowledge; (ii) management and sustainable resource use; (iii) community-based monitoring and co-production of knowledge; and (iv) habitat conservation and restoration.

III. Study area: classification of Indigenous Lands and other protected areas (e.g., National Parks, RESEX) (SNUC, 2000).

IV. Indigenous co-authorship: presence and position of Indigenous authors in publications.

V. Taxa investigated: biological groups addressed in each study.

Integration of Indigenous perspectives and participatory approach

In addition to the bibliometric analysis, we incorporated a qualitative stage involving Indigenous researchers connected to the study contexts. This approach aimed to broaden interpretation through lived experience and support knowledge co-production. Preliminary results were shared with Indigenous collaborators from different Amazonian territories (Panará, Sateré-Mawé, Kumaruara, and Kuikuro) who reflected on: (i) Indigenous co-authorship; (ii) Global North leadership; (iii) research priorities; (iv) necessary changes in scientific practice.

Contributions were obtained through direct communication, including written feedback, videos, and dialogical exchanges. These perspectives were systematically described and incorporated into the interpretation of the results, preserving authorship and narrative integrity. This stage enabled the contextualization of bibliometric patterns through underrepresented perspectives, strengthening an inclusive and reflexive research approach (Levis et al. 2024; Berkes et al. 2000).

Authorization to access Indigenous territories was granted by the Fundação Nacional dos Povos Indígenas (FUNAI) under administrative process No. 08620.012263/2023-71. The Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA; SISBIO permit no. 4681-1) authorized the capture, collection, and transport of biological material, and the study was approved by the Animal Use Ethics Committee of the Federal University of Pará (CEUA No. 8293020418).

Data analysis

Data were analyzed using descriptive statistics and graphical visualization. All analyses were conducted in RStudio (version 4.4.0) using the Bibliometrix/Biblioshiny packages (Aria and Cuccurullo, 2017). Figures were finalized using Canva.

Results and Discussion

Temporal patterns and trends in scientific production

Between 1997 and the early 2000s, only a small number of studies were identified, with sporadic records and no publications in some years. From 2007 onwards, scientific production began to increase modestly, with a first more pronounced rise in 2008 (Fig. 2). Between 2012 and 2016, publication output remained relatively stable, ranging from two to four studies per year. These patterns suggest that although recognition of the importance of Indigenous peoples to biodiversity conservation has advanced, its incorporation into scientific literature has been gradual rather than linear.

>> Fig. 2

This temporal pattern indicates that growth in scientific production on the role of Indigenous communities in Amazon biodiversity conservation has coincided with political, institutional, and environmental milestones that increased the visibility of Indigenous leadership in conservation agendas. One important landmark was the 1992 United Nations Conference on Environment and Development (Earth Summit), whose Agenda 21 included a chapter dedicated to the role of Indigenous communities in environmental management and the sustainable use of natural resources (UN 1992). This was followed by the strengthening of international agreements such as the Convention on Biological Diversity, which recognized traditional knowledge as central to biodiversity conservation and sustainable use (Dutfield 2000).

The earliest studies identified in the 1990s reflect the growing recognition of Indigenous knowledge, particularly in interdisciplinary fields such as ethnobotany, ethnoecology, and ethnoichthyology (Athayde et al. 2025). Pioneering studies, such as Posey (1997), highlighted the relevance of traditional knowledge by demonstrating that Kayapó plant knowledge was consistent with the principles of the Convention on Biological Diversity. A few years later, *Conservation and development alliances with the Kayapó of south-eastern Amazonia* (Zimmerman et al. 2001) assessed the ecological success achieved by the Kayapó in partnership with Conservation International (CI). The authors demonstrated the value of participatory monitoring strategies and of cooperation between Indigenous communities and conservation organizations, highlighting the active roles of these populations in environmental governance. Together, these early studies helped establish the importance of traditional knowledge in environmental science and laid methodological foundations for participatory approaches that later became important references for conservation research in Indigenous territories.

The increase in scientific production observed from 2018 onwards may be associated with the consolidation of international initiatives such as the Nagoya Protocol (2010), together with national policies aimed at valuing Indigenous knowledge, which created a more favorable environment for research grounded in Indigenous peoples. The publication peak recorded in 2024 may reflect the recent strengthening of international debate on Indigenous roles in conservation, driven by events such as COP16 in Cali, Colombia, which emphasized the central role of Indigenous peoples in biodiversity conservation. It may also be linked to the launch of the Kuntari Katu Program, which seeks to expand Indigenous participation in climate negotiations and environmental public policy (MPI 2023). Taken together, these milestones suggest that international and national agendas have played an important role in shaping the visibility and growth of scientific production on Indigenous peoples.

By contrast, the temporary decline in scientific output between 2019 and 2021 may be related to the impacts of the COVID-19 pandemic and the weakening of environmental policies in Brazil. Contributing factors include the weakening of the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm), the suspension of the Amazon Fund in 2019 (Marcovith and Pinsky 2020), and the weakening of environmental agencies such as the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) and the Chico Mendes Institute for Biodiversity Conservation (ICMBio) (MPI 2023). Overall, although the temporal trend indicates a gradual increase in scientific production, especially over the past 5 years, only 41.48 % of the articles initially compiled directly addressed the role of Indigenous communities in Amazon biodiversity conservation.

Geographic distribution of studies

Countries with the highest academic output

The analysis of the geographic distribution of studies by country showed that Brazil had the highest number of publications (n = 26), followed by Ecuador (n = 25) and Peru (n = 22). Bolivia accounted for 10 articles, Colombia for 7, French Guiana for 3, and Venezuela for 1 (Fig. 3, Table S1). These differences may be associated with differences in the legal and institutional frameworks governing territorial rights and Indigenous participation in each country. This directly influences research agendas, analytical focus, and the extent to which local communities are involved in scientific studies (Athayde et al. 2025; Ortiz et al. 2025).

>> Fig. 3

The Brazilian Amazon stood out as a major center of scientific production. Brazil contains approximately 60% of the Amazon biome, harbors exceptionally high biodiversity, and plays a key role in regional and global ecosystem and climate processes (Guayasamin et al. 2024; Levis et al. 2024; Guerrero-Moreno et al. 2025; Flores et al. 2024). This prominence may also reflect Brazil's relatively robust legislative framework, particularly the National System of Protected Areas (SNUC), which organizes protected areas and creates institutional conditions favorable to scientific research within legally recognized territories.

Collaborative conservation programs such as the Amazon Region Protected Areas Program (ARPA) have also played a major role in protecting millions of hectares of forest through international funding and community participation (Brazil 2018). Another relevant framework is the National Policy for the Sustainable Development of Traditional Peoples and Communities (PNPCT), which recognizes and strengthens traditional ways of life and the sustainable use of natural resources, helping to integrate biodiversity conservation with sociocultural rights (Brazil 2007).

Most studies identified in Brazil were conducted on legally recognized Indigenous Lands, including the Kayapó, Baniwa, and Zó'é territories. Studies were also carried out in protected areas such as Biological Reserves and Extractive Reserves, which, although not legally classified as Indigenous Lands, were included because they are inhabited by Indigenous communities or embedded within territories of traditional use (Toledo et al. 2015). Research in these areas has focused mainly on management and conservation strategies linked to participatory Indigenous practices, including environmental monitoring and participatory biodiversity inventories. One emblematic example is the leading role of Indigenous communities in monitoring flooded forests affected by the Belo Monte dam (Utsunomiya et al. 2024; Quaresma et al. 2025). Another is the ethnobotanical survey conducted among the Baniwa in the Rio Negro region near Manaus, which documented traditional knowledge of campinarana landscapes and the use of forest resources (Abraao et al. 2008).

Despite these advances, major challenges remain in the Brazilian Amazon, including rising illegal deforestation, mining, and land conflicts, which frequently threaten both biodiversity and the rights and agency of Indigenous peoples (Rorato et al. 2021; Mataveli et al. 2022). Even with a relatively well-established environmental framework, stronger public policies are still needed, particularly for land demarcation, because formal recognition of

Indigenous territories supports both the maintenance of traditional knowledge systems and biodiversity conservation (Gonçalves et al. 2021).

In Ecuador, Indigenous ancestral knowledge receives particular recognition in the Constitution, which is widely regarded as pioneering for incorporating the rights of nature into the legal system (Pacheco 2012). This framework recognizes nature, or *Pacha Mama*, as a subject of rights, a concept deeply rooted in Indigenous worldviews (Pacheco 2012; Barcellos et al. 2023). Originating from Quechua, *Pacha Mama* can be translated as "Mother Earth" or "Mother Cosmos", reflecting a view of the planet as living and interconnected (Pacheco 2012). Its incorporation into the Constitution resulted from a long process of Indigenous struggle and advocacy. It marked a major advance in environmental law by recognizing nature as a rights-bearing subject rather than merely an object of exploitation (Barcellos et al. 2023). Ecuador has also implemented initiatives such as the *Socio Bosque* program, which provides economic incentives to Indigenous communities that maintain their forests, thereby strengthening partnerships between the state and traditional populations in sustainable natural resource management (Koning et al. 2010; Holland et al. 2014).

Among the most studied territories in Ecuador were Yasuní National Park and the Sumaco Biosphere Reserve, both in the Ecuadorian Amazon. Research focused on these areas may reflect the overlap between protected areas and Indigenous territories, thereby favoring collaborative conservation and sustainable management initiatives (Holland et al. 2014). In this context, interactions between public policies and community practices have produced positive outcomes for forest conservation (Bremner and Lu 2006).

In the Peruvian Amazon, studies were conducted mainly in Manu National Park, the Maijuna-Kichwa Regional Conservation Area (MKRCA), and the Imiría Regional Conservation Area. This pattern may be linked to initiatives under Peru's National System of

State-Protected Natural Areas (SINANPE), which promotes the conservation of biological diversity and ecosystem services nationwide.

One relevant example is the collaboration between the Indigenous Shipibo community of Nuevo Saposoa and the government platform *Geobosques*, designed to combat illegal logging (World Resources Institute 2017). Through this partnership, Shipibo community members received training to operate drones and conduct satellite-based monitoring, enabling them to capture detailed images of threatened forest areas. These data are shared with local authorities, strengthening enforcement and increasing Indigenous autonomy in forest conservation, natural resource protection, and territorial defense

By contrast, Bolivia, Colombia, French Guiana, and Venezuela were less well represented in the analyzed literature. Although these countries also contain important portions of the Amazon and high biological diversity, they accounted for relatively few studies. This lower representation may be associated with funding limitations, logistical challenges, and structural inequalities in the distribution of research resources and scientific infrastructure (Barlow et al. 2016; Fernandes et al. 2025).

Comparative analysis between the most productive countries and the most studied countries

We observed a clear mismatch between where research is conducted and where academic leadership is based. Although Brazil, Ecuador, and Peru accounted for most of the studies, academic leadership was concentrated in the Global North, especially the United States (n = 17), the United Kingdom (n = 11), and Spain (n = 8) (Fig. 4).

>> **Fig. 4**

Taken together, these results show that although the Amazon is the main focus of study, much of the knowledge produced is driven by institutions outside the region. This disparity may reflect the greater availability of scientific infrastructure, funding, and international collaboration networks in the Global North, which facilitate both the development and publication of research on conservation and Indigenous peoples in the Amazon (Guerrero-Moreno and Oliveira-Junior 2024; Da Silva et al. 2025).

Main institutional affiliations and Indigenous co-authorship in Amazon biodiversity conservation

The analysis of authors' institutional affiliations showed that a relatively small group of institutions plays a central role in scientific production on biodiversity conservation involving Indigenous peoples in the Amazon (Fig. 5). The most represented institutions were the National Institute of Amazonian Research (INPA) and Amazonas State University (UEA), with 13 studies each (13.82% of the total). These were followed by the Universitat Autònoma de Barcelona (n = 12; 12.76%), the University of East Anglia (n = 10; 10.63%), George Mason University (n = 9; 9.57%), the University of Manchester (n = 7; 7.44%), Wageningen University (n = 7; 7.44%), the University of Leeds (n = 6; 6.38%), and the University of São Paulo (n = 6; 6.38%). The Instituto Socioambiental (ISA), a non-governmental organization with a strong socio-environmental presence in the Amazon, also stood out, appearing in 6 publications (6.38%) (Fig. 5).

>> **Fig. 5**

The strong presence of Amazon-based institutions such as INPA and UEA reflects their longstanding role in advancing research on biodiversity and on the relationships between science and traditional knowledge in the region. INPA has become one of the leading institutions dedicated to studying Amazonian biodiversity and training researchers in ecology and conservation (Manzi et al. 2020). Likewise, Amazonas State University has played an important role in the academic training of Indigenous students and in strengthening initiatives centered on intercultural education and the valuing of traditional knowledge, thereby bringing scientific production closer to the sociocultural realities of the region (Estácio and Almeida 2016).

Among the initiatives linked to this process is a CAPES-approved project aimed at training teachers, preferably Indigenous teachers, to work in their own communities. This initiative promotes the integration of traditional and academic knowledge, strengthens intercultural education, and expands Indigenous participation in teaching and research (FAPEAM, 2025).

Despite these initiatives, authorship analysis showed that Indigenous participation in the scientific literature remains limited (Guerrero-Moreno et al. 2024). Only six of the studies identified included Indigenous co-authors. This highlights a discrepancy between the central role of Indigenous peoples in Amazon biodiversity conservation and their representation in formal academic production. Such underrepresentation may be linked to historical inequalities in access to formal education and scientific training, as well as to the limited implementation of public policies that support Indigenous academic training at advanced levels (Barbalho et al. 2025). The historical marginalization of traditional knowledge systems, often treated as peripheral to Western science, further contributes to the underrepresentation of Indigenous researchers in the scientific literature (Levis et al. 2024). Another source of these asymmetries is structural inequality in global scientific production. Although much of the research is conducted in the Amazon, many editorial networks, funding structures, and research centers remain concentrated outside the region, particularly in the Global North (Ordóñez-Matamoros et al. 2011).

Research investment also remains unevenly distributed within Brazil. Although the Brazilian Amazon is one of the most studied regions, financial resources for biodiversity research are not equitably distributed across regions. Investments linked to the Brazilian National Institutes of Science and Technology (INCT) have contributed significantly to advancing biodiversity knowledge, but resources remain concentrated elsewhere. For example, the Southeast has the largest number of funded research networks, whereas in the North, only Manaus and Belém host networks dedicated to Amazonian biodiversity research (Resende et al. 2025; Athayde et al. 2025). Although 13 INCT networks are currently active in the North, research specifically focused on Amazonian biodiversity remains concentrated in these two cities.

Efforts to reduce these inequalities include the Amazon Biodiversity Synthesis Network (INCT-Symbian), launched in Belém in December 2023. The network brings together researchers from multiple institutions and regions to consolidate Amazon biodiversity research and strengthen interdisciplinary collaboration, including knowledge co-production with Indigenous communities (Resende et al. 2025). Practical examples of this approach include *Human & Planet-Xingu Biodiversity Monitoring*, developed with Conservation International (CI), which involves Panará leaders and researchers from the Federal University of Pará (UFPA). This initiative strengthens community autonomy of Indigenous territories by integrating scientific monitoring with traditional knowledge. Another recent initiative is the Advanced Research-Action Center for Amazonian Ecosystem Conservation and Recovery (CAPACREAM), launched in 2025 to promote research on Amazonian socio-biodiversity and the recovery of degraded ecosystems. In one of its associated projects, *SocioBIO,* it integrates traditional knowledge and academic science in conservation and ecological restoration strategies in the Amazon region (CAPACREAM, 2025). Despite these initiatives, further investment and stronger public policies for Indigenous academic training are crucial for supporting the diversity of perspectives in scientific knowledge production and biodiversity conservation in Indigenous territories (Flores et al. 2024).

Indigenous contributions to biodiversity conservation documented in the scientific literature

The reviewed literature revealed four main categories through which Indigenous peoples were reported to contribute to biodiversity conservation in the Amazon (Fig. 6). Community-based monitoring and management was the most prominent category (n = 39; 41.48%), followed by cultural practices and ecological knowledge (n = 36; 38.29%) and management and sustainable use of natural resources (n = 18; 19.14%). In contrast, habitat conservation and restoration were the least documented.

>>**Fig. 6**

These findings indicate that the reviewed studies frequently documented Indigenous peoples as central actors in generating and interpreting environmental information. These initiatives include systematic tracking of species abundance, monitoring of environmental change, and territorial management grounded in local knowledge. Participatory monitoring can improve the reliability of environmental assessments and strengthen conservation decision-making (Walker et al. 2004; Silva et al. 2024). A relevant example is the work developed by Conservation International (CI) in partnership with Indigenous communities. In the Kayapó territory of A'Ukre, collaborative projects assessed and documented threatened species by combining scientific methods with traditional knowledge (Zimmerman et al. 2001). Likewise, initiatives promoted by the Instituto Socioambiental (ISA) through the *Y Ikatu Xingu* project have trained socio-environmental agents around the Xingu Indigenous Park, helping to strengthen territorial protection and restore springs and riparian forests threatened by agricultural expansion.

The category of cultural practices and ecological knowledge reflects how traditional communities perceive and interact with nature through knowledge systems grounded in cultural values, traditional practices, and accumulated experiences across generations. These systems guide the sustainable use of natural resources and play a fundamental role in maintaining biodiversity (Fernandes et al. 2025). Their importance is well documented in ethnobotanical studies that show close links among culture, biodiversity, and the use of plants for medicinal, culinary, and spiritual purposes (Prance 1997). One example is Pilnik et al. (2023), who worked with the Huni Kuin people to document the cultural values associated with food plants and highlighted both the utilitarian and symbolic dimensions of plant species.

Studies conducted in partnership with Indigenous communities have also documented fauna through inventories and observations. These include records of Indigenous traditional knowledge of birds (Greeney et al. 2018), surveys of fish species (Bogotá et al. 2024), and studies of mammals (Stafford et al. 2016). Other works, including Levis et al. (2018), Thomas et al. (2010), Robert et al. (2012), and Abraao et al. (2008), further reinforce the role of Indigenous traditional knowledge in the use and sustainable management of landscapes and ecosystems.

The category management and sustainable use of natural resources includes practices that promote balanced resource use and maintain productive systems compatible with environmental conservation. Strategies documented in the literature include traditional agroforestry systems, such as *chakra* systems in the Ecuadorian Amazon (Rodriguez et al. 2021), as well as sustainable fishing and hunting practices regulated by community norms that define permitted periods, locations, and species (Ohl-Schacherer et al. 2007; Constantino et al. 2008). These practices have generated positive outcomes for both biodiversity conservation and food security. Furthermore, the Indigenous Agroforestry Agents program, developed by the

Comissão Pró-Índio do Acre (CPI-AC), provides long-term training to strengthen territorial management and the sustainable management of fauna and flora in Indigenous territories. The program was created in response to requests from Indigenous leaders for support in managing the use of wild fauna in Kaxinawá territory.

Environmental conservation and restoration were the least-represented category. It includes initiatives focused on ecosystem restoration, the creation and management of protected areas, and the recovery of degraded habitats. The only study identified in this category described the return of the giant otter (*Pteronura brasiliensis*) to the Içana River in Baniwa territory, highlighting the potential of Indigenous territorial conservation strategies to support the recovery of threatened species (Pimenta et al. 2018).

Overall, these results indicate that despite the ecological relevance of Indigenous territories and the active role of Indigenous communities in biodiversity conservation, traditional knowledge remains underrepresented in parts of the scientific literature. The absence of these perspectives can limit understanding of Amazonian socioecological systems and constrain the development of more inclusive and effective conservation strategies. In this sense, integrating traditional knowledge and academic science has been recognized as a key approach for developing fairer and more effective environmental policies, strengthening Indigenous autonomy, and improving the ecological information used in environmental governance (Levis et al. 2024).

Taxa assessed and ecosystem types studied in biodiversity conservation in Indigenous territories in the Amazon

Research conducted in Indigenous territories across the Amazon covers a wide diversity of taxa, reflecting the biological richness of these ecosystems. The most frequently investigated groups were plants, mammals, fish, birds, and insects, chosen because of their ecological, cultural, and economic importance to Indigenous communities (Fig. 7).

>> **Fig. 7**

Among the taxa investigated, plants were the most frequently studied group (n = 37; 42.5%). Most studies focused on cultivated species (Arango-Ulloa et al. 2009; Thomas et al. 2010), medicinal and food plants (Pilnik et al. 2023; Guachamin-Rosero et al. 2022), and species associated with traditional agroforestry systems (Oldekop et al. 2013; Torres et al. 2024; Robert et al. 2012). For Indigenous communities, plants are central to subsistence, traditional medicine, and cultural and religious practices (Leret-Cámara et al. 2019). These studies were conducted in territories including the Sumaco Biosphere Reserve (Ecuador), the Kaxinawá and Baniwa Indigenous Lands (Brazil), and Kichwa communities in Ecuador. These data combined workshops, interviews, and floristic inventories.

Mammals were the second-most-studied group (n = 26; 29.9%). Many studies were conducted in the Kaxinawá and Kayapó Indigenous Lands (Brazil), the Cofán territory (Ecuador), the Tsimane territory (Bolivia), and Manu National Park (Peru). Their prominence reflects their importance to Indigenous subsistence, both as primary hunting resources and as biological indicators in wildlife monitoring (Iwamura et al. 2014; Wallace et al. 2012). The main methods included camera trapping, semi-structured interviews, and assessments of hunting sustainability.

Fish ranked third (n = 9; 10.3%). Studies were conducted in areas such as Yasuní National Park (Ecuador) and Maijuna territory (Peru), using inventories and population monitoring (Bogotá et al. 2024), as well as analyses of the relationships between fish and community use of aquatic resources (Mora et al. 2018; Oviedo et al. 2017). These studies combined capture-based methods, interviews, and modeling approaches.

Birds were relatively underrepresented (n = 6; 6.9%). Research was conducted in the Kaxinawá Indigenous Lands (Brazil), Amacayacu National Park (Colombia), and the Yasuní Biosphere Reserve (Ecuador), with a primary focus on population monitoring, management, and conservation practices. The most common methods were visual and acoustic surveys, combined with interviews on local perceptions and practices associated with birdlife (Arcilla et al. 2025; Greeney et al. 2018).

Insects were among the least represented groups (n = 5; 5.7%). These studies were conducted mainly in Kichwa communities and the Yasuní Biosphere Reserve in Ecuador, as well as Extractive Reserve areas in Brazil. They focused especially on edible insects such as beetles and ants, which play important roles in the diets and food cultures of many Amazonian communities (Gasca-Álvarez et al. 2022). The studies combined traditional knowledge, specialized collection techniques, and ethno-entomological analyses. Some also highlighted the potential of insects as key organisms for ecotourism and citizen science, thereby contributing to the appreciation of local biodiversity (Guerrero-Moreno et al. 2024; Ribeiro et al. 2025).

Among vertebrates, amphibians (n = 3; 3.4%) and reptiles (n = 1; 1.1%) were the least studied groups. Research on both was conducted on the Kayapó Indigenous Land (Brazil) and in Manu National Park (Peru), primarily using these organisms as indicators of environmental impacts (Oldekop et al. 2013).

Overall, studies conducted in Indigenous territories across the Amazon show a strong predominance of terrestrial organisms, to the detriment of aquatic organisms. This reflects a widely documented trend in biodiversity research, which tends to focus on plants and vertebrates while leaving other taxonomic groups underrepresented (Troudet et al. 2017; Mammola et al. 2020). Aquatic ecosystems such as streams, rivers, and lakes remain underexplored despite their ecological and cultural importance for Amazonian populations (Castello et al. 2018; Lopes et al. 2019). This gap is also shaped by the logistical complexity of research in Amazonian aquatic environments, which often requires specialized equipment, longer expeditions, and extensive travel to remote areas (Carvalho et al. 2023).

In addition to these structural barriers, the limited inclusion of Indigenous communities in research processes may further constrain advances in knowledge about these ecosystems. The historical marginalization of traditional knowledge within Western science has contributed to the underuse of local knowledge that could substantially expand understanding of Amazonian biodiversity (Levis et al. 2024; Athayde et al. 2025). Given the central role of aquatic ecosystems in the subsistence and territorial organization of Indigenous communities across the Amazon, expanding research in these environments is essential for a more integrated understanding of biodiversity dynamics in the world's largest river basin.

Indigenous perspectives on scientific production and pathways for change

The results of this study reveal low Indigenous representation in scientific authorship and a concentration of academic leadership in institutions based in the Global North. Because these asymmetries cannot be understood solely from an external academic perspective, we shared this manuscript with Panará Indigenous researchers and representatives of other Amazonian peoples, inviting them to contribute to the critical interpretation of the findings. These contributions broaden the debate by incorporating Indigenous researchers' experiences and perceptions of how science has been produced in their territories.

The Indigenous researchers' narratives help illuminate how these inequalities are expressed in practice and what changes are needed to support genuinely collaborative science.

In this sense, this section represents an exercise in knowledge co-production, in which different knowledge systems engage in dialogue to critically interpret the existing scientific literature. These contributions were incorporated as direct narratives, while formally recognizing all Indigenous researchers as co-authors of the manuscript.

For the Panará representatives, the small number of scientific studies that include Indigenous people as authors reflects a long history of inequality in knowledge production. In many cases, Indigenous peoples participate in fieldwork and contribute deep knowledge of territories, species, and forest dynamics. Yet, these contributions do not always appear formally in the authorship of scientific publications (Haelewaters et al. 2021). Participants also interpreted the predominance of institutions from the Global North as resulting from structural inequalities in science, particularly in access to funding, infrastructure, and international research networks. At the same time, this context reinforces the importance of strengthening research institutions in the Amazon and Brazil, and of expanding the leadership of local researchers, especially Indigenous researchers.

Based on their experience in the biodiversity monitoring project in the Panará territory, participants identified biodiversity monitoring, water quality, environmental change, dynamics of fauna and flora, and the documentation of traditional knowledge related to plants and forest relationships as priority research themes in Indigenous territories. Participants further emphasized that science in Indigenous territories must advance in dialogue, transparency, and participation. Communities should be involved from the planning stage, participate in field activities, and have access to results in practical and accessible formats. Initiatives that promote training and direct participation by Indigenous researchers are likewise essential to strengthening autonomy in producing knowledge about their own territories.

For the Indigenous researcher Tyson Ferreira-Sateré: "*Although we are beginning to occupy some spaces within scientific culture through affirmative action policies and institutional invitations, this participation is still limited and often not accompanied by recognition or trust from other scientists and institutions. We are frequently seen as incapable or as holders of incomplete knowledge, reduced to myths, beliefs, or folklore. Yet that same knowledge, when appropriated by external researchers, becomes validated as universal science, rendering Indigenous leadership in scientific production invisible. As an Indigenous person, I interpret this predominance as a form of scientific colonialism, in which Indigenous peoples are treated as objects of study rather than as subjects of knowledge. Researchers collect data and traditional knowledge and publish them without ensuring that this knowledge returns to the communities or is properly recognized at its source. In light of this, a profound paradigm shift is needed: moving from an extractive logic to a collaborative one. Science should not be conducted 'about' Indigenous peoples, but with them. Research questions should emerge from the needs of the territories, and results should be returned to communities in accessible formats*" (Ferreira-Sateré, personal communication, 2026).

Taken together, these narratives show that the patterns identified in the bibliometric analysis reflect concrete experiences lived by Indigenous peoples in the Amazon in relation to scientific production. Their contributions reinforce the need for structural transformation in science, grounded in inclusion, recognition, and knowledge co-production, and for aligning scientific practices more closely with the sociocultural realities of Indigenous territories.

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Figure captions

Fig. 1. General flowchart of the methodology used to search for, consolidate, clean, and analyze articles.

Fig. 2 Annual scientific output on the participation of Indigenous peoples in Amazon biodiversity conservation.

Fig. 3 Geographic distribution map of studies addressing the participation of Indigenous peoples in Amazon biodiversity.

Fig. 4 Most-studied countries and countries leading in academic production on Indigenous peoples' participation in Amazon biodiversity conservation.

Fig. 5 Institutions involved in producing studies on Indigenous peoples' participation in Amazon biodiversity conservation.

Fig. 6 Main contributions of Indigenous peoples to biodiversity conservation as documented in the scientific literature.

Fig. 7 Taxa or taxonomic groups assessed in studies involving Indigenous peoples and biodiversity conservation in the Amazon.

Figures

Figure 1

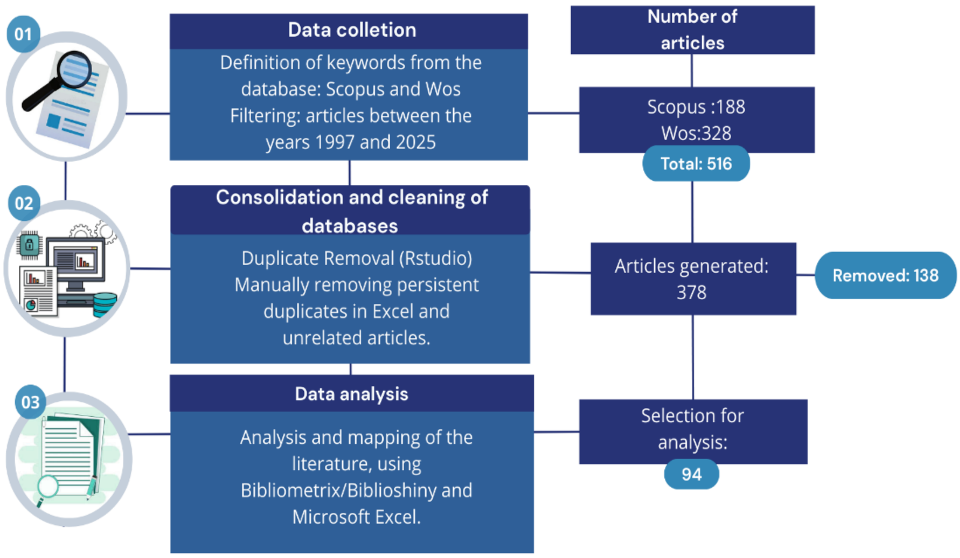
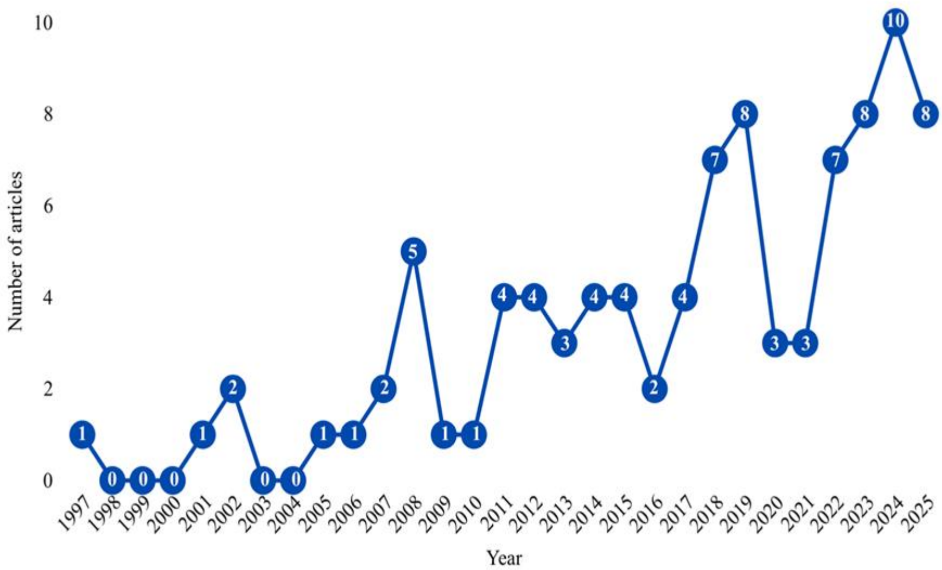


Figure 2



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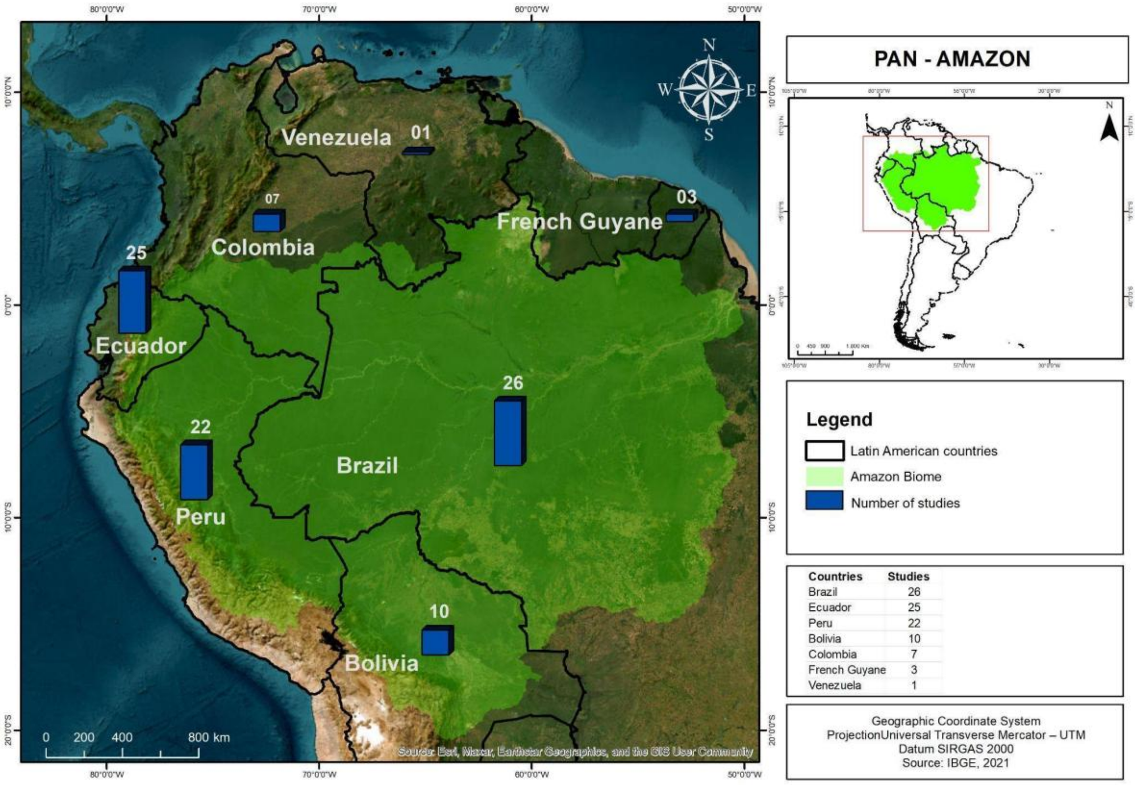

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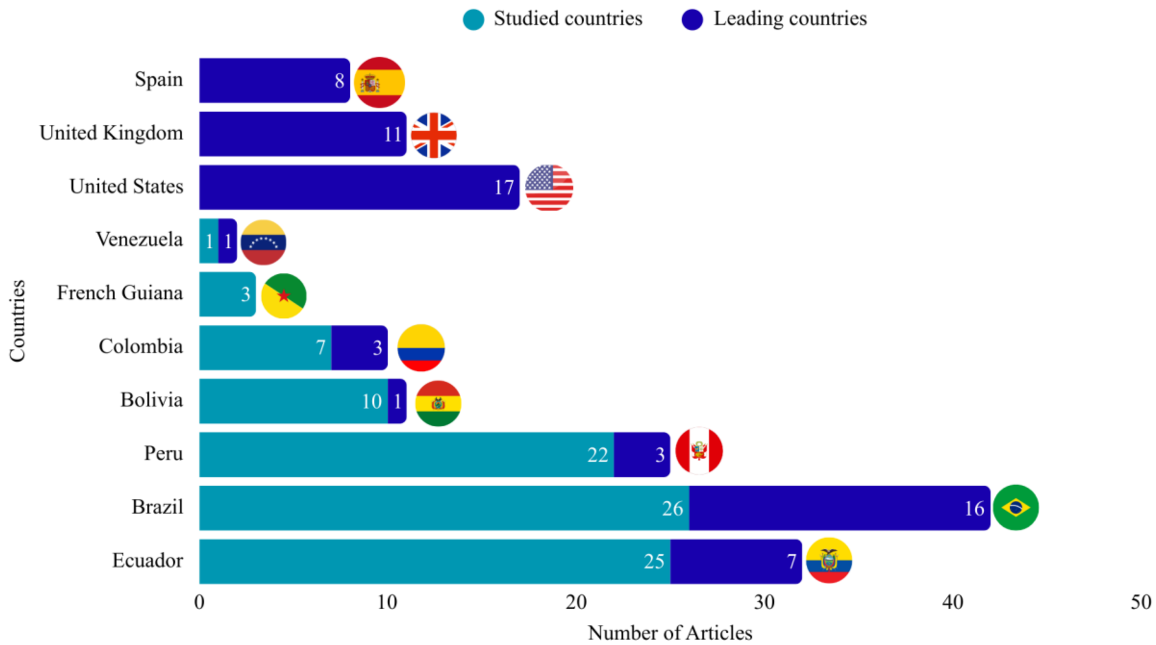

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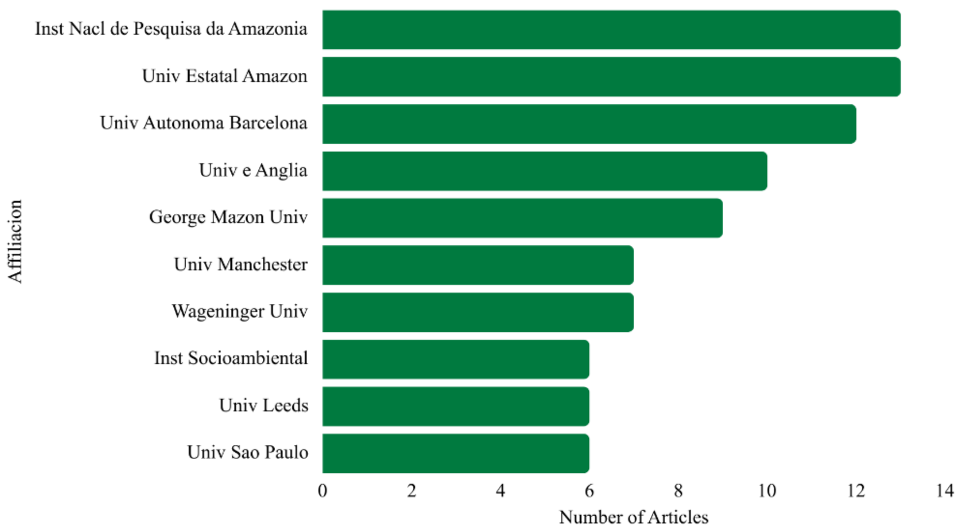


Figure 6

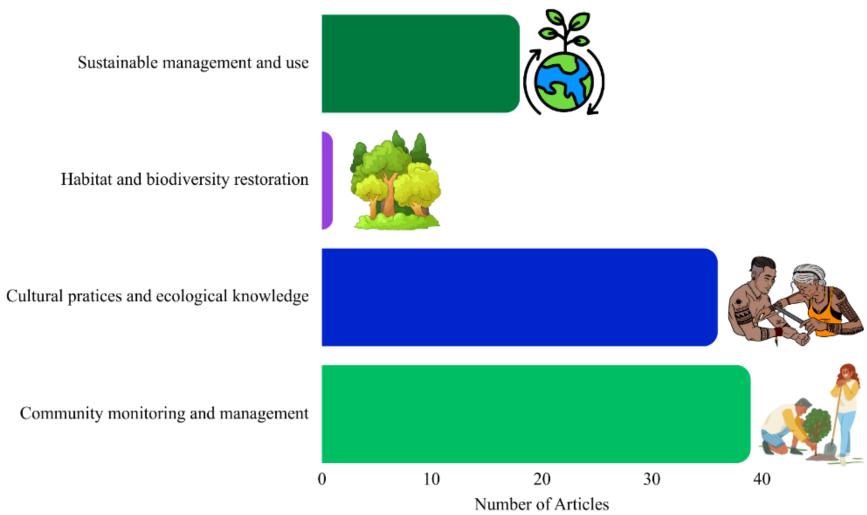
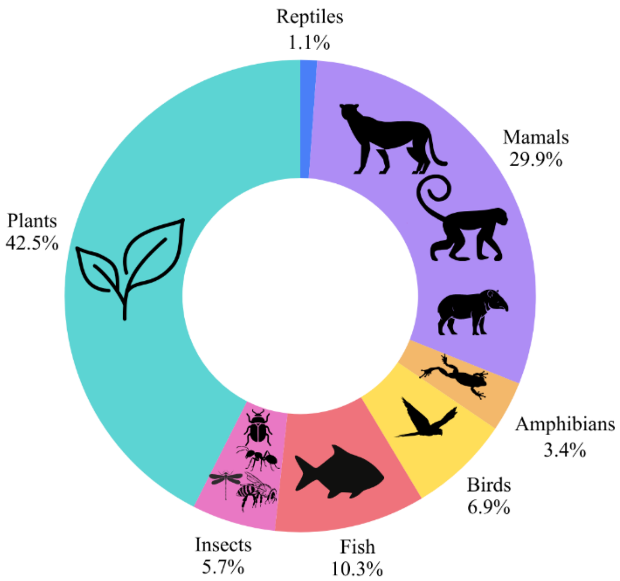


Figure 7


Reptiles
1.1%
Mamals
29.9%
Plants
42.5%
Amphibians
3.4%
Birds
6.9%
Insects
5.7%
Fish
10.3%

3. Sessão II

Taxonomic replacement, but functional stability: taxonomic–functional decoupling in Amazonian streams from an Indigenous territory

A segunda sessão desta dissertação foi elaborada e formatada conforme as normas da publicação científica *Insect Conservation and diversity* disponível em: https://resjournals.onlinelibrary.wiley.com/journal/17524598

Taxonomic replacement, but functional stability: taxonomic–functional decoupling in Amazonian streams from an Indigenous territory

Abstract

Indigenous territories play a critical role in conserving Amazonian freshwater ecosystems, yet their aquatic biodiversity remains poorly understood. We investigated taxonomic and functional beta diversity of Ephemeroptera, Plecoptera, and Trichoptera (EPT) assemblages in streams within the Panará Indigenous Territory, Brazil, to evaluate whether taxonomic and functional dimensions of biodiversity respond similarly to environmental and spatial gradients. We quantified total beta diversity and its replacement and richness-difference components and assessed the relative influence of habitat, limnological, landscape, and spatial variables. Field surveys were conducted in collaboration with Panará Indigenous researchers, using standardized ecological protocols integrated with participatory biodiversity monitoring. Taxonomic beta diversity was dominated by genus replacement and was jointly structured by environmental heterogeneity and spatial processes, whereas functional beta diversity was primarily associated with differences in richness and responded mainly to local environmental conditions. Consequently, pronounced taxonomic replacement was not accompanied by proportional functional replacement, revealing taxonomic-functional decoupling across streams. In contrast to patterns often reported in disturbed landscapes, this decoupling occurred within a high-integrity Indigenous territory and likely reflects the maintenance of functional redundancy across a taxonomically heterogeneous regional assemblage rather than biodiversity erosion. Our findings demonstrate that the ecological interpretation of taxonomic-functional decoupling depends on landscape context and highlight the importance of Indigenous territories for conserving Amazonian freshwater biodiversity while improving ecological understanding through collaborative research.

Keywords: Indigenous territories; Freshwater conservation; Functional redundancy; Beta diversity; EPT; Amazonian streams; Participatory monitoring.

INTRODUCTION

Taxonomic and functional dimensions of biodiversity often respond differently to environmental and spatial gradients, revealing complementary aspects of community organization (Mouchet et al., 2010; Villéger et al., 2013). While taxonomic beta diversity reflects changes in species or genus composition among communities, functional beta diversity captures variation in ecological strategies and potential contributions to ecosystem processes (Purschke et al., 2013). Consequently, high taxonomic replacement does not necessarily result in proportional functional replacement when different taxa share similar ecological roles (Petchey & Gaston, 2002; Villéger et al., 2013; McGill et al., 2006). This pattern, known as taxonomic–functional decoupling, has important implications for biodiversity conservation because its ecological interpretation depends on the environmental context in which it occurs (Mouillot et al., 2013; Jarzyna & Jetz, 2018). In disturbed ecosystems, taxonomic–functional decoupling may reflect biodiversity erosion, selective loss of sensitive taxa, or biotic homogenization (Mouillot et al., 2013). Conversely, in relatively intact ecosystems, similar patterns may indicate the persistence of functional redundancy within taxonomically heterogeneous communities, suggesting that different taxa maintain comparable ecological strategies despite variation in community composition (Yachi & Loreau, 1999; Lansac-Tôha et al., 2022). Understanding when and why taxonomic and functional dimensions of biodiversity become decoupled remains, therefore, essential for interpreting ecological change and conservation status.

Relatively intact landscapes provide a unique opportunity to investigate whether taxonomic–functional decoupling reflects natural patterns of community organization rather than the consequences of environmental degradation. Among these landscapes, Amazonian Indigenous territories are among the largest remaining socioecological systems with high levels of environmental integrity, maintaining extensive forest cover, complex freshwater networks, and comparatively low direct anthropogenic disturbance (Façanha et al., 2026; Carvalho et al., 2023; Osborne et al., 2024). Beyond their recognized importance for biodiversity conservation, these territories offer valuable ecological contexts for understanding how biological communities are assembled under conditions where environmental heterogeneity, dispersal processes, and ecological interactions continue to operate within relatively intact landscapes.

Amazonian freshwater ecosystems, such as streams and headwaters, are particularly well-suited to investigating these processes because these systems are characterized by strong interactions between terrestrial and aquatic environments, creating complex gradients in habitat, resource availability, and connectivity (Junk et al., 1989; Ward et al., 1989; Tockner et al., 2010). Despite their importance for regional biodiversity, ecosystem functioning, and biogeochemical cycles, small freshwater systems in remote Amazonian regions remain poorly documented, with knowledge gaps especially pronounced within Indigenous territories where logistical constraints have historically limited systematic ecological surveys (Malhi et al., 2008; Carvalho et al., 2023). These gaps limit our understanding of how freshwater communities are organized in some of the largest remaining areas of relatively high ecological integrity.

Although Indigenous territories often maintain high levels of environmental integrity, they should not be considered isolated or completely unaffected systems. Historical land-use changes, pressures from surrounding landscapes, and climate-related disturbances may influence local environmental conditions and biological communities over time (Associação IAKIÔ; ISA, 2018). Therefore, streams within Indigenous territories should be understood as high-integrity socioecological landscapes in which ecological processes can be investigated along natural environmental gradients while accounting for potential external influences. This context provides an opportunity to reassess the ecological meaning of taxonomic–functional decoupling. In human-modified landscapes, similar patterns have frequently been associated with environmental degradation, species filtering, or loss of functional diversity (Mouchet et al., 2010; Villéger et al., 2013; Castro et al., 2020). However, whether taxonomic replacement without proportional functional replacement occurs in high-integrity Indigenous landscapes, and whether it reflects different ecological processes, remains poorly understood.

If taxonomic replacement occurs while functional strategies remain comparatively conserved, this pattern may indicate the persistence of functional redundancy within diverse regional assemblages rather than biodiversity erosion (Petchey & Gaston, 2002; Villéger et al., 2013; McGill et al., 2006). In such cases, high taxonomic replacement may emerge from environmental heterogeneity, spatial structure, and dispersal processes that naturally organize communities across landscapes (Leibold et al., 2004; Heino et al., 2015; Soininen et al., 2018). Comparing taxonomic and functional beta diversity, therefore, provides a powerful framework for distinguishing whether communities differ primarily in biological identity or in ecological strategies, allowing a more mechanistic interpretation of biodiversity patterns across conservation contexts (Mouchet et al., 2010; Villéger et al., 2013).

Aquatic insects of the orders Ephemeroptera, Plecoptera, and Trichoptera (EPT) are particularly suitable for evaluating these patterns in Amazonian streams. These organisms are widely used in freshwater ecological studies because of their sensitivity to environmental variation, diverse ecological strategies, and dependence on specific habitat and water-quality conditions (Rosenberg & Resh, 1993; Brasil et al., 2020; Callisto et al., 2023). Their variation in traits associated with habitat use, feeding strategies, locomotion, respiration, and life-history characteristics allows the evaluation of whether environmental gradients influence community composition through taxonomic replacement, functional filtering, or both (Poff et al., 2006; Dolédec & Bonada, 2013).

Research in Indigenous territories also requires approaches that recognize Indigenous peoples as active partners in biodiversity knowledge production. Participatory monitoring has increasingly been recognized as a strategy for expanding ecological surveys in remote regions while incorporating local knowledge, strengthening territorial governance, and supporting long-term conservation initiatives (Chiaravalloti et al., 2018; Pereira et al., 2022). In this study, collaboration with Panará Indigenous researchers was not only a logistical component of fieldwork but an integral part of the research process, influencing access to remote streams, field planning, sampling implementation, and the generation of ecological knowledge in a historically underrepresented region. By combining standardized ecological protocols with collaborative monitoring, this approach helps expand knowledge of freshwater biodiversity while supporting conservation strategies aligned with local priorities and socioenvironmental contexts.

Here, we assessed taxonomic and functional beta diversity of Ephemeroptera, Plecoptera, and Trichoptera (EPT) assemblages in streams within the Panará Indigenous Territory, Brazil. Specifically, we evaluated the relative contributions of local environmental variables, landscape composition, and spatial structure to total beta diversity and its replacement and richness-difference components. We tested two hypotheses: (I) taxonomic beta diversity is jointly structured by environmental and spatial processes, whereas functional beta diversity is primarily driven by local environmental filtering; and (II) taxonomic beta diversity is dominated by replacement, while functional beta diversity is mainly associated with richness differences, indicating taxonomic–functional decoupling. By examining this pattern within a high-integrity Indigenous territory, we investigate whether taxonomic replacement without proportional functional replacement represents biodiversity erosion or instead reflects the maintenance of functional redundancy within diverse Amazonian stream assemblages.

MATERIAL AND METHODS

Study Area

The study was conducted in 31 streams located within the Panará Indigenous Territory, situated between the municipalities of Guarantã do Norte, Mato Grosso State, and Altamira, Pará State, Brazil. The territory is part of the Brazilian Legal Amazon and covers approximately 500,000 hectares (FUNAI, 2023). The region is predominantly drained by the Iriri River, the main tributary of the Xingu River basin. The landscape is characterized by Open Ombrophilous Forest, Dense Ombrophilous Forest, and transitional zones between Savanna and Seasonal Forest. The regional climate is classified as tropical savanna (Aw) under the Köppen climate classification (Köppen, 1936), with a mean annual precipitation of 1,500-2,000 mm (Instituto Socioambiental & Associação Iakiô, 2025) (Figure 1).

The Panará Indigenous Territory represents a high-integrity socioecological landscape in which extensive forest cover, low levels of direct anthropogenic disturbance, and an interconnected freshwater network provide an opportunity to investigate the organization of biodiversity under relatively intact environmental conditions. The territory is inhabited by the Panará people, whose traditional ecological knowledge and territorial management practices have played a central role in maintaining the region's ecological integrity. The contemporary configuration of the territory reflects a history of profound socio-environmental transformation. Following decades of displacement associated with the expansion of colonization fronts, road construction, mining, and other extractive activities during the twentieth century, the Panará progressively reoccupied part of their ancestral lands after the official recognition and demarcation of the territory in the late 1990s (Giraldin, 1997; Indigenous Peoples in Brazil, 2004; Moutinho et al., 2025). Since then, Indigenous territorial governance has promoted an ongoing process of socio-environmental recovery that has helped maintain large, contiguous forest areas and relatively intact freshwater ecosystems.

Freshwater ecosystems in the Panará Indigenous Territory

Freshwater ecosystems are central to Panará livelihoods, providing water, food resources, transportation routes, and supporting cultural practices closely associated with the territory. Consequently, the conservation of rivers and streams is directly linked to both biodiversity maintenance and Indigenous well-being. Although the Panará Indigenous Territory retains high levels of environmental integrity, it also represents a heterogeneous socioecological landscape. Remnants of historical land uses, including small pasture areas established before territorial demarcation, remain within portions of the territory, while its southern boundaries are influenced by surrounding agricultural landscapes (Associação IAKIÔ; ISA, 2018; Pignati et al., 2017; Rocha et al., 2024). This spatial heterogeneity generates natural variation in riparian conditions, catchment land cover, and potential edge influences, while preserving the watershed's overall ecological integrity. Such conditions provide an ideal setting for investigating how environmental gradients operating within a largely conserved Indigenous landscape influence the taxonomic and functional organization of EPT assemblages, allowing ecological processes to be evaluated under relatively low levels of anthropogenic disturbance.

Ethical approval and authorization to access the Indigenous territory

The capture, collection, and transport of biological material were authorized by the Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA; SISBIO permit No. 4681-1) and approved by the Animal Use Ethics Committee of the Federal University of Pará (CEUA No. 8293020418). Authorization to access the Indigenous territory was granted by the Fundação Nacional dos Povos Indígenas (FUNAI) under administrative process No. 08620.012263/2023-71.

Collaborative research with Panará Indigenous researchers

This research was developed within the Panará Indigenous Territory Environmental Monitoring and Sustainable Management Project, an initiative established through partnerships among the Associação IAKIÔ, Brazilian research institutions, Conservation International (CI), and the Panará communities. The project aims to strengthen participatory environmental monitoring, support territorial management, and generate ecological information relevant to biodiversity conservation within the territory.

Accordingly, this study adopted a collaborative research approach in which Panará Indigenous researchers actively participated throughout the research process. Community representatives contributed to planning discussions, the selection of sampling areas, logistical organization, and field activities, ensuring that the research objectives were aligned with local priorities for environmental monitoring and territorial management.

Before field sampling, training sessions were conducted with Panará researchers using illustrated educational materials and practical field demonstrations. The training included the identification of aquatic insects, their ecological importance as freshwater bioindicators, standardized sampling procedures, and measurements of environmental variables. This collaborative approach strengthened field implementation while promoting knowledge exchange between scientific and Indigenous monitoring practices (Corrigan et al., 2018; Resende et al., 2025). The collaborative design adopted in this study also provided access to streams distributed across different sectors of the territory, including areas that are rarely sampled in conventional ecological surveys. Consequently, the partnership with Panará researchers not only strengthened the ethical conduct of the research but also expanded the sampling design's ecological representativeness by incorporating local knowledge of the territory.

Streams habitat and limnological variables

To characterize local environmental conditions, a 150-m reach was established at each sampling site and subdivided into 11 equidistant transects, labeled from "A" downstream to "K" upstream, defining 10 longitudinal sections between transects. These procedures followed the United States Environmental Protection Agency protocol (US-EPA; Peck et al., 2006), adapted for tropical regions (Callisto et al., 2014; Juen et al., 2025).

At each transect, physical habitat variables were measured, including channel width (m), depth (cm), and canopy cover (%). Channel width was measured with a measuring tape, depth with a graduated ruler at representative points within each section, and canopy cover was estimated using a spherical densiometer or a standardized visual assessment. Substrate composition was determined through visual estimation of the relative proportion of sand, fine sediment, and organic matter within the wetted area of each section. Habitat integrity was assessed using the Habitat Integrity Index (HII; Nessimian et al., 2008), which integrates riparian vegetation attributes, channel structure, and substrate characteristics.

Limnological variables were recorded at three points along each reach, corresponding to the beginning, middle, and end of the sampled section, represented by transects A, F, and K. These variables included dissolved oxygen (mg L^{-1}), water temperature (°C), pH, electrical conductivity (µS cm^{-1}), and turbidity (NTU), measured using a multiparameter probe (Horiba U-50; Asko, São Leopoldo, RS, Brazil). Limnological variables were measured before biological sampling and physical habitat assessment to avoid sampling-induced alterations in water chemistry (Maués-Silva et al., 2024).

Land use and land cover variables

To obtain land-use and land-cover variables, we first delineated the boundaries of each stream micro-catchment from the geographic coordinates of the downstream point (section "A") using digital elevation models (INPE Topodata) in QGIS 3.34, applying flow accumulation and drainage algorithms. The delineated micro catchments were visually inspected to ensure consistency with the hydrographic network.

Land use and land cover data were obtained from MapBiomas Collection 8 (2024) and verified using Landsat 5 TM imagery (30-m spatial resolution; NASA/USGS) to ensure classification accuracy within each micro catchment. For this study, land use was categorized into two dominant classes: (i) forest, including native perennial and alluvial forest formations; and (ii) agriculture, primarily associated with maize cultivation. The proportion of each class within the micro catchments was calculated and used as a landscape-scale predictor in subsequent analyses.

Spatial variables

Spatial variables were obtained using distance-based Moran's Eigenvector Maps (dbMEM; Legendre et al., 2012), based on the Euclidean distance matrix among the geographic coordinates of sampled streams. The resulting eigenvectors were used as explanatory spatial variables in canonical ordination models. The dbMEM approach allows the detection of spatial structures across multiple scales. Analyses were performed using the dbmem function in the "adespatial" package (Dray et al., 2025) within RStudio (version 4.0.4)

Biological sampling

Each longitudinal section was subdivided into three 5-m segments; however, only the first two segments were sampled because sampling the third could disturb the substrate of the subsequent section (Faria et al., 2017). Sampling was conducted during the dry season, when substrate stability is higher, reducing the likelihood of larval drift (Faria et al., 2024; Schulting et al., 2019). Within each segment, two substrate samples were collected using a hand net (rapiché) with an 18-cm diameter and 250-µm mesh size. Each sampled segment yielded one subsample, for a total of 20 subsamples per stream (Juen et al., 2016; Faria et al., 2017; Shimano et al., 2018). Subsamples from each stream were subsequently pooled into a single composite sample, representing the EPT diversity of each sampling unit.

Collected EPT specimens were sorted and preserved in 85% ethanol. In the laboratory, individuals were identified to genus level using specialized identification keys (Dominguez et al., 2006; Hamada et al., 2014). After identification, specimens were deposited in the aquatic insect collection of the Laboratory of Ecology and Conservation (LABECO) at the Federal University of Pará.

Functional traits

Functional traits were compiled for EPT genera based on Santos et al. (2024), which provides trait information for genera with distribution records in the Amazon. Seven traits were selected to represent functional dimensions related to habitat use, trophic role, locomotion, respiration, resistance to hydraulic stress, and population resilience: (i) body size, represented by body width (cm), associated with energetic efficiency, predation vulnerability, and dispersal capacity; (ii) functional feeding group, including shredder, collector-gatherer, collector-filterer, scraper, and predator, related to organic matter processing and trophic position; (iii) locomotion type, including swimmer, sprawler, burrower, and clinger, reflecting microhabitat use and substrate interaction; (iv) body shape, classified as flattened, cylindrical, or streamlined, related to resistance to hydraulic stress; (v) body flexibility, associated with the ability to occupy microhabitats under different flow regimes; (vi) respiration type, classified as branchial or tegumentary, indicative of tolerance to variation in dissolved oxygen availability; and (vii) life cycle/voltinism, classified as univoltine or multivoltine, related to population resilience to hydrological disturbance.

These traits were selected because they represent ecological mechanisms through which EPT genera may respond to environmental filtering, habitat structure, resource availability, flow conditions, and limnological variation. Together, they describe functional strategies relevant to community organization in tropical streams and allow the assessment of whether taxonomic variation among sites is accompanied by proportional changes in functional structure (Poff et al., 2006; Dolédec & Bonada, 2013; Heino et al., 2015).

Data analysis

Each stream was considered a sampling unit, for a total of 31 sampling units. Taxonomic and functional beta diversity were calculated using Sørensen dissimilarity, based on EPT abundance data previously standardized using the Hellinger transformation (Legendre & Gallagher, 2001). Total beta diversity (β_total) was then partitioned into replacement (β_repl) and richness difference (β_rich) components, following Podani and Schmera (2011) and Carvalho et al. (2012), using the beta function and the packages “FD” (Laliberté et al., 2014), “BAT” (Cardoso et al., 2020), and “stats” (Bolar, 2019).

Before functional beta diversity analysis, the functional trait matrix was transformed into a Gower distance matrix (function gowdis) and subsequently converted into a hierarchical clustering structure (functional dendrogram) using the hclust function from the “BAT” package. Gower distance is a robust dissimilarity measure that efficiently handles mixed data types, allowing the integration of continuous and categorical variables. The resulting functional dendrogram, combined with the standardized abundance matrix, was used to calculate functional beta diversity.

To assess the relative contributions of environmental (microhabitat and limnological), spatial, and landscape variables to explaining the different facets of beta diversity and their components (Borcard & Legendre, 2002; Peres-Neto et al., 2006), we performed variation partitioning using distance-based redundancy analysis (db-RDA). This analysis was used because the response variables were dissimilarity matrices derived from beta diversity components (total, replacement, and richness difference). Analyses were conducted using the capscale and varpart functions in the “vegan” package (Oksanen et al., 2019). The significance of predictors was tested using ANOVA (function anova).

Before db-RDA, multicollinearity among variables was assessed using the variance inflation factor (VIF), and variables with VIF < 10 were retained (via the vif.cca function). Predictors were selected using forward selection (function forward.sel; Blanchet et al., 2008). The spatial component was represented by Moran’s eigenvector maps (MEMs); the landscape component by the percentage of natural forest and agricultural cover; and local environmental variables by limnological and microhabitat descriptors. All analyses were conducted in R (version 4.4.0).

RESULTS

EPT community structure

A total of 3,417 EPT specimens were recorded. Of these, 773 individuals belonged to Ephemeroptera, distributed across 20 genera. Plecoptera was represented by 30 individuals, all belonging to a single genus. Trichoptera comprised 2,614 individuals across 14 genera. The most abundant genera within each order were *Leptonema* (n = 459), *Miroculis* (n = 286), and *Anacroneuria* (n = 30).

Taxonomic and functional beta diversity showed contrasting patterns of decomposition. Total taxonomic beta diversity was moderate ($\beta_{total} = 0.539$) and was mainly explained by the replacement component ($\beta_{repl} = 0.488$), whereas richness differences contributed only slightly to total dissimilarity ($\beta_{rich} = 0.051$). This indicates that variation in EPT genus composition among streams was primarily attributable to taxonomic replacement rather than to differences in genus richness.

Functional beta diversity showed a different decomposition pattern. Total functional dissimilarity was high (F-β_total = 0.648) and was predominantly associated with functional richness differences (F-β_rich = 0.467), while functional replacement contributed less to total functional dissimilarity (F-β_repl = 0.180; Figure 3). Thus, although EPT assemblages showed marked taxonomic replacement among streams, this replacement was not accompanied by proportional functional replacement, indicating a taxonomic–functional decoupling in beta-diversity patterns.

Drivers of taxonomic β-diversity of EPT

Taxonomic beta diversity was significantly associated with both local environmental variables and spatial structure. For total taxonomic beta diversity, habitat variables explained 13% of the variation ($F = 1.948$; $p < 0.001$), with organic matter, fine substrate fraction, and wetted width selected as the main predictors. Limnological variables explained 7% of the variation, with water temperature retained as a significant predictor ($F = 2.270$; $p = 0.018$). Spatial variables, represented by MEM1 and MEM4, explained 14% of the variation ($F = 2.246$; $p < 0.001$), indicating that EPT genus composition was structured by both local environmental gradients and spatial arrangement among streams.

The replacement component of taxonomic beta diversity showed a similar pattern. Taxonomic replacement was significantly explained by spatial variables, represented by MEM1 and MEM4, which accounted for 16% of the variation ($F = 1.604$; $p = 0.041$), and by habitat variables, particularly organic matter and fine substrate fraction, which explained 11% of the variation ($F = 1.831$; $p = 0.012$). In contrast, the richness-difference component of taxonomic beta diversity was explained only by water temperature, which accounted for 37% of the variation ($F = 2.284$; $p = 0.042$; Figure 4).

Landscape variables did not independently explain components of taxonomic beta-diversity after accounting for local environmental and spatial predictors. However, the contribution of habitat and spatial variables indicates that genus-level variation among streams was mainly associated with local substrate conditions, channel structure, water temperature, and spatial organization within the stream network.

Drivers of functional β-diversity of EPT

Functional beta diversity was mainly associated with local environmental variables. Total functional beta diversity was significantly explained by habitat variables, which accounted for 11% of the variation ($F = 2.048$; $p = 0.025$), with sand proportion and depth selected as the main predictors. Limnological variables also explained 11% of the variation, with water temperature and dissolved oxygen retained as significant predictors ($F = 2.057$; $p = 0.017$). In contrast, spatial variables did not significantly explain total functional beta diversity ($F = 1.087$; $p = 0.370$), indicating that functional dissimilarity among streams was more strongly associated with local environmental filtering than with spatial structure.

None of the predictor sets significantly explained the replacement or richness-difference components of functional beta diversity when analyzed separately. However, shared fractions among habitat, limnological, landscape, and spatial variables indicated that some environmental gradients were spatially structured across the study area (Figure 5). Overall, these results suggest that functional structure varied primarily in relation to local habitat and limnological conditions, whereas spatial processes contributed more clearly to taxonomic than to functional beta-diversity patterns.

DISCUTION

Our study demonstrates that taxonomic and functional dimensions of biodiversity can respond differently even within a highly conserved Amazonian landscape. Although EPT assemblages exhibited pronounced taxonomic replacement among streams, this variation was not accompanied by proportional functional replacement, revealing a clear taxonomic-functional decoupling. Taxonomic beta diversity was dominated by genus replacement, whereas functional beta diversity was primarily associated with differences in richness, indicating that changes in taxonomic composition occurred without equivalent shifts in ecological strategies. Together, these findings suggest that environmentally heterogeneous streams within the Panará Indigenous Territory support distinct taxonomic assemblages while maintaining a relatively conserved functional structure.

The ecological significance of this pattern depends strongly on the landscape context. In disturbed ecosystems, taxonomic-functional decoupling is commonly associated with biodiversity erosion, biotic homogenization, or the selective loss of environmentally sensitive taxa (Mouchet et al., 2010; Villéger et al., 2013; Castro et al., 2020). In contrast, our findings indicate that within a high-integrity Indigenous landscape, the same pattern is more likely to reflect the maintenance of functional redundancy across a diverse regional species pool than to reflect ecological degradation. Rather than representing biodiversity loss, the observed taxonomic replacement appears to result from natural environmental heterogeneity operating across well-preserved stream habitats.

This interpretation is consistent with metacommunity theory, which predicts that community assembly is jointly shaped by environmental filtering and spatial processes (Leibold et al., 2004; Heino et al., 2015). In our study, taxonomic beta diversity responded to both habitat characteristics and spatial structure, indicating that genus replacement was driven by local environmental variation together with dispersal-related processes. Organic matter, fine-substrate fraction, and wetted width influenced taxonomic composition by modifying resource availability, hydraulic conditions, and benthic habitat complexity (Benone et al., 2017; Perez-Rocha et al., 2018; Branco et al., 2020), whereas the contribution of spatial eigenvectors suggests that stream-network configuration and dispersal limitation further promoted differentiation among assemblages (Brown & Swan, 2010; Nunes et al., 2020). These results indicate that the high taxonomic replacement observed across streams is primarily a consequence of natural ecological heterogeneity rather than landscape degradation.

In contrast, functional beta diversity was structured mainly by local environmental conditions and showed no detectable influence of spatial processes. Sand proportion, stream depth, water temperature, and dissolved oxygen explained variation in functional composition, indicating that local habitat filters selected for ecological strategies best suited to prevailing environmental conditions. Because many EPT genera share similar combinations of ecological traits, changes in taxonomic composition did not necessarily produce equivalent functional replacement. This pattern is consistent with functional redundancy, whereby different taxa perform comparable ecological roles despite differences in taxonomic identity (Yachi & Loreau, 1999; Cadotte et al., 2011; Lansac-Tôha et al., 2022). Together, these results suggest that spatial processes primarily determine which genera occur in each stream, whereas environmental filtering determines which functional strategies persist, thereby allowing taxonomic differentiation while maintaining a relatively stable functional organization across the landscape.

The contrasting responses of taxonomic and functional diversity emphasize that taxonomic-functional decoupling cannot be interpreted in isolation from the landscape context. Most studies reporting decoupling have been conducted in ecosystems affected by deforestation, agricultural intensification, pollution, or hydrological alteration, where taxonomic change is frequently accompanied by functional homogenization or the progressive erosion of ecological strategies (Villéger et al., 2013; Castro et al., 2020; Hernández-Mendoza et al., 2024). Under these conditions, functional redundancy may represent only a temporary buffer before continued species loss leads to declines in ecosystem functioning.

Our results suggest a different interpretation. The streams of the Panará Indigenous Territory occur within one of the best-preserved freshwater landscapes in the southeastern Amazon, where Indigenous stewardship has maintained extensive forest cover and relatively intact stream networks despite increasing pressures in the surrounding region. In this context, taxonomic-functional decoupling is more likely to reflect natural environmental heterogeneity and the persistence of a diverse regional species pool than ecological simplification. Environmental variation among streams promotes the replacement of genera, while functional redundancy allows key ecological strategies to be maintained across the landscape. Consequently, taxonomic replacement should not necessarily be interpreted as biodiversity erosion but rather as an important component of the organization of regional biodiversity within conserved Amazonian stream networks.

These findings reinforce the importance of integrating taxonomic and functional perspectives when evaluating freshwater biodiversity. Had our assessment been based exclusively on taxonomic composition, the high genus replacement would have suggested strong ecological differentiation among streams. Conversely, considering only functional diversity would have indicated a comparatively homogeneous regional fauna. Examining both dimensions simultaneously revealed that these apparently contrasting patterns are complementary, reflecting different components of community assembly. Taxonomic diversity captured changes in community identity associated with environmental heterogeneity and spatial processes, whereas functional diversity reflected the persistence of ecological strategies shaped primarily by local environmental filtering.

From a conservation perspective, this distinction is particularly relevant because it suggests that maintaining ecosystem functioning does not require identical biological communities across the landscape. Instead, different streams may contribute unique taxonomic assemblages while collectively sustaining similar functional attributes. Such complementarity increases the ecological value of stream networks by simultaneously supporting regional biodiversity and preserving ecosystem functioning. However, functional redundancy should not be interpreted as evidence of ecological resilience without limits. If deforestation, climate change, agricultural expansion, or hydrological alteration continue to intensify throughout the Amazon, multiple genera sharing similar ecological roles may be lost simultaneously, eventually reducing the functional capacity of freshwater communities (Malhi et al., 2008; Intergovernmental Panel on Climate Change, 2021; Carvalho et al., 2023). Preserving environmental integrity, therefore, remains essential for maintaining both taxonomic diversity and the functional resilience of Amazonian stream ecosystems.

Beyond its ecological implications, this study also highlights the value of collaborative research for freshwater conservation in Indigenous territories. Freshwater ecosystems within Indigenous lands remain underrepresented in ecological research despite their exceptional biodiversity and their importance for local livelihoods (Ceron & Silva, 2023; Carvalho et al., 2023; Santos et al., 2024). By involving Panará Indigenous researchers throughout field planning, biological sampling, and environmental monitoring, this study combined standardized ecological methods with local territorial knowledge, strengthening both biodiversity assessment and community participation. Such collaborative approaches expand ecological monitoring in remote regions while generating information that is directly relevant to territorial governance and conservation planning (Chiaravalloti et al., 2018; Pereira et al., 2022; Resende et al., 2025).

Some limitations should be considered when interpreting our findings. First, EPT larvae were identified at the genus level, preventing direct inference about species-level replacement. Second, sampling was conducted only during the dry season, and seasonal hydrological variation may influence both taxonomic composition and functional organization. Third, functional traits were compiled from the best available information for Amazonian genera and therefore could not account for intrageneric variation. Finally, our study focused exclusively on streams within the Panará Indigenous Territory, precluding direct comparisons with streams in surrounding human-modified landscapes. Future studies spanning broader gradients of environmental integrity will help determine whether the mechanisms underlying taxonomic-functional decoupling remain consistent across different Amazonian landscapes.

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TABLES

TABLE 1. Functional attributes for EPT orders

Functional attributes	Category types
Body Size	Size 1 (<1.5)
	Size 2 (≥ 1.5 – < 2.5)
	Size 3 (≥ 2.5 – <3.5)
	Size 4 (≥3.5 – < 5.0)
	Size 5 (≥5.0 – < 10.0)
	Size 6 (>10.0)
Body Shape	Cylindrical (CL)
	Streamlined (SL)
	Flattened (FT)
Body flexibility (°)	< 10°
	≥ 10° to ≤ 45°
	> 45°
Types of locomotion	Climber (CB)
	Sprawl (SW)
	Clinger (CLG)
	Swimmer (SM)
	Burrow (BW)

Refuge	Free living (FL) Silk net builder (SB) Sand and wood refuge builder (SRB) Leaf refuge builder (LB)
Life History	<1 – Univoltine >1 – Multivoltine
Respiratory	Skin breathing (SK) Branchial breathing (BH)

TABLE 2. Communities of Ephemeroptera, Plecoptera, and Trichoptera (EPT) collected in the Panará Indigenous Territory.

Ordem/família	**Gênero**
EPHEMEROPTERA	*Aturbina*
Baetidae	*Baetodes* *Callibaetis* *Cloeodes* *Zelusia*
Caenidae	*Brasilocaenis* *Caenis*
Leptohyphidae	*Trichorythodes* *Trichorythopsis*
Leptophlebiidae	*Miroculis* *Ulmeritoides* *Paramaka* *Farrodes* *Simothraulopsis* *Hangenulopsis* *Fittkaulus* *Terpides*

	Tikuna *Ulmeritoides*
Oligoneuridae	*Oligoneuria*
PLECOPTERA	*Anacroneuria*
TRICHOPTERA Calamoceratidae	 *Phylloicus*
Helycopsyche	*Helycopsyche*
Hydropsychidae	*Smicridea* *Leptonema* *Macrostemum*
Hydroptilidae	*Neotrichia*
Leptoceridae	*Oecetis* *Triplectides*
Odontoceridae	*Marilia*
Polycentropodidae	*Cernotina* *Polyplectropus*
Philopotamidae	*Chimarra*

FIGURES

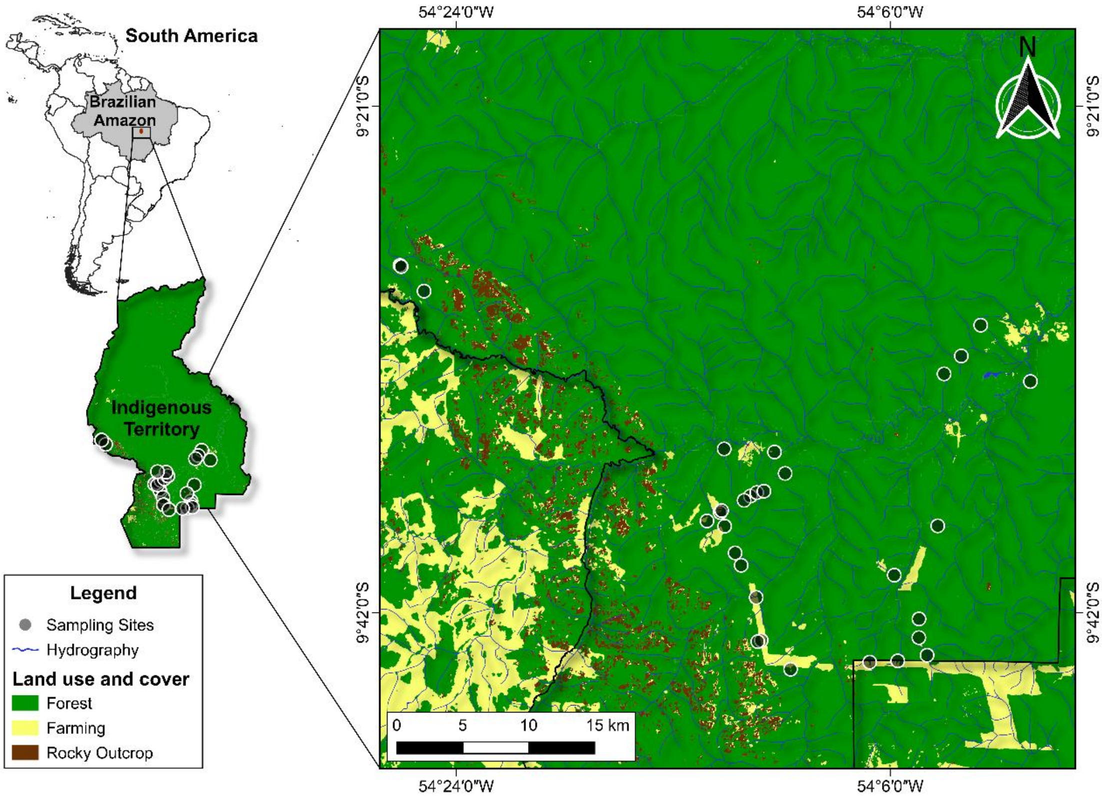

Figure 1. Map showing the sampling sites in the Indigenous territory, covering the municipalities of Guarantã do Norte (Mato Grosso State) and Altamira (Pará State) in Brazil.

Figure 2. Collaborative monitoring of aquatic biodiversity with Panará Indigenous researchers.

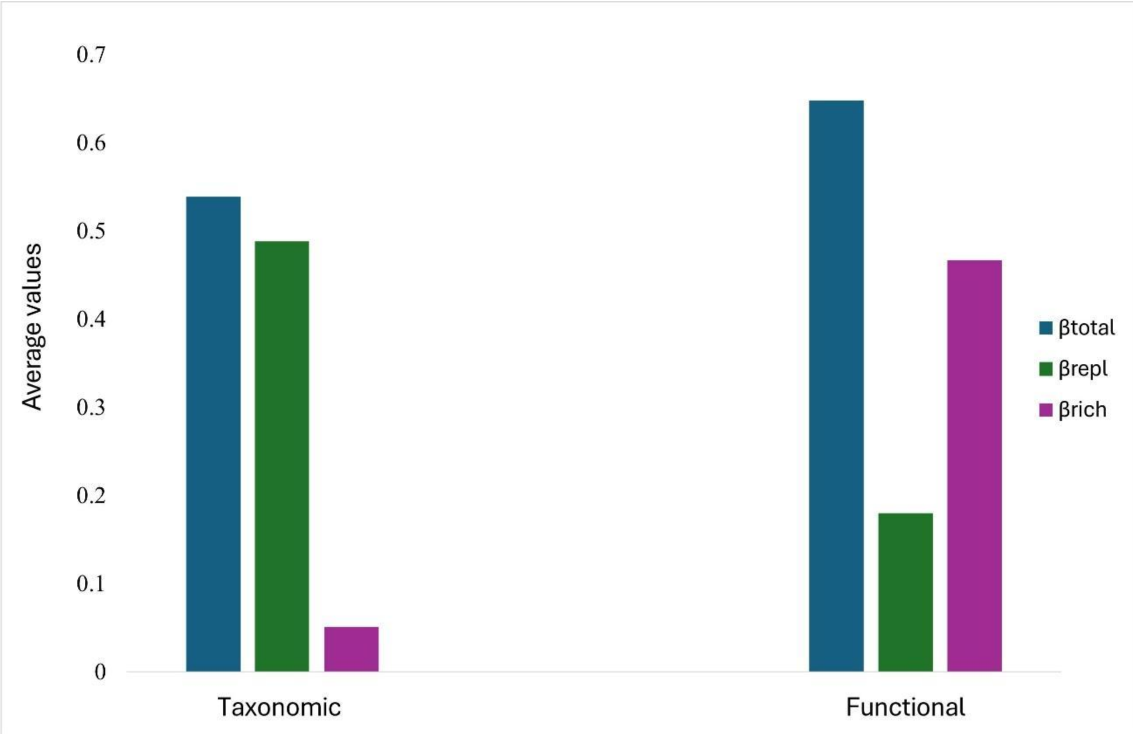

Figure 3. Taxonomic and Functional beta diversity values (average). β_total = total beta; β_repl = replacement; β_rich = richness difference.

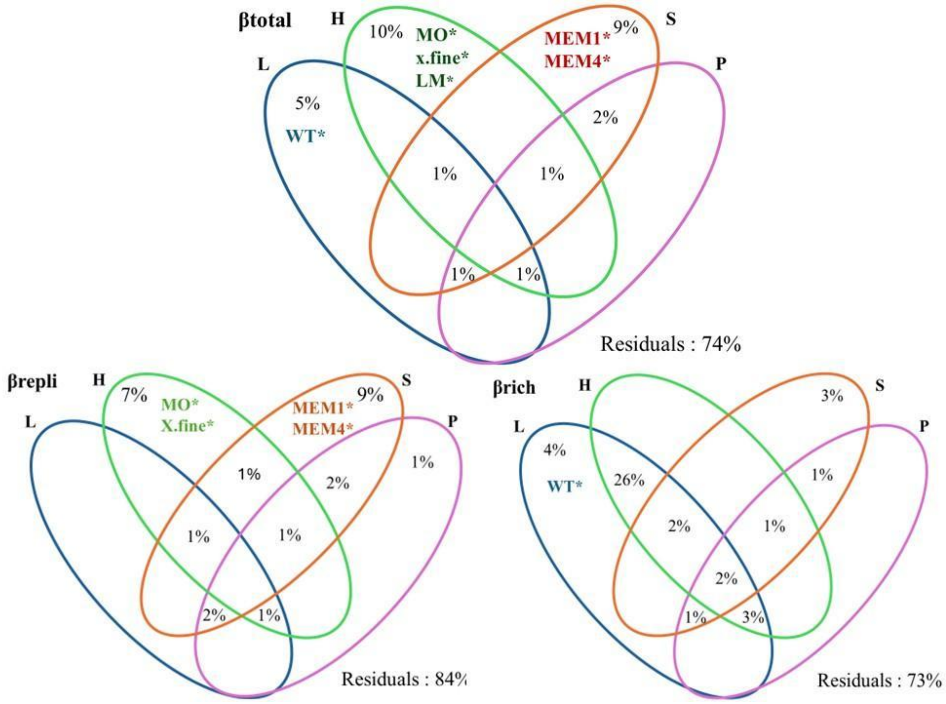

Figure 4. Venn diagrams representing the relative contribution of microhabitat (H), limnological (L), spatial (S), and landscape (P) variables in explaining taxonomic beta diversity: (a) total beta diversity (β_total), (b) replacement component (β_repl), and (c) richness difference (β_rich) of EPT communities.

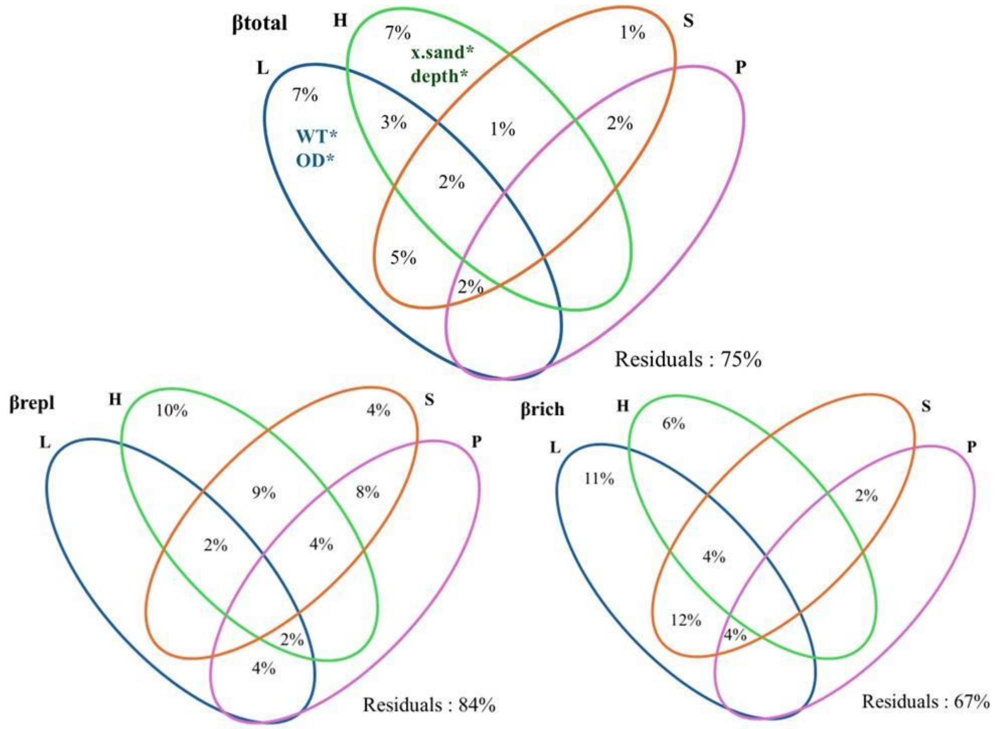

Figure 5. Venn diagrams representing the relative contribution of microhabitat (H), limnological (L), spatial (S), and landscape (P) variables in explaining functional beta diversity: (a) total functional beta diversity (F-β_total), (b) traits replacement (F-β_repl), and (c) functional richness difference (F-β_rich) of EPT communities.

4. CONCLUSÃO GERAL

Em conjunto, os dois capítulos desta dissertação demonstram que a conservação da biodiversidade amazônica deve ser compreendida simultaneamente como um processo ecológico e social. Por um lado, a análise bibliométrica revelou que a produção científica sobre povos indígenas e conservação da biodiversidade na Amazônia se expandiu nas últimas décadas, mas permanece marcada por assimetrias na autoria, na liderança e na tomada de decisão, com limitada participação indígena e predominância de instituições do Norte Global. Esse cenário evidencia a necessidade de abordagens mais equitativas e colaborativas na produção do conhecimento, com maior protagonismo indígena, autoridade compartilhada e atenção à governança de dados e à ética da pesquisa em territórios indígenas.

Por outro lado, a análise ecológica mostrou que a diversidade beta de EPT nos riachos do Território Panará é estruturada por mecanismos distintos, porém complementares, nas dimensões taxonômica e funcional. Enquanto a diversidade beta taxonômica foi predominantemente determinada pela substituição de gêneros associada a gradientes ambientais e componentes espaciais, a diversidade beta funcional foi dominada pela diferença de riqueza e explicada principalmente por filtros ambientais locais. Esse desacoplamento entre as dimensões taxonômica e funcional indica que diferentes processos de montagem governam a composição das comunidades e a distribuição dos atributos funcionais em riachos amazônicos, sugerindo ainda que a redundância funcional pode amortecer os efeitos da substituição taxonômica sobre o funcionamento ecossistêmico.

Tomados em conjunto, esses resultados reforçam que a conservação da Amazônia não pode se apoiar apenas em inventários de espécies ou em análises ecológicas isoladas, assim como não pode avançar por meio de práticas científicas que marginalizam os povos locais e seus sistemas de conhecimento. A conservação efetiva depende da integração entre abordagens ecológicas multidimensionais e formas de colaboração científica mais simétricas, inclusivas e eticamente comprometidas. Nesse sentido, tanto a produção social do conhecimento quanto a organização ecológica da biodiversidade revelam a importância de conservar não apenas espécies, habitats e processos ecossistêmicos, mas também a autonomia, a liderança e os saberes dos povos indígenas, historicamente fundamentais para a manutenção da resiliência socioecológica amazônica.

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6. MATERIAL SUPLEMENTAR

Capítulo 1

Table S1. Amazonian countries and their respective Indigenous territories, together with the number of articles per country included in this study.

Amazonian Countries	Indigenous Territories with recorded Studies	Number of articles
Brazil	TI Kayapó; TI Zoé; TI Gavião, TI Kaxinawá; TI Baniwa;TI Santeré - Mawé; Reserva Biológica do Gurupi; Reserva Extrativista Tapajós-Arapiuns	26
Ecuador	Parque Nacional Sumaco; Cofán, Kichwa; Shuar; Achuar: Estação Biológica Timburí Cocha (TCBS); Parque Nacional Yasuní; Pakayaku	25
Peru	Parque Nacional de Manu;Conservação Regional Maijuna-Kichwa (MKRCA); Área de Conservação Regional Imiría;	22
Bolivia	Tsiname; Parque Nacional Isiboro-Sécure; Reserva da Biosfera Pilón-Lajas	10
Colombia	Reserva Indígena Uitoto de Monochoa; Arhuaco; Cubeo; Parque Nacional Amacayacu	7
French Guiana	Wayãpi; Makushi e Wapishana	3
Venezuela	Sierra Maigualida	1