24 (2026) 34–39

Contents lists available at ScienceDirect

Perspectives in Ecology and Conservation

journal homepage: www.perspectecolconserv.com

Policy Forums

Beyond Boundaries: Rethinking Biomes Interdependencies in Conservation Policies

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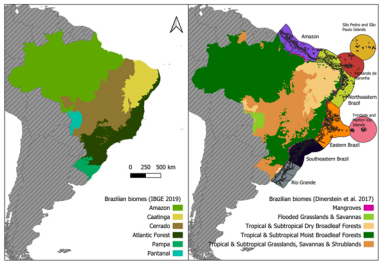
https://doi.org/10.1016/j.pecon.2025.12.001

Available online 19 January 2026

HIGHLIGHTS

- Current policies isolate biomes, overlooking crucial ecological interdependencies
- Biomes are linked by cross-boundary processes like water cycles and migrations
- Isolated biome approaches limit conservation success and ecological understanding
- An integrated strategy recognizing biome links is needed for robust conservation

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Biodiversity management
Brazil
Conservation strategies
Ecosystem interconnectivity
Sociobiodiversity
Socioecology.

ABSTRACT

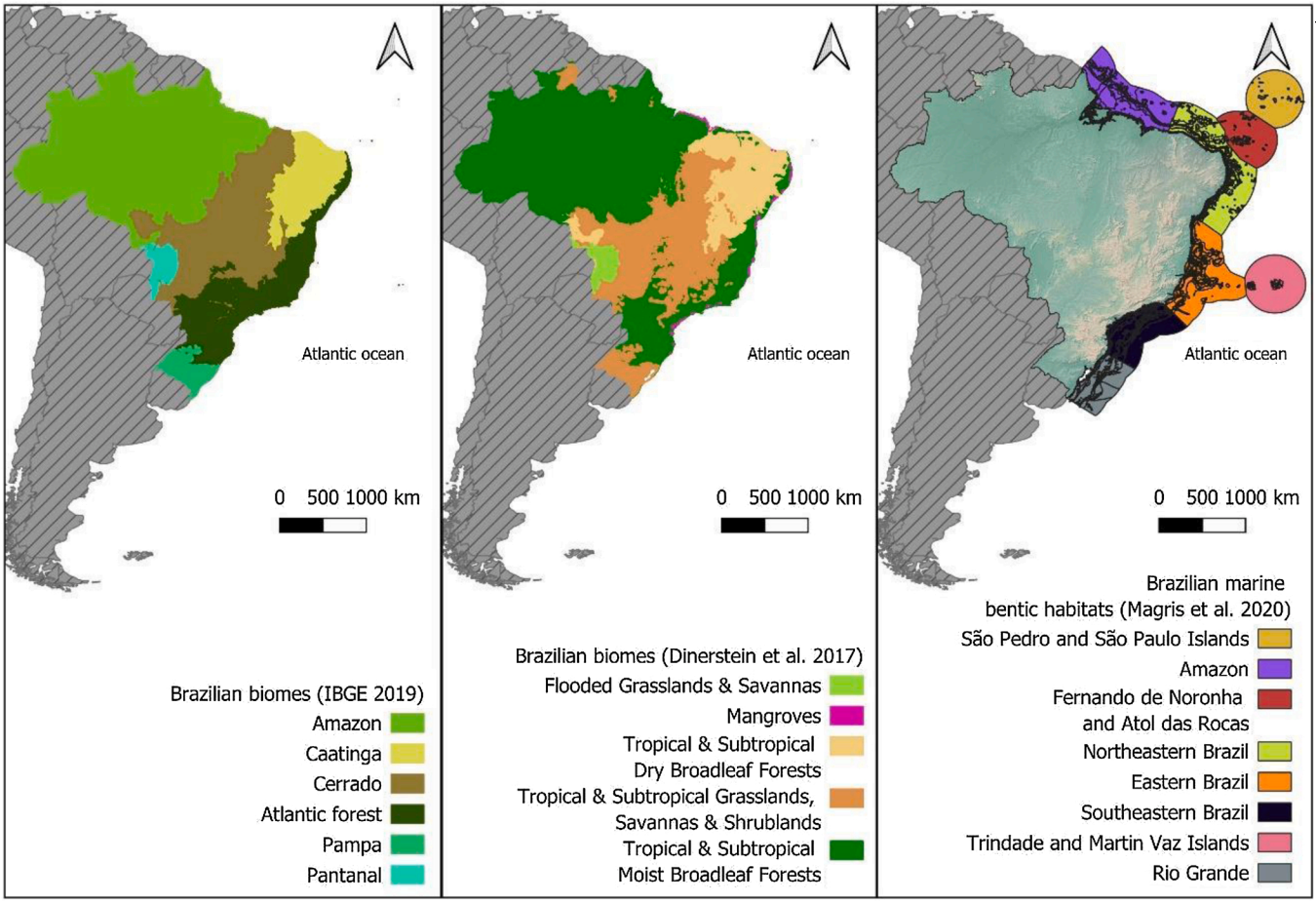
Biomes are fundamental units for biodiversity conservation given their large geographical coverage and peculiarities. The interconnectivity among biomes maintains biodiversity and climate patterns at larger spatial and temporal scales. Therefore, treating biomes as isolated entities can undermine the effectiveness of environmental policies and governance towards sustainability goals. In Brazil, for instance, such fractional perspectives could create fragmented or limited understanding of important socio-ecological interconnections among biomes, ultimately constraining effective conservation strategies and policies. Yet much has been done to integrate Brazilian biomes in scientific research or conservation projects, here we portray how the adoption of an integrated view that considers the synergies and interdependencies among biomes is critical for promoting effective conservation. This is important to ensure the persistence of significant ecological benefits derived from the natural resources of these biomes.

In the current world where policies are increasingly retrogressive with lapse economic and environmental protection measures, a thorough understanding of ecological interconnections has become imperative to safeguarding biodiversity from rapid decline. Policies, nature management and conservation initiatives worldwide often treat biomes as isolated entities, overlooking their interconnectedness and the broader ecological processes that transcend boundaries (Fernandes et al., 2023). Specifically, in Brazil, conservation policies and research initiatives are mainly structured around the country's officially designated biomes, as defined by the Brazilian Institute of Geography and Statistics (IBGE, 2019), linked to the Planning and Budget Ministry of the Brazilian government (Box 1). This connection reflects the strategic role of this institute (IBGE) in producing essential statistical and geographical data for planning and formulating public policies. The biome-based perspective is a useful and operational reference scale for landscape planning, geopolitical identity, and ecological assessments, and has brought important advances to biodiversity knowledge, conservation, restoration and land-use planning, improving the capacity to organize data, establish monitoring systems, and create identity and visibility for each biome. However, legal and institutional frameworks often focus excessively on biome uniqueness, overlooking their complex interconnections. Less attention is given to the reality that biomes are not homogenous entities, but rather large compositions of numerous, diverse ecosystems with distinct characteristics that often evade clear delimitations. Regional biodiversity does not always conform to defined/limited geographical, spatial and other physical boundaries. For example, the Brazilian law for the Protection of Native Vegetation establishes biome-specific regulations but overlooks the ecological connections among biomes, which call for conservation strategies focused on addressing the sources of environmental impacts rather than their isolated effects (Marques et al., 2020). The Cerrado biome, notably, serves as the source of numerous Brazilian river basins, which merge further downstream with larger systems situated in adjacent biomes (Oliveira et al., 2014). Thus, a more conservative protection of the riparian vegetation within the Cerrado is crucial for the conservation and maintenance of biodiversity and ecosystem services across biomes. However, current legislation does not adequately account for cross-biome interactions or for the disproportionate effects that conservation actions in one biome can have on another. Similarly, many research institutions and non-governmental organizations (NGOs) operate within biome-specific mandates (e.g. the National Institutes of Amazonia, Pantanal, Atlantic Forest, Caatinga, and Cerrado). This fragmented focus raises several important questions. For instance, when will research and policy agendas finally move beyond biome-specific frameworks to embrace integrated, cross-biome approaches? And when will the relevant authorities establish a National Institute dedicated to cross-biome biodiversity research and conservation?

Educational materials also contribute to this fragmented understanding. Textbooks and reference works commonly organize content around individual biomes, reinforcing a compartmentalized view of evolutionary, biogeographical, and ecological relationships. A quick Google search using the terms "book," "biodiversity," and "Brazil" reveals many titles focused on single biomes—such as the Amazon, Atlantic Forest, Cerrado, or Pantanal—but almost none combining them (e.g., Amazon–Cerrado or Atlantic Forest–Cerrado). Even comprehensive syntheses of Brazilian biodiversity tend to follow this biome-based structure. While such classifications have didactic and even dialectical value—highlighting both similarities and differences—they also inadvertently reinforce rigid conceptual boundaries. Consequently, the public is largely unaware that many species occur in more than one biome, and that they can be linked through migration and other ecological processes. This is exemplified with the analyses of several plant species that portray broad ranges and distributions across Brazil (Flora e Funga do Brasil, 2025), as well as bird species, of which approximately 10% are migratory (Somenzari et al., 2018). A notable example is that of two quite "distinct" Brazilian biomes, the Caatinga and Cerrado, which share approximately 60% of their bird species (Lima et al., 2022). In this case, scientific knowledge or documented long-term records on local migration, particularly regarding seasonality and foraging, remain scarce. In the marine realm, the concept of a biome is

Box 1
Brazilian biomes

Brazil has six officially recognized biomes (IBGE, 2019): Amazon, Atlantic Forest, Caatinga, Cerrado, Pampa and Pantanal. These biomes (*sensu* IBGE) also correspond to the major phytogeographic regions of the country. The corresponding biomes in an international biome classification (Dinerstein et al., 2017) are 'Tropical Moist Broadleaf Forests' (including IBGE's Amazon, Atlantic Forest), 'Tropical and subtropical Dry Broadleaf Forests' (Caatinga), 'Tropical and Subtropical Grasslands, Savannas and Shrublands' (Cerrado, Pampa) and 'Flooded Grasslands and Savannas' (Pantanal). Note that the two classification systems differ concerning biome boundaries, reinforcing that biome-based conservation strategies can be problematic, as they depend on the details of specific classifications. In addition, the country is slowly moving towards officially recognizing eight distinct coastal-marine ecosystems in its Exclusive Economic Zone (Magris et al., 2021), which is central to advance our understanding on the ecological interconnections between land and sea ecological processes and develop better-informed conservation policies.



even more elusive, as the distinctions and potential "boundaries" between marine ecosystems are concealed beneath the water's surface, beyond human sight. Yet there are still diverse marine ecosystems and their habitats, such as coastal biomes, coral and rocky reefs, mesophotic reefs, the deep and open oceans, not to mention the polar seas (Box 1). Within coastal biomes, mangroves and estuaries act as crucial bridges, not only between terrestrial and marine environments but also among marine ecosystems. They foster these connections through biogeochemical cycles, species' life cycles, ecosystem processes, and the social and cultural services they provide. Because the boundaries and processes of coastal-marine ecosystems are fluid and multidimensional, these environments often remain excluded from biome-driven policies, even though this reflects an inherent challenge of marine classification rather than a limitation of the biome concept itself, risking the loss of the numerous benefits they provide to human populations from nutritional security to coastal protection and climate regulation. Liévano-Latorre et al. (2025) highlight the importance of cross-biome restoration planning based on functional connectivity and adequate habitat conditions for achieving biodiversity conservation goals and tackling climate change. Moreover, within-biome divisions further aggravate the problems, as large interconnected systems are often divided into independent units (Araújo et al., 2022). Additionally, funding calls for conservation and research projects on biodiversity tend to be structured around specific biome-based objectives or geopolitical boundaries, further entrenching these divisions. Some large-scale research initiatives, such as the Programa de Pesquisa em Biodiversidade (PPBio - Brazilian Biodiversity Research Program), and Programa de Pesquisas Ecológicas de Longa Duração (PELD - Long Term Ecological Research) also exemplify these divisions (Rosa et al., 2021). Despite the evident success of both Programs, they also started with a focus on terrestrial biomes while long term monitoring of coastal-marine ecosystems is more recent in the PELD Program (Cordeiro et al., 2022). Coastal-marine ecosystems were incorporated in the PPBIO Program only in 2024.

Biogeochemical and socio-ecological processes are not restricted by

biome boundaries. Deforestation across Amazonia, for example, has already reduced annual rainfall across large areas of Brazil and other parts of South America (Bottino et al., 2024). Similarly, in 2024, smoke from fires in Amazonia, Cerrado and Pantanal affected human populations and ecosystems in the Atlantic Forest and the Pampa biome (Monteiro dos Santos et al., 2024). In the same way, the ocean plays a fundamental role in the interconnection of terrestrial biomes, particularly through the water cycle. Recent record-high ocean temperatures have disrupted hydrological cycles, altering precipitation patterns and intensifying extreme weather events across South America (Luiz-Silva et al., 2021; Santos et al., 2023). These changes directly affect terrestrial biomes, modifying their functioning and exacerbating environmental stressors such as droughts and wildfires. Moisture transport from the ocean, including aerial rivers that carry humidity across continents, is a crucial component of cross-biome interactions and should be considered in conservation and climate adaptation strategies. Cross-biome influences are particularly pronounced in ecotones. Here, shared animal and plant species, as well as joint environmental characteristics create unique mosaic landscapes and environments with multiple influences that demand specific conservation approaches (Kark, 2007). Even at the global level, there are clear examples of biomes and ecoregions that influence one another, such as the Sahara desert's dust, which fertilizes and increases productivity in the Amazon (Bristow et al., 2010).

In advocating for a conservation approach that transcends biome boundaries, it is important to recognize that each biome faces high, yet different, levels of anthropogenic pressure and conservation urgency. The Amazon Rainforest, for instance, harbors the most species-rich and biodiverse ecosystems on Earth. It provides essential ecosystem services at regional and global scales, yet continues to experience one of the highest global deforestation rates (Bottino et al., 2024). This persistent threat is exacerbated by a history of inadequate funding for Amazonian research, limiting the comprehension of its ecological systems (Guimaraes et al., 2024). Conservation efforts have also failed to fully engage local communities, Indigenous peoples, and Amazonian institutions, whose knowledge is crucial for sustainable strategies (Fernández-Llamazares et al., 2021). While external expertise is valuable, initiatives must prioritize the contributions of those who have lived in and cared for the territory for generations, ensuring their voices in shaping decisions. Another example, the South Brazilian Pampa region is often overlooked in conservation, even though its high conversion and low coverage of protected areas makes it highly threatened (Overbeck et al., 2015). Biome awareness disparities persist in the conservation debate (Silveira et al., 2022; Overbeck et al., 2024). A well-balanced conservation strategy should not divert critical resources from high-priority areas, rather it should enhance their protection by reinforcing their ecological and sociobiological interdependencies with adjacent biomes. Likewise, research on zoonotic diseases, such as the hantaviruses, should be extended across biomes to increase the comprehension of transmission dynamics and ecological drivers (Mello et al., 2024). Coastal-marine ecosystems also suffer from lack of appropriate funding both for research and to face the challenges of implementing effective conservation actions given its size and logistical constraints (Magris et al., 2021). Acknowledging the ocean's role in planetary regulation and its links to terrestrial biomes, the United Nations launched the Decade of Ocean Science for Sustainable Development (2021–2030) (Ryabinin et al., 2019) to promote cross-system research and foster conservation and sustainable use.

Empirical evidence has increasingly revealed that biomes are not separated by hard boundaries (Moncrieff et al., 2016), and often, ecological studies are conducted across their official limits. For example, the grasslands Pampas in southern Brazil, extend into the southern part of the Atlantic Forest biome (Marques and Grelle, 2021; Overbeck et al., 2024). Biome boundaries were dynamic throughout the history of the Planet, and will possibly change in the future, tentatively, at a more rapid rate than existing forecasts, given climate change (Maksic et al., 2022). Pivotal ecosystem processes, such as telecoupling, where distant regions are ecologically and socioeconomically linked, and "aerial rivers", where moisture from one biome impacts precipitation patterns in another, critically illustrate the deep interconnections among biomes (Arraut et al., 2012). Furthermore, there are significant hydrological dependencies, socio-ecological spillover effects, and animal migrations across the boundaries of these biomes. Some studies have even drawn attention to the risks that strict deforestation limits in a biome, for instance, may unintentionally shift deforestation pressures to adjacent ones (Kuschnig et al., 2021; Fernandes et al., 2023). Interconnections among systems (e.g. ecotones, groundwater/surface-water networks, terrestrial-aquatic systems, terrestrial, freshwater, and marine systems) are still currently understudied. It highlights the necessity for an integrative approach to merge biomes within a larger connected research and conservation framework.

While the permeability and ecological interdependence of biome boundaries are widely acknowledged within the scientific community (e.g., Gosz and Sharpe, 1989; Ferro and Morrone, 2014, and the above references), this understanding has not yet been fully reflected in research practices and policy frameworks. In practice, many biogeographic classifications, large-scale assessments, and conservation programs continue to use biome limits as fixed reference units, reinforcing the perception of rigid boundaries. This persistence creates a form of closed circular loop, in which conceptual simplifications are institutionalized through policies and monitoring frameworks and subsequently reabsorbed into scientific analyses. Consequently, the challenge extends beyond institutional or operational barriers—it also involves epistemological and systemic feedbacks between scientific paradigms and governance structures. This dynamic, reminiscent of Kuhn's (1962) notion of paradigm persistence, helps explain why, despite robust scientific evidence of ecological interconnectivity, biome-based thinking remains deeply rooted in conservation planning and environmental management.

Given these complexities, we are not advocating for the deconstruction of the biome-based approach, but rather highlighting the need for more cross-biome initiatives, as well as the incorporation of social and environmental biome interconnectivity measures that are more explicit into conservation strategies. Recognizing and addressing the aforementioned linkages among systems can yield robust and resilient approaches to biodiversity conservation. On this premise, we outline seven practical steps to achieve an integrated vision of cross-biome conservation: **1) Redesign or Improve Organizational Structures**: Conservation organizations currently focused on single biomes should expand their scope to include inter-biome connections. This could involve forming interdisciplinary and transdisciplinary teams capable of addressing social-ecological linkages across biomes and ecosystems. **2) Funding for Interconnected Systems**: Research and conservation funding should emphasize projects that explore cross-biome interdependencies and relationships. Investments should support initiatives that protect ecological corridors, river networks, ocean-terrestrial connections and key transition areas such as mangroves, estuaries, coastal sand dune vegetation, riparian zones, mountain chains, and migratory paths. **3) Research Institute Collaboration and Mobility**: Teams in biome-focused research institutes could increase mobility and foster collaborations across biomes. Also, expanding programs, such as Brazil's PELD and PPBio, should include cross-biome research initiatives that can facilitate knowledge exchange and holistic ecological assessments. In this regard, improving cross-border collaborations among South American countries is essential. Fortunately, initiatives, such as those among Amazonian nations represent steps in this direction. Other closely-knit ecosystems, such as the Pantanal and Chaco can adopt their success strategies, most probably through significant investments in cooperative research and conservation efforts. **4) Legislative and Policy Aspects**: Although relevant environmental legislations cut across all biomes, the implementation process—including the formulation and enforcement—varies significantly from biome to biome. Therefore, more balanced and deliberate efforts are required to ensure effective

legal processes abound across biomes. This new approach will require a well-designed co-production process for regulations, ensuring that cross-biome initiatives incorporate differential implementations based on the interconnections between biomes. **5) Education and Training**: Teaching materials for all ages, including textbooks, should contain instructive content on biome interdependencies. For instance, courses in biogeography, ecology, conservation biology, and sociobiodiversity should incorporate inter-biome dynamics. This would start from the insertion of this discussion both at schools and academic-level courses to prepare future professionals for work within an integrative framework rather than on isolated biome models. Moreover, the processes of co-learning and co-production are fundamental to transforming concepts and approaches in both scientific research and policy frameworks. **6) Broader Research Questions**: Research efforts should begin to address critical questions and solutions to conservation problems in the context of cross-biomes systems, such as the biogeochemical cycles, traditional knowledge systems, species migrations, evolutionary and ecological processes across biomes and ecotones. Programs should prioritize studies on spillover effects, system's connectivity (e.g. hydrological and biodiversity fluxes), and telecoupling impacts to inform policies aligning the interconnected dynamics of biomes. **7) Social Actors Involvement in Cross-Biome Initiatives:** Effective cross-biome conservation requires the inclusion of all social actors—local communities, Indigenous peoples, researchers and policymakers. Traditional, local and Indigenous knowledge is essential for creating culturally-appropriate and socially-equitable conservation strategies. Engaging these stakeholders fosters collaboration, enhances knowledge transfer, and ensures conservation efforts are scientifically grounded and context relevant. This holistic approach is key to addressing the interconnected ecological challenges across biomes. **8) Enhance the Visibility of Cross-Biome Initiatives:** Building a shared sense of belonging around the idea of interconnected biomes can strengthen public support for integrated conservation. Brazil already hosts several protected areas located in transitional zones, such as "Refúgio da Serra dos Montes Altos" (Caatinga-Cerrado transition), PARNA Araguaia (Cerrado-Amazon), APA Serra da Ibiapaba (Caatinga-Cerrado), Estação Ecológica Iquê (Cerrado-Amazon), and FLONA Passo Fundo (Atlantic Forest-Pampa) and ecological corridors connecting different biomes, such as: "Corredor Central da Mata Atlântica", "Corredor Ecológico da Caatinga", "Áreas Protegidas: Cerrado e Caatinga" project (Fundação Pró-Natureza), the "Corredor da Onça-Pintada" project (Instituto Onça-Pintada), and watershed-based initiatives across biomes. However, these initiatives often remain poorly coordinated and insufficiently recognized as cross-biome perspectives. Promoting greater visibility and coordination among such efforts—through communication campaigns, public engagement, and cross-institutional networks—can help consolidate a collective identity around the notion of "Brazilian cross-biome protected areas". Highlighting regions where terrestrial, freshwater, and marine systems converge holds significant transformative potential, not only for advancing scientific understanding but also for mobilizing societal and media interest in integrated conservation strategies.

Our eight recommendations above should not be understood as isolated initiatives or idealized academic exercises, but rather as components of a broader transitional socio-scientific-technical-cultural process. This process involves collective change, the strengthening of belonging and shared purpose, and diplomacy among stakeholders, aligned with existing administrative capacities, funding mechanisms, and legal frameworks. Transitioning to cross-biome approaches requires not only conceptual shifts but also fundamental restructuring of institutional mandates, budget allocations, and inter-governmental coordination mechanisms. For example, promoting research in transitional areas could be facilitated by identifying priority zones where socio-ecological processes are particularly vulnerable, land-use pressures are intensifying, and climate change impacts are strongest. Likewise, recommendations for stakeholder participation should address strategies for reconciling competing priorities, drawing lessons from river basin committees or Indigenous Territorial Management Plans that already operate across multiple biomes. Within academia, the transition also entails making these topics more explicit in disciplinary and interdisciplinary curricula, incorporating active learning approaches that enable students to engage with cross-biome problem-solving in practical, context-sensitive ways.

It is important to highlight that despite our primary focus on the conservation of Brazilian biomes, it is expedient to consider the steps outlined above for adoption in conservation across other biomes and territories. As in the case of Brazil, most biomes are not uniquely spatially-contained within specific countries. Thus, international research collaborations are crucial for comprehensive exchange of ideas around the emerging cross-biome conservation approach. A notable example is the Chaco, which despite not being recognized as a Brazilian biome is important for other countries in South America. The Amazon, located in a large part of the national territory and in lands of neighboring countries, such as Guiana, Suriname, Venezuela, Ecuador, Colombia, Peru and Bolivia is another example of a transboundary challenge. The Atlantic countries are discussing an international agreement of the All-Atlantic Ocean Research and Innovation Alliance (https://allatlanticocean.org/about/) that can inspire multinational partnerships for other biomes. In conclusion, an integrated and interconnected approach accounting for interdependencies among biomes has potentials to advance biodiversity conservation on a global scale. This will foster the development of effective and sustainable strategies around the complex socio-ecological and dynamic relationships among biomes. Through considerations for the cross-biome approach, researchers can promote robust, scalable, and resilient conservation actions, with higher weight given to biodiversity and ecosystem protection for the benefit of future generations.

Declaration of competing interest

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

Acknowledgements

We thank the financial support by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq/PPBio), and Knowledge Center for Biodiversity (INCT/CNPq: 406757/2022-4).

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