



ECOSYSTEMS

The Program for Biodiversity Research in Brazil: The role of regional networks for biodiversity knowledge, dissemination, and conservation

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Abstract: The Program for Biodiversity Research (PPBio) is an innovative program designed to integrate all biodiversity research stakeholders. Operating since 2004, it has installed long-term ecological research sites throughout Brazil and its logic has been applied in some other southern-hemisphere countries. The program supports all aspects of research necessary to understand biodiversity and the processes that affect it. There are presently 161 sampling sites (see some of them at Supplementary Appendix), most of which use a standardized methodology that allows comparisons across biomes and through time. To date, there are about 1200 publications associated with PPBio that cover topics ranging from natural history to genetics and species distributions. Most of the field data and metadata are available through PPBio web sites or DataONE. Metadata is available for researchers that intend to explore the different faces of Brazilian biodiversity spatio-temporal variation, as well as for managers intending to improve conservation strategies. The Program also fostered, directly and indirectly, local technical capacity building, and supported the training of hundreds of undergraduate and graduate students. The main challenge is maintaining the long-term funding necessary to understand biodiversity patterns and processes under pressure from global environmental changes.

Key words: Biodiversity, Long-term Ecological Research, stakeholders, knowledge production, data availability, capacity building.

INTRODUCTION

Tropical ecosystems hold more than two-thirds of the world's biodiversity (Raven 1988), maintaining ecological functions and services needed for human health and global environmental quality (Kilpatrick et al. 2017). At the same time, most tropical ecosystems are in countries with high social vulnerability and, therefore, with few resources devoted to research and practical biodiversity conservation. This situation led to concerted international attention focused on reducing natural-habitat conversion and halting global biodiversity and ecosystem-service losses by strengthening local communities. International biodiversity-conservation agreements, such as the Convention on Biological Diversity and the 2030 Agenda for Sustainable Development, require that signatory countries monitor and report their progress towards established goals. Although most of this monitoring uses ex-situ metrics (e.g., remote sensing), long-term, systematic, and standardized in-situ biodiversity-monitoring data are needed to understand long-term patterns of biodiversity change and its drivers. This approach could help to improve the assessment of progress towards biodiversity conservation agendas (Lindenmayer & Likens 2010a, Geijzendorffer et al. 2016, Proença et al. 2017, Bayraktarov et al. 2019).

In-situ biodiversity-monitoring systems have a clear connection to policy and management, and the potential to contribute substantially to reducing the research-implementation gap in conservation science (Fazey et al. 2005, Cook et al. 2010, Karam-Gemael et al. 2018), and is the best way to circumvent well-known shortfalls that prevent large-scale understanding of biodiversity (Hortal et al. 2015). With this perspective, the Program for Biodiversity Research (PPBio) was created in 2004. Linked to the Brazilian Ministry

of Science, Technology, and Innovation (MCTI), the PPBio is a program that aims to expand and disseminate knowledge of Brazilian biodiversity. Hence, PPBio is a network organized into regional and local hubs in all Brazilian biomes, and its scope is to integrate academic institutions with stakeholders, researchers in regional centers, indigenous groups, non-indigenous traditional owners, farmers, foresters, fishermen, and hunters. The Program aims to foster biodiversity studies in Brazil, reduce regional inequalities in scientific research, integrate research activities, and disseminate knowledge to promote environmental management and education. PPBio did not replace existing programs and projects on biodiversity, and indeed the resources were much more limited than those of other biodiversity-research initiatives. The goal was to enhance the use of resources from various Brazilian ministries and the private sector to create scientific knowledge-production chains on biodiversity that would meet the demands of different segments of society.

In this paper, we present the history, structure and main results of the PPBio and perspectives of in-situ biodiversity monitoring. We also show how the program enables studies at different scales integrating different interfaces of the environment (e.g., biosphere and anthroposphere) and the implementation of conservation actions in some of the most biologically diverse areas of the world.

PPBIO: AN INTEGRATED BIODIVERSITY PROGRAM

Forging an integrated research network

Public concern about natural resources and environmental conservation has increased since the last century, culminating in the United Nations Conference on Environment and Development in Rio de Janeiro (Rio-92

- Earth Summit). During Rio-92, Brazil and other countries led efforts to establish goals to prevent erosion of biodiversity and associated environmental services. To advance the implementation of the goals of the Convention on Biological Diversity, the MCTI organized a series of meetings with the main actors involved with Brazilian biodiversity. These meetings revealed that the country's infrastructure for biodiversity studies was poorly dimensioned and distributed with geographical biases. After two years of discussions to determine the best form of action, the MCTI created the PPBio, which formally started in 2004 (MCTI act no. 268, 18th July, 2004).

Due to limited resources, the first PPBio research networks were established in Amazonia and the Caatinga (the semi-arid region in northeastern Brazil), where extensive gaps in biodiversity knowledge existed. Even though there were no specific resources for other biomes (*sensu* IBGE 2004), the experience obtained was used by the MCTI to plan activities of the Research Center in the Pantanal (CPP) and the Research Network for Sustainable Use and Conservation of the Cerrado (COMCERRADO). Despite the modest budget, the program was highly successful, and MCTI recognized its national and international influence. In 2012, a second call was made for applications of additional projects in other biomes, such as Atlantic Forest, Cerrado and Pampa.

The PPBio supported regional and local hubs. At the beginning of 2004, there were two regional hubs, one in Manaus (Instituto Nacional de Pesquisas da Amazônia) that covers western Amazonia, and the other in Belém (Museu Paraense Emílio Goeldi) responsible for research in eastern Amazonia. Within these regional groups, local hubs were established in other Amazonian states. The program had three primary components: inventories, scientific

collections, and thematic projects. Inventories aim at structuring the experimental design, the choice of research areas and strategies, the establishment of sites for carrying out surveys and long-term monitoring biodiversity, and the development of sampling protocols for different biological groups. The collections component involved identifying vouchers in existing collections, surveying demands for infrastructure and institutional support, defining curatorial protocols, exchanging and sharing material, identifying knowledge gaps, and qualifying and digitizing collections. For example, the exsiccates from around 1600 plants collected in the RAPELD modules are available online at JABOT (<http://rb.jbrj.gov.br>). In turn, ecological data are available on DataOne (<https://www.dataone.org/>) and PPBio is a SiBBR data provider (<https://www.sibbr.gov.br/page/provedores-de-data.html>).

The thematic component focused on integrating local demands and research, such as screening biomolecules for pharmaceutical or medicinal uses. All involved the training of human resources, strengthening regional centers, creating and supporting the development of graduate programs, and offering research opportunities for students and local researchers. With the present emphasis on integration, the Program was expanded to include other biodiversity-related activities. In 2012, PPBio aggregated two new components: data management and information, and the synthesis of knowledge promoting scientific dissemination, decision-making and the formulation of public policies. It was recognized as the National Biodiversity Monitoring Program by the MCTI, with a structured network connecting research and biodiversity agendas in all terrestrial Brazilian biomes: Amazonia, Cerrado, Atlantic Forest, Caatinga, Pantanal, and Pampa.

Core and Regional Hubs

To guarantee the functionality of biodiversity monitoring at a national scale, PPBio promoted a network of regional and local hubs that involve a consortium of local stakeholders in biodiversity in all aspects of the research. The PPBio is structured with both horizontal and vertical networks that form a biodiversity knowledge-production chain. This chain depends on many different experts, including traditional landowners, indigenous people, field biologists, geneticists, physiologists, law-enforcement and educational institutions, and private companies. The production chain involves (1) field data collection to assess distribution patterns and abundance; (2) evaluation of social relationships with biodiversity and knowledge production; (3) evaluation of the economics of production for scientific and economic chains; (4) analysis of the relations with policy and governance; and (5) market assessments for commercial solutions and products based on biodiversity and natural resources.

Today, PPBio has 161 data-collection sites in Brazil, including 63 sites in protected areas (Figure 1, Supplementary Material - Table SI). Site administration comprises nine core hubs: Western Amazonia; Eastern Amazonia; Semi-arid, South Brazilian grasslands (including sites in the Pampa and the highland grasslands in the south of the Atlantic Forest), Pantanal; two cores in the Cerrado, and two cores in the Atlantic Forest (Table SI). Hubs and sites cover a wide range of Brazilian ecosystems, including primary and secondary lowland and montane forests, savannas, grasslands, wetlands, and arid environments.

Importantly, PPBio does not usually provide funding for installing field infrastructure, and most hubs are not self-sufficient in terms of research ability and financial resources to study all aspects of biodiversity and the ecosystem

processes that affect it. However, there is enormous potential for collaboration among the research groups. The infra- and scientific structure provided is recognized by state funding agencies, private companies, technicians responsible for reserves, and government agencies responsible for environmental-impact assessments. Hence, local hubs can obtain funding to integrate with other such hubs and developed regions that have more resources.

In general, the hubs are structured to (a) support the maintenance of sampling sites, (b) develop scientific strategies aimed at integrated management of interdisciplinary research, (c) use standardized methods for surveys and monitoring of biodiversity, (d) conduct studies on vegetation structure, carbon stocks, climate change, fragmentation and hydrological resources in long-term ecological sites, (e) organize studies of biodiversity and the factors that affect it at different spatial and temporal scales, (f) assist in the restructuring and modernization of biological collections, (g) contribute to the development of genetics applied to biodiversity, (h) contribute to bioprospecting associated with regional biodiversity, (i) build support for human-resources training at different levels, including local communities and researchers, (j) support database preparation, and production and integration of biodiversity data, as well as, (k) produce outreach and dissemination materials on Brazilian biodiversity.

Sampling: RAPELD and alternatives for gathering comparable biodiversity data

Long-term ecological research sites have greatly aided our understanding of ecosystem processes worldwide and many biodiversity monitoring systems have been developed in recent years (Craine et al. 2007). However, they are generally small, focus on a limited number

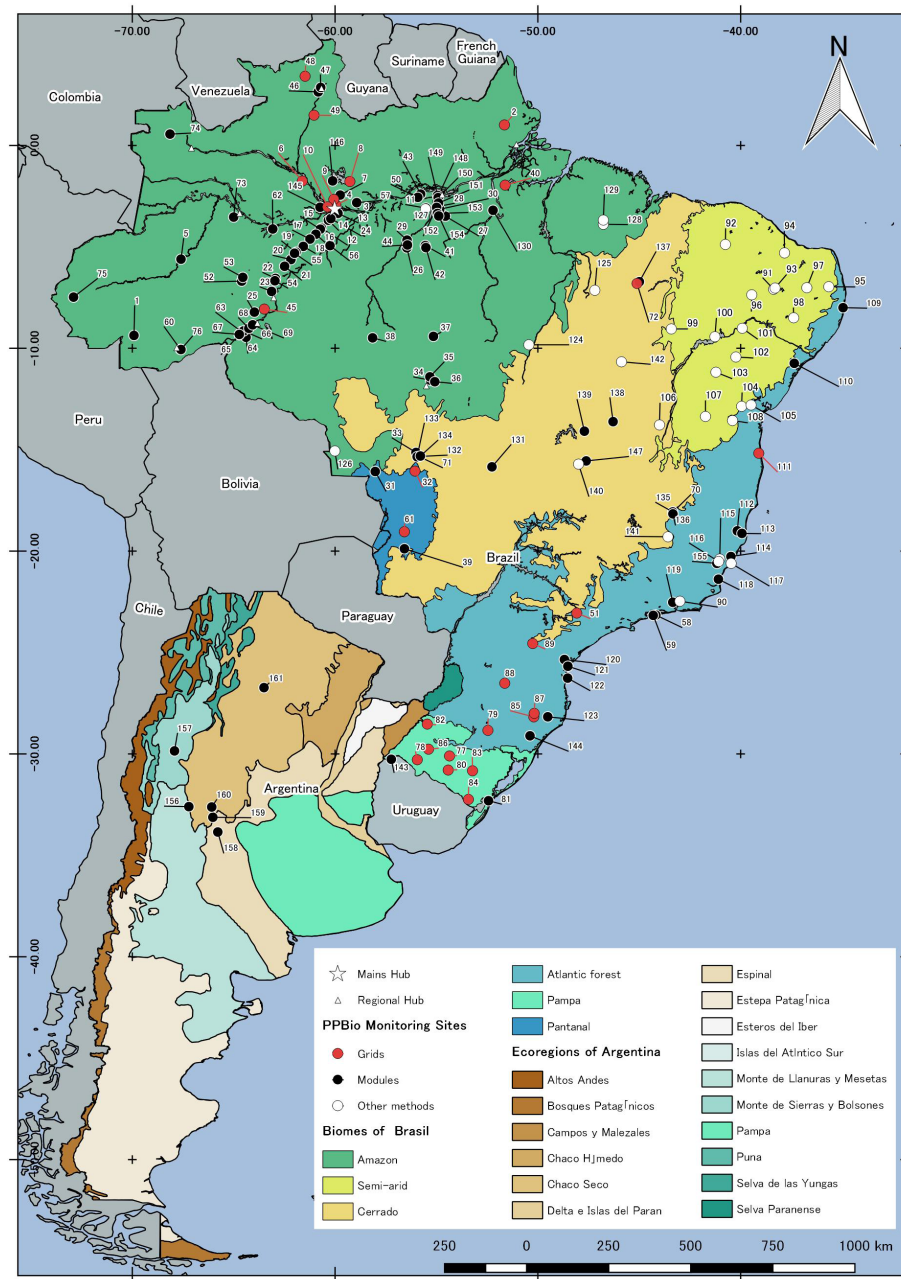


Figure 1. Sampling sites of the Brazilian and the Argentine Program for Biodiversity Research networks. See the identification and coordinates of each site in Table S1.

of taxa (e.g., the CTFs 50-ha plots, Anderson-Teixeira et al. 2015), or are arbitrarily selective in the landscape features they sample (e.g., TEAM plots, Rovero & Ahumada 2017). While these initiatives are excellent for examining local processes, they generally do not provide the sort of data required by land managers or politicians (but see Forest plots 2020).

In this scenario, some hubs adopted the RAPELD system as sampling method. The RAPELD system consists of a combination of trails and permanent plots for standardized surveys and monitoring of biodiversity and ecosystem processes (Magnusson et al. 2005, Figures S1, S2). The RAPELD system grew out of the Brazilian Long-term Ecological Research Program (Costa et al. 2015) and developed within PPBio

(Magnusson et al. 2013). The impetus to develop the system grew from land managers' demands for a standardized monitoring system that was landscape-oriented, rather than taxonomy-oriented. It would provide the data required by many different biodiversity stakeholders, such as local communities, wildlife managers, foresters, farmers, managers of protected areas, catchment-management authorities, local councils, and politicians.

RAPELD attempts to meet the need for rapid surveys while providing the infrastructure necessary for long-term research. It had to be relevant to all scientists doing basic research, such as ecologists and taxonomists, and of use to local groups (e.g., local communities, protected-area managers) that need to integrate biodiversity and ecosystem processes into their daily living (Gotelli 2004). RAPELD attempts to meet the following criteria: (1) be standardized; (2) allow integrated surveys of all taxa; (3) be large enough for monitoring all elements of biodiversity and ecosystem processes; (4) be modular to allow sampling of small areas and comparisons with small samples taken over extensive areas; (5) be compatible with existing initiatives; (6) be implementable with the existing human resources; (7) make data available quickly and in a usable form to managers and other stakeholders; (8) allow long-term monitoring. Extension, grain, and taxonomic groups are defined to address specific questions, focusing on the interplay between spatial and temporal scales (Wiens 1989). The standardized methods used in RAPELD can return information at the landscape scale, so it is of use to municipal, state, and federal decision-makers and allows comparisons across biomes and ecosystems, countries, and continents. Its primary components are conventional and easily installed, and many sampling procedures can be conducted by traditional people and

technicians with little experience of complicated laboratory or statistical analyses. RAPELD does not provide the questions, rather it provides spatial standardization so that questions can be answered in an integrated manner at scales relevant to land managers.

Besides Brazilian hubs and sites, the RAPELD protocols were adopted in Australia, Nepal, and Argentina. Studies started in Argentina in 2014, in collaboration with PPBio Atlantic Forest. Currently, there are six sites throughout central semi-arid Argentina (Figure 1; Table SI). They are distributed in localities with different ecological conditions, following local and regional heterogeneity. In Australia, the first RAPELD sites were established in 2007 (Hero et al. 2010). To date, five sites in Australia have RAPELD modules (Table SI), covering dry eucalypt forest, semi-arid shrubland, coastal wallum heath, lowland forest, and grasslands. The value of the RAPELD sites in Australia is apparent in the dissertations and publications on ecosystem management, monitoring, and the protection of threatened species (Lollback et al. 2017).

Besides this, some studies developed by PPBio partners have designs based on specific goals and themes, such as climate change, changes in land-use and land-cover, and disease ecology that do not use RAPELD. As with the studies that use RAPELD methodology, they are developed with goals, objectives, and specific questions to be answered, as suggested by Lindenmayer & Likens (2010b) and Gardner (2012).

Data Management

Data management is the basis of communication between data collected by researchers and society. However, most scientific data are in office drawers or not fully used by researchers (Huang & Qiao 2011). PPBio has a particular concern for sharing information to expand the results

and use them at different local, regional, and national scales, or even to respond to ecological issues of international interest. Also, much of the program's financial resources come from public funding sources, and the data is of public interest. Therefore, PPBio works with an online and public data-management system, where researchers are encouraged to deposit their field data and metadata in publicly available repositories. The Program also invests in capacity-building courses for data management. One of its executive hubs is currently the only node in South America for the international data consortium known as Data Observation Network for Earth (DataONE).

The PPBio data repositories contain data collected in the field, videos, and photos, following the principle that all collected information must be adequately documented in the form of metadata, associated with the respective set of validated data, and made available on a website with free access. The metadata present in repositories follows the EML standard (Ecological Metadata Language, <http://knb.ecoinformatics.org/software/eml/>; Fegraus et al. 2005), developed by the Knowledge Network for Biocomplexity (KNB, <http://knb.ecoinformatics.org/index.jsp>), an international network that aims to integrate data from various collection sites, laboratories and researchers. They are organized as follows: title and summary, key-words, owner, contact, associated parties, research project, use rights, geographic coverage, temporal coverage, taxonomic coverage, methods, access information, data files, and information on the attribute table.

The PPBio also works in collaboration with international consortiums, such as RAINFOR, ADTN and ForestPlots, that have developed databases for the analysis of specific questions related to vegetation structure and composition throughout the tropics.

MAIN RESULTS OF PPBIO

PPBio has evolved into the current structure, integrating more and more researchers in Brazil and other countries. The Program expanded nationwide, and similar networks were created in other countries (Australia, Nepal, and Argentina), a thermometer of the program's success. Also, human resources and capacity building are essential for the maintenance and expansion of PPBio. Many of the masters and doctors trained are now coordinators and researchers in different regional centers, reflecting the quantity and quality of scientific studies produced by the PPBio team.

The topics and questions of publications are as heterogeneous as those of any other open network, reflecting the local research agendas and capacities. Later, these topics were integrated to answer broad questions. Until 2012, most of the publications referred to Amazonia; however, after the expansion of the network, Amazonia was proportionally less mentioned in scientific studies, with an increase in publications from other biomes and broader focuses on Brazil (Figure 2). Much of the PPBio effort directly concerns the distribution of species, but given the broad scope of the network, no taxonomic group dominates the research agenda. As biodiversity conservation is the ultimate goal of PPBio, many studies are on surveys and monitoring of populations and biological assemblages (e.g., Almeida-Gomes et al. 2015, Moreira et al. 2016, Bitar et al. 2017), natural history (e.g., Magalhães et al. 2013, Simões et al. 2019), and description and analysis of the distribution of new species (e.g., Tourinho et al. 2010 Bellini et al. 2013; Aldrete & Neto 2014), filling critical knowledge gaps in all Brazilian biomes. A preliminary evaluation of output indicated that the Amazon still accounts for 55% of publications, followed by Atlantic

Fungoteca: macrofunga - <https://ppbio.inpa.gov.br/fungoteca/paginainicial>, Ixodoteca: ticks - https://ppbio.inpa.gov.br/ixoditeca_Inicio, Opilioteca: harvestmen - <https://ppbio.inpa.gov.br/opilioteca/paginainicial>), which provide photos and species information, including vocalization, morphology, and other biological information. This material has been used widely by researchers, undergraduate and graduate students, and professors from national and international institutions.

Studies developed under the coordination of researchers linked to PPBio have 1) provided a better understanding of the distribution of species from several taxonomic groups (e.g. amphibians, reptiles, mammals, invertebrates, funga, vascular plants) present in Brazil, producing explanatory models of the variation in the distribution of populations and assemblages of these organisms in relation to biotic and abiotic variables; 2) provided bases for further studies on the dynamics of populations from different taxonomic groups, allowing for future monitoring and evaluations; 3) helped define sampling protocols with lower cost and better results, allowing quick evaluations in future studies; 4) offered necessary infrastructure to master's dissertations and doctoral theses, and trained many undergraduate students; 5) made available resources and infrastructure to identify and describe new species or larval stages of species already described; 6) helped researchers to deposit specimens of animals and plants in the Brazilian scientific collections, with the perspective to further expand the holdings of these collections; 7) fostered integrated analysis of different taxonomic groups seeking to determine ecological patterns at different spatial and temporal scales, 8) analyzed the effects of land-use change on biotic communities and abiotic factors; 9) identified threats to biodiversity and sought solutions to

reduce impacts; 10) integrated different social actors, such as local communities, managers of protected areas and researchers for the expansion of knowledge and conservation of biodiversity; 11) trained and retained qualified professionals, stimulating research on biodiversity and consequently promoting scientific and technological development in the most remote regions of Brazil; and 12) identified and filled gaps in biodiversity knowledge.

RESEARCH AND SOCIETY

PPBio has worked with local communities in the generation of bioproducts, such as extraction and marketing of oils and edible mushrooms in the Amazon. The program works to transfer knowledge to society through talks, lectures and workshops offered in communities close to the sampling areas, training of community members to collect biological data and monitor, radio and television interviews (national and international networks) and official channels, projects of environmental education, video production, and interactions with elementary-school students.

In addition to the strong involvement of PPBio with local communities, the projects developed have influenced public policies. Inspired by PPBio, government agencies, such as IBAMA (Brazilian Institute of the Environment and Renewable Natural Resources), the federal environmental licensing body, and the Brazilian Forest Service, have adopted standardized biodiversity monitoring systems. The EU BON and GEO BON consortia have used PPBio experience in the development of biodiversity monitoring and biological-data management. Also, through bioprospecting, there is the possibility of obtaining products from plant species to increase local communities' incomes. The program also contributed to the Brazilian

Biodiversity Information System (SiBBr) designed by the MCTI to meet the needs for storage and availability of data by all Brazilian researchers working with biodiversity.

The PPBio experience has shown that it is possible to integrate many stakeholders into biodiversity decisions, even when they are not from the academic world. The PPBio does not work alone in these actions as many researchers collaborate in initiatives focused on the conservation and use of biodiversity, such as the Brazilian Platform for Biodiversity and Ecosystem Services (BPEBS).

NEXT STEPS

Despite the many advances since its creation, PPBio faces social, legal, and political restrictions (Magnusson et al. 2018). One of the greatest challenges for maintaining long-term monitoring programs is the lack of guaranteed funding, which has consequences not only for scientific research and biodiversity knowledge but also for conservation (Fernandes et al. 2017; Overbeck et al. 2018). The network and capacity-building activities presently rely on short-term funds raised by individual researchers. Therefore, PPBio requires a strategic funding plan explicitly destined for its maintenance and maintenance of the data it generates. With financial support guaranteed, researchers would be able to focus on major ecological questions, such as the scientific basis for the conservation of the high social and biological diversity typical of tropical and subtropical environments.

Brazil and other signatory countries are far from reaching the 20 targets of the five strategic objectives of the Aichi Goals. Brazil's failure to meet the goals was due to setbacks in environmental protection that started in the years before the COVID-19 crisis, and that

intensified during the pandemic, such as the dismantling of environmental agencies, weakening of environmental legislation, the dismantling of surveillance, among others activities. The PPBio will have to intensify studies of biodiversity to evaluate the impacts caused by environmental deregulation, strengthen local communities through training, and further increase integration by making more data readily available. The program, with its country-wide extent, can contribute to solving many environmental problems. The current site network already allows for the detection of human impacts at different spatial scales. Monitoring data obtained in natural environments can serve as a baseline for the ecological restoration of degraded ecosystems, one of the most important fields for conservation today. Increased extension of the network into anthropogenic landscapes offers the potential to assess and better understand the effects of human land use on biodiversity and ecosystem services, which can then guide conservation and restoration planning. In doing so, it seems promising to include standardized procedures of ecosystem-process analyses (Leidinger et al. 2017) and link ecosystem functioning to biodiversity across Brazil's varied ecosystems.

Among the challenges and future actions, the PPBio network needs to strengthen and consolidate actions by the regional hubs, especially those created recently or in regions with less financial resources. Their consolidation will allow higher permeability of actions at the state and regional levels, allowing sustainable development and reducing social inequities in Brazil. Training human resources (e.g., undergraduates, graduate students, local communities), consolidating and producing new partnerships are the strategies that need to be adopted in the regional hubs.

Scientific activity should be collaborative and science education is essential so that all citizens can participate in decision making. For this reason, PPBio must seek scientific training that allows all the people involved to participate in relevant discussions and social-interest decisions. These are significant challenges for large hyperdiverse countries, such as Brazil, with marked social inequalities, and only an extensive and active network can overcome those barriers.

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SUPPLEMENTARY MATERIAL

Table S1. Location of sites of the Brazilian Program for Biodiversity Research network.

Supplementary Appendix.

Figure S1. Example of a RAPELD grid in the Ecological Station of Cuniã, Amazon.

Figure S2. Example of a RAPELD module in Mato Grosso state, Amazon.

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