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Biases in Amphibian Sampling in the Amazon: Using Infrastructure and Accessibility Data to Identify Sampling Gaps

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Anfíbios amazônicos | déficit wallaceano | macroecologia | padrões de biodiversidade

ABSTRACT

Biogeographic knowledge of Amazonian amphibians is limited by spatial and temporal coverage, resulting in biases that affect the understanding of their diversity patterns. This study analyzed a database of 951 species based on 213,072 georeferenced occurrence records distributed across 24,319 locations in the Amazon. The objective was to identify sampling biases related to infrastructure and accessibility predictors. The overall results indicate that rivers are the primary drivers of amphibian sampling, while roads had a limited influence, reflecting the historical reliance of the region on river transport. Regarding infrastructure, both cities and hydroelectric plants had a moderate effect on sampling, whereas transmission lines had a negligible effect. However, with the expansion of hydroelectric projects from the mid-1970s onwards, intensifying after 2008 with the Brazilian government's Growth Acceleration Plan (PAC), the high volume of records obtained from these ventures distorted the sampling pattern, overestimating rivers and hydroelectric plants while underestimating highways as a source of sampling bias. We conclude, therefore, that amphibian sampling in the Amazon exhibits significant geographic and temporal bias due to unevenly distributed research efforts, which are largely constrained by logistical challenges and inadequate infrastructure. To overcome these challenges, it is necessary to promote collaboration between researchers and decision-makers, invest in research infrastructure, and improve data dissemination. Additionally, we emphasize the importance of conducting a rigorous preliminary evaluation of datasets, particularly when a substantial volume of data are rapidly generated by infrastructure projects such as hydroelectric power plants, to prevent analytical biases and ensure accurate results. These measures aim to strengthen amphibian research and support biodiversity conservation, particularly in response to increasing deforestation and climate change in the Amazon.

RESUMO

O conhecimento biogeográfico dos anfíbios amazônicos é limitado pela cobertura espacial e temporal, resultando em vieses que afetam a compreensão de seus padrões de diversidade. Este estudo analisou um banco de dados de 951 espécies com base em 213.072 registros de ocorrência georreferenciados, distribuídos em 24.319 localidades na Amazônia. O objetivo foi identificar vieses de amostragem relacionados a preditores de infraestrutura e acessibilidade. Os resultados gerais indicam que os rios são os principais condutores da amostragem de anfíbios, enquanto as estradas tiveram influência limitada, refletindo a dependência histórica da região no transporte fluvial. Em relação à infraestrutura, tanto as cidades quanto as usinas hidrelétricas tiveram um efeito moderado na amostragem, enquanto as linhas de transmissão tiveram efeito insignificante. No entanto, com a expansão de projetos hidrelétricos a partir de meados da década de 1970, intensificando-se após 2008 com o Plano de Aceleração do Crescimento (PAC) do governo brasileiro, o alto volume de registros obtidos nesses empreendimentos distorceu o padrão de amostragem, superestimando rios e hidrelétricas e subestimando rodovias como fonte de viés. Concluímos, portanto, que a amostragem de anfíbios na Amazônia apresenta significativo viés geográfico e temporal devido a esforços de pesquisa desigualmente distribuídos, amplamente limitados por desafios logísticos e infraestrutura inadequada. Para superar esses desafios, é necessário promover colaboração entre pesquisadores e tomadores de decisão, investir em infraestrutura de pesquisa e melhorar a disseminação de dados. Além disso, destacamos a importância de realizar uma avaliação preliminar rigorosa de conjuntos de dados, especialmente quando grandes volumes de informações são rapidamente gerados por projetos de infraestrutura, como usinas hidrelétricas, a fim de evitar vieses analíticos e garantir resultados precisos. Essas medidas visam fortalecer a pesquisa sobre anfíbios e apoiar a conservação da biodiversidade, especialmente em resposta ao aumento do desmatamento e às mudanças climáticas na Amazônia.

1 | Introduction

The synergy between technology and conservation enables scientists and conservationists to adopt more effective approaches to biodiversity and ecosystem conservation (Arts et al. 2015; Moreto 2015; Adams 2019; Toivonen et al. 2019; Vargas-Ramírez and Paneque-Gálvez 2019; Sandbrook et al. 2021). Computational modeling has revolutionized our capacity to simulate, analyze, and understand global biodiversity patterns, facilitating the identification and monitoring of species dispersal (Michelot et al. 2016; Borowicz et al. 2019), as well as predict the impacts of human activities and climate change on ecosystems (Hopkins 2007; Santos et al. 2015; Stropp et al. 2020; de Albuquerque et al. 2021; Carvalho et al. 2023). However, the robustness of models depends on the data quality used, which can be affected by data sampling methodologies, evaluation processes, tabulation techniques, and taxonomic identification, among other factors (Hortal et al. 2015; Meyer et al. 2016). Therefore, the gaps and biases constantly present in biodiversity data pose substantial risks to the accuracy of ecological interpretation. Ignoring these discrepancies may lead to misleading interpretations about biodiversity patterns and dynamics (Boakes et al. 2010; Martin et al. 2012; Beck et al. 2014; Hortal et al. 2015; Gueta and Carmel 2016; Anderson et al. 2020; Hughes et al. 2021).

One of the most important barriers to understanding biodiversity distributions is geographical sampling shortcomings, known as the Wallacean shortfall (Hortal et al. 2015). This occurs when some regions are sampled more extensively than others, resulting in uneven knowledge of biodiversity across geographic space (Boakes et al. 2010; Martin et al. 2012; Amano and Sutherland 2013; Hortal et al. 2015; Pelayo-Villamil et al. 2018; Hughes et al. 2021; Tessarolo, Ladle, et al. 2021; Tessarolo, Lobo, et al. 2021; Zizka et al. 2021; Castro-Souza et al. 2024). Inaccessibility of remote areas, which is common in the Amazon, due to a lack of infrastructure such as roads and cities, or even legal restrictions, such as bureaucratic hurdles to accessing Indigenous lands, may contribute to biases in data collection (Santos et al. 2015; Carvalho et al. 2023). In addition, biases related to accessibility and the tendency to study charismatic groups (e.g., mammals and birds, Troudet et al. 2017) or easily identifiable species can lead to an underestimation of the real diversity (Diniz-Filho et al. 2010; Theobald et al. 2015; Amano et al. 2016; Oliveira et al. 2016; Troudet et al. 2017; Hughes et al. 2021). Therefore, this is one of the reasons why the distribution of some taxa continues to be neglected, contributing to knowledge biases in mega-diverse regions such as the Amazon (Carvalho et al. 2023).

The Amazon hosts the world's largest tropical forest (Vale and Jenkins 2012; Malhado et al. 2013; Santos et al. 2015) comprising approximately 20% of the planet's terrestrial diversity (Peres et al. 2023) and has contributed to the extensive exchange of evolutionary lineages among different regions over tens of millions of years (Antonelli et al. 2018; Guayasamin et al. 2024). Consequently, it plays a fundamental role in maintaining biodiversity, ecosystems, and regulating global climate (Garda et al. 2010; Aragón 2018; Tigre 2019). However, the knowledge about Amazonian biodiversity is still insufficient and influenced by biases and sampling gaps (Hopkins 2007; Santos et al. 2015; Stropp et al. 2020; de Albuquerque et al. 2021; Carvalho et al. 2023), especially for more taxonomically complex and less charismatic groups such as amphibians (Guerra et al. 2020; Fouquet et al. 2021). The spatial shortcomings in understanding lead to ineffective public policies for the conservation of Amazonian biodiversity and the correlated ecosystem services.

Amphibians are one of the three taxa with the greatest species richness among terrestrial vertebrates (AmphibiaWeb Team 2023). This taxon is characterized by a high rate of endemism, particularly in the Amazon, where approximately 82% of amphibian species are endemic (Vacher et al. 2020; Penhacek et al. 2024). Alarmingly, amphibians also face the highest extinction risk among vertebrates, with approximately 41% of their species at risk (Amaral et al. 2019; Luedtke et al. 2023). Furthermore, amphibians are recognized as important indicators of environmental change (Toledo 2009; Becker et al. 2010; Amaral et al. 2019), due to their high vulnerability to climate change and landscape modification (Amaral et al. 2019; Luedtke et al. 2023), making them an important study model for understanding the consequences of anthropogenic and climatic changes on the distribution of Amazonian biodiversity.

Historically, amphibian sampling in the Amazon has been concentrated along the Amazon River, with gradual expansion into its tributaries (Santos et al. 2015; Andrade-Silva et al. 2022). In this context, navigable rivers are significant predictors of accessibility and have contributed to increased knowledge of regional biodiversity across several taxonomic groups (Santos et al. 2015; Oliveira et al. 2016; Alvez-Valles et al. 2018; de Albuquerque et al. 2021; Andrade-Silva et al. 2022; Carvalho et al. 2023). Although highways also exert a strong influence on biodiversity knowledge (Oliveira et al. 2016; Andrade-Silva et al. 2022), their presence in the Amazon remains relatively recent and limited.

Another relevant factor is the “museum effect” (Ponder et al. 2001), a bias stemming from the proximity of scientific collections to research institutions, driven by logistical and practical considerations (Werneck et al. 2011). This effect leads to the undersampling of protected and remote areas (Alvez-Valles et al. 2018; Daru et al. 2018; Andrade-Silva et al. 2022). On the other hand, infrastructure projects—including hydroelectric dams and transmission lines—have expanded into vast and often remote regions of the Amazon since the 1970s (Fearnside 1989; Instituto Socioambiental [ISA] 2016). Among the first major hydroelectric projects were the Coaracy-Nunes Dam (1975, Amapá) and the Curuá-Una Dam (1977, Pará), followed by the controversial 1980s projects Tucuruí (1984) and Balbina (1989), notable for their socio-environmental costs (Fearnside 1989, 2005, 2015; Zhouri 2010). From the 2000s onward, Brazil's Growth Acceleration Program (PAC) spurred a new wave of projects, including the Madeira River Complex (Santo Antônio and Jirau, operational between 2012 and 2013), Belo Monte on the Xingu River (operational since 2016), and the Teles Pires Complex (Colider, Teles Pires, São Manoel, and Sinop, operational between 2015 and 2018). Due to their substantial socio-environmental impacts, such projects have been required, under regulations such as Normative Instruction no 146 (IBAMA 2007) to implement comprehensive research and monitoring programs, generating extensive biodiversity datasets—though critics argue these measures often fail to mitigate irreversible environmental damage (ISA 2020; Finer and Jenkins 2012).

Nevertheless, despite the socio-environmental impacts caused by these projects, they also represent potential predictors of the quality and scope of biodiversity knowledge in the region. Therefore, in this study, we analyze the spatial and temporal distribution of amphibian sampling in the Amazon, assessing how accessibility (rivers and roads) and infrastructure (cities, hydroelectric dams, and transmission lines) influence geographical biases in amphibian knowledge. Given the vast territorial extension of the Amazon region, combined with its structural and environmental complexity, we postulate that accessibility variables, initially navigable rivers and later roads, primarily determine the spatial distribution of sampling effort. Structural variables, such as cities (CIT)—particularly regional hubs that host research institutions; hydroelectric projects (HPP)—including large hydroelectric plants and small hydroelectric plants; and power transmission lines (PTL), act as later secondary predictors. Thus, the biases and gaps identified here may indicate similar sampling biases in the geographic knowledge of biodiversity for other Amazonian terrestrial taxa, thereby guiding future biodiversity research and conservation actions.

2 | Materials and Methods

2.1 | Study Area

The study covered all the Amazonian boundaries proposed by the WWF (WWF 2019). Located in northern South America, the Amazon basin covers an area of approximately 6.5 million km^2 and includes nine countries: Bolivia, Brazil, Colombia, Ecuador, Guyana, French Guiana, Peru, Suriname, and Venezuela (WWF 2019; Tigre 2019). Although its vast territory encompasses approximately 50% of all remaining tropical rainforests on the planet, the region also encompasses limited areas of non-forest vegetation, such as savannas and seasonally flooded grasslands (Schulman et al. 2007; Peres et al. 2010; Castuera-Oliveira et al. 2020). The Amazon basin holds the largest reserves of liquid freshwater, with more than 7000 tributaries and about 20% of the world's freshwater flow (Tigre 2019), which also serve as important transport routes and accessibility. Regarding mineral resources, the region has attracted global attention for its vast reserves of aluminum, iron, niobium, and gold, among others. Mineral extraction affects traditional communities, indigenous peoples, and biodiversity (de Mello 2013), due to road construction (Laurance et al. 2009) and mining-related infrastructure (Siqueira-Gay et al. 2020). Additionally, the vast expanse of arable land and high rainfall have led to a significant expansion of agribusiness, resulting in forest fragmentation, soil, air, and water pollution, posing threats to biodiversity and ecosystem services (Fearnside 2015).

We built a robust dataset of anuran occurrence in Amazon. First, we utilized the database compiled by Penhacek et al. (2024). This database was constructed from four primary sources (Figure 1A): (I) digitally accessible data platforms—GBIF, SiBBr, SISBIO, SpeciesLink, and VertNet. In this phase, all available data for the class Amphibia and Lissamphibia in South America were downloaded between January and February 2022, (II) peer-reviewed articles—searches were conducted on AmphibiaWeb (https://amphibiaweb.org/amphibian/newspecies.html), Google Scholar (https://scholar.google.com.br/?hl=pt), and Web of Science (https://www.webofknowledge.com) using the keywords “Amphibia” AND “Amazon” AND “Checklist” OR “Herpetofauna” OR “New Record” OR “New Species”. This step compiled data from 150 scientific articles published in indexed journals that describe new species, expand known spatial distribution ranges, or provide species checklists, including descriptions

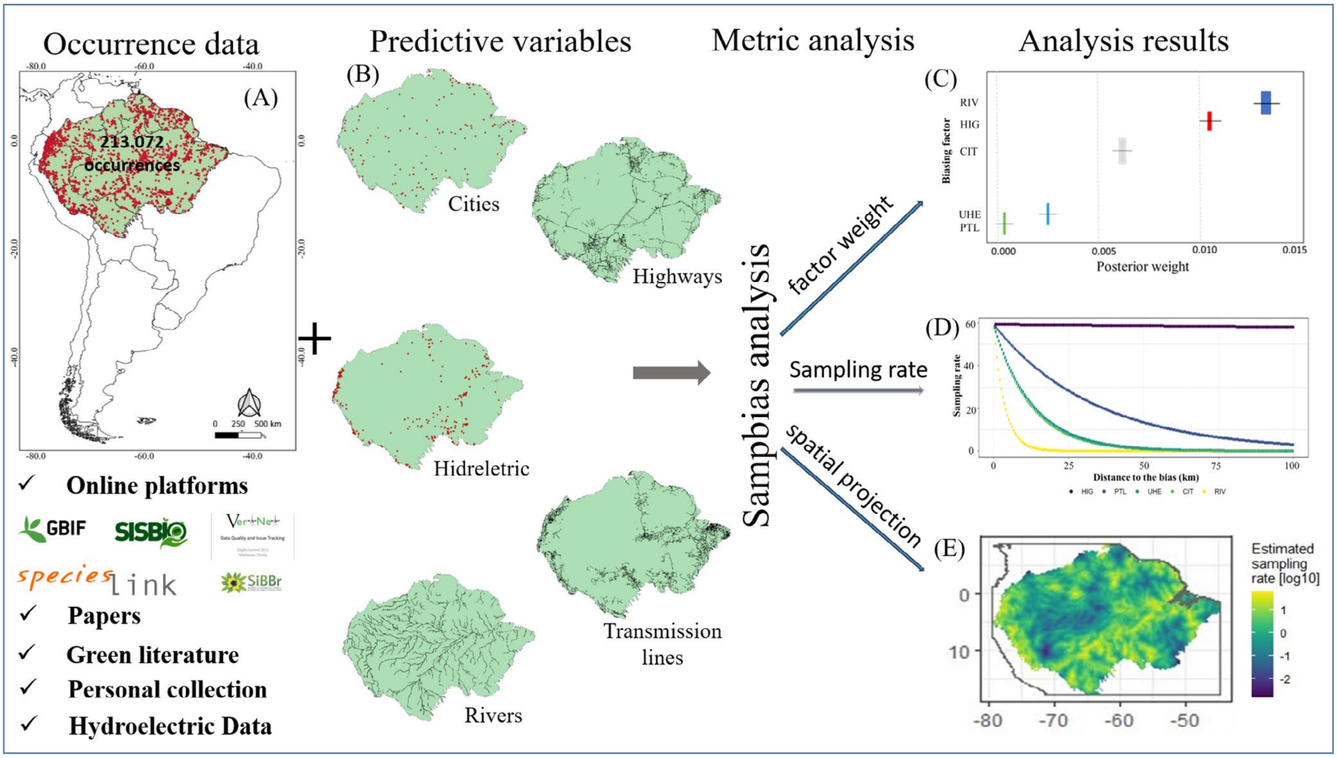

FIGURE 1 | Methodology for evaluating accessibility and infrastructure drivers in Amazonian amphibian sampling biases. Occurrences of amphibian records in the Amazon (A); predictive variables: cities, rivers, hydroelectric plants, roads, and transmission lines (B); weights of variables in sampling bias (C); sampling rate as a function of distance for each variable (expected number of occurrences) (D) and spatial projection of the combined bias effect from accessibility and infrastructure variables (E).

of sampling locations with geographic coordinates (Penhacek et al. 2024—supporting information 3, https://doi.org/10.3897/BDJ.12.e109785), (III) Gray literature, including technical reports from Environmental Impact Assessments (EIA) and Environmental Impact Reports (RIMA), as well as records from the rescue and monitoring efforts of amphibians at four hydroelectric power plants (UHEs) in the Amazon (Penhacek et al. 2024—supporting information 3, https://doi.org/10.3897/BDJ.12.e109785), (IV) Original data, comprising the authors' personal collections over 15 years (2007–2022) in the southern Brazilian Amazon. A total of 902,986 primary amphibian records were compiled at this stage (Penhacek et al. 2024—supporting information 5, https://doi.org/10.3897/BDJ.12.e109785).

After compiling the database, it underwent a filtering and validation process. First, records that were not taxonomically refined to the species level were excluded, such as those classified only at the family level, genus (sp.), species group (gr.), related species (aff.), or species yet to be confirmed (cf.). In this process, approximately 220,000 records were removed, highlighting a significant Linnaean shortfall (Hortal et al. 2015) in amphibian records currently available for the Amazon. In the next step, an additional filter was applied to exclude all records lacking geographic coordinates, resulting in the removal of approximately 356,000 occurrences. Subsequently, the remaining occurrences were plotted on a map showing the study area boundaries, and occurrences outside the limits of the Amazon were excluded, leading to the removal of approximately 165,000 records. Finally, the remaining records were taxonomically updated by consolidating synonyms and adopting the most recent valid species names according to Frost (2024). The final database comprised 160,643 primary records, encompassing 948 species distributed across the Amazon (available in Penhacek et al. 2024—supporting information 5, https://doi.org/10.3897/BDJ.12.e109785).

To this database, we added 52 529 records from 98 species collected between 2011 and 2019 during monitoring and rescue programs at four HPPs: Colíder, São Manoel, Sinop, and Teles Pires. These data were obtained from the respective licensing agencies: the Mato Grosso State Secretariat for the Environment (SEMA-MT) for Colíder and Sinop HPPs, and the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA) for São Manoel and Teles Pires HPPs. Thus, the final database has 213,072 primary records from 24,319 sampling points on the Amazon, encompassing 951 species (Penhacek et al. 2025).

2.2 | Accessibility and Infrastructure Variables

To understand the drivers (Figure 1B) of bias in amphibian sampling, we used five explanatory variables (drivers) related to accessibility: (i) distance to navigable rivers (RIV), (ii) distance to highways (HIG) and (iii) distance to infrastructure cities (CIT), (iv) distance to UHE, and (v) distance to PTL. We used data from the HydroRIVERS database, specifically focusing on rivers classified within the first five levels of magnitude based on water flow capacity (Lehner and Grill 2013).

For highways, we considered federal, state, and/or municipal highways obtained from the Center for International Earth Science Information Network (2013), the Rede Amazônia de Informação Socioambiental (RAISG 2023), and the Instituto Brasileiro de Geografia e Estatística (ISA 2016). We also used information from the following sources: (i) Cities (143 cities, towns, and villages) that are considered regional urban reference centers and that provide infrastructure to support biodiversity research, obtained from Natural Earth Data (Natural Earth 2023–supporting information 1), (ii) Hydroelectric Power Plants (HPPs = 312 hydroelectric power plants, HPPs and small hydropower plants—SHPPs) under construction and/or in operation, obtained from the Amazon Network of Georeferenced Socio-Environmental Information—RAISG (2023), and (iii) PTLs, sourced from Arderne et al. (2020). These shapefiles were incorporated into vector files with a resolution of 0.05° (5 × 5 km in Equator), containing points representing cities and HPPs/SHPPs, and lines representing the PTLs.

2.3 | Data Analysis

To assess the influence of accessibility and infrastructure on amphibian sampling, we used the Bayesian analysis proposed by Zizka et al. (2021). This analysis compares the statistical distribution of observed distances (actual occurrences) with a null model (expected distribution simulated by random sampling). Initially, we evaluated the weight of each driver, indicating the intensity of the bias generated by the presence of each driver in the study area (Figure 1C). We then calculated the correlation between sampling (number of known amphibian occurrences per grid) and distance (km) for each bias-inducing variable within the study area (Figure 1D).

Finally, we created a spatial projection map that illustrates the combined effects of accessibility and infrastructure variables on the estimated sampling of amphibian occurrence records. This map highlights the regions where these variables have a greater effect on sampling bias, indicating areas that are oversampled (Figure 1E). In this context, we measured the effect based on the variable with the highest bias, combining it in descending order with the other variables. These approaches allow us to comprehend the relative influence of different bias-inducing variables on the sampling of amphibians and spatially project their combined effects. This is crucial for better understanding the distribution and representativeness of amphibian occurrence records in the Amazonia, as well as for identifying areas where sampling effort needs to be optimized.

2.4 | Sampling Bias Sensitivity Analysis Over Time

Since some records were compiled before the creation of accessibility and infrastructure predictors, we conducted a temporal sensitivity analysis by dividing the dataset into three distinct periods: (1) pre-1975, (2) 1975–2008, and (3) post-2008. For the pre-1975 period—when no hydroelectric plants had yet been constructed in the Amazon—the analysis was restricted to three existing variables: navigable rivers (RIV), highways (HIG), and cities (CIT), allowing us to assess sampling bias in a historical context prior to major infrastructure interventions.

For subsequent time frames (1975–2008 and post-2008), we progressively incorporated additional predictors (including UHE and PTL) to reflect infrastructure expansion under Brazil's Growth Acceleration Plan (PAC). Finally, we developed an overarching model covering the entire temporal scope of the database (from the 19th century to recent years); though we excluded records from hydroelectric power plants fauna monitoring and rescue programs to prevent overrepresentation of locations near major projects—A crucial step to minimize distortions from sampling effort concentrated near these developments.

All analyses were carried out in the R program (R Core Team 2022). Sampbias biases were analyzed using the sampbias package (Zizka et al. 2021). QGIS 3.4 software (Free 2023) was used to create all cartographic projections, including the bias maps.

3 | Results

3.1 | Amphibian Sampling Distribution in the Amazon

The extensive database compiled here, comprising 213,072 occurrence records, revealed a sampling effort concentrated in recent decades, peaking in the 2000s and 2010s, demonstrating a strong temporal bias in amphibian sampling across the Amazon (Figure 2). Biogeographic projections also highlighted an uneven sampling distribution, with over-sampled (biased) regions primarily in the central-east, south-west, and west, and under-sampled regions (knowledge gaps) in the central-west, south-east, and north, indicating pronounced geographic bias for this taxon in the region (Figure 3).

3.2 | Geographic Sampling Bias

Preliminary evaluation of our database revealed distortions in overall sampling patterns due to the inclusion of data obtained directly from hydroelectric plants. To mitigate this, 74,548 records from wildlife monitoring and rescue programs at five Amazonian dams were excluded from the broad-scale analysis. However, we retained all publicly available data from online platforms, peer-reviewed literature, gray literature, and personal records deposited in scientific collections, spanning 1818 to 2022. Data from hydroelectric plants were included only for post-2008 historical analyses (see Section 2.4).

The general analysis showed that RIV had the strongest effect on sampling bias, followed by HIG, CIT, and UHE, while transmission lines (PTL) had a marginal impact (Figures 4 and 5). Approximately 80% of samples were concentrated within 120 km of navigable rivers compared to 220 km from highways, 290 km from cities, and over 450 km from hydroelectric plants and transmission lines (Figure 4B).

The data further revealed uneven sampling, with over-sampled (biased) and under-sampled (knowledge gap) regions (Figure 6).

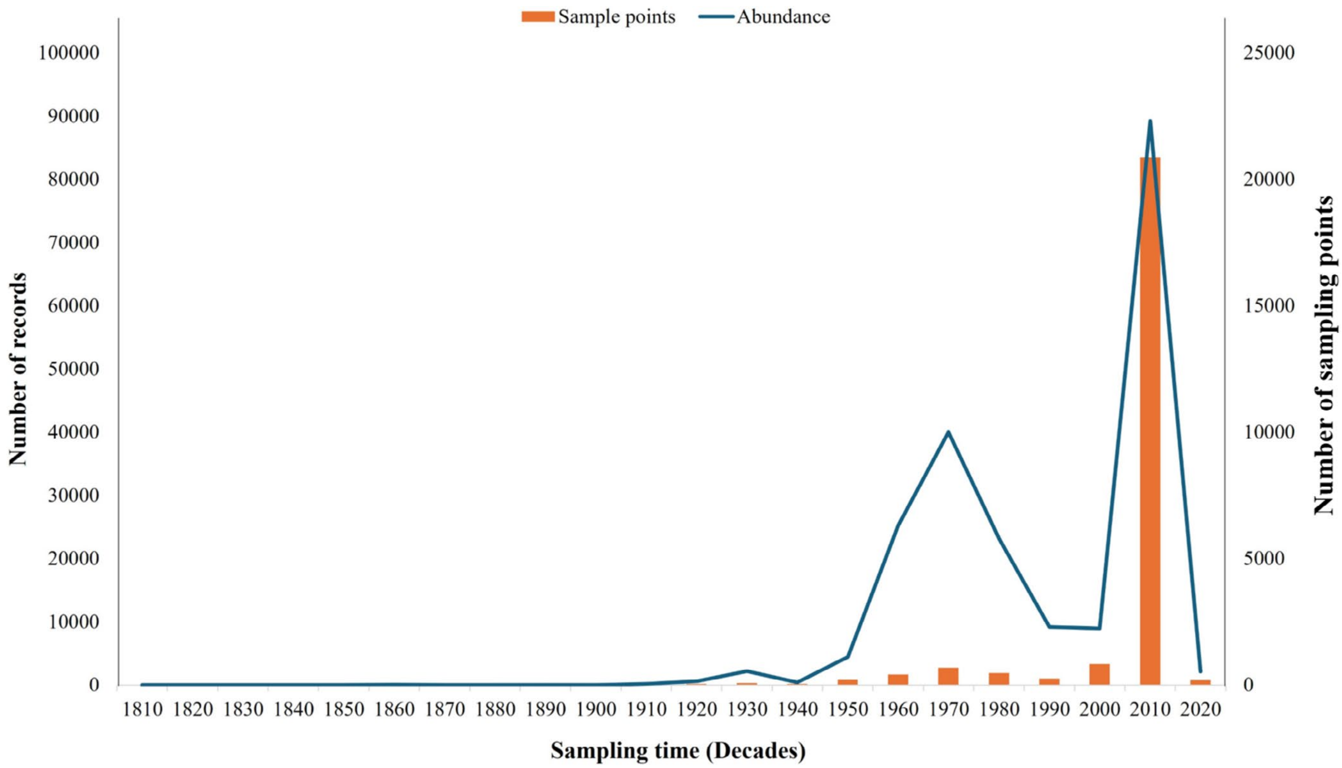

FIGURE 2 | Cumulative distribution by decade of the 213,073 occurrence records for 951 amphibian species in the Amazon recorded between the years 1818–2022.

Over-sampling was pronounced in the South-West and West Amazon, particularly near the Andes Mountains (southern Peru to northern Ecuador). In the Brazilian Amazon, biases were evident in the Madeira River basin (Rondônia) and the upper/lower Tapajós River basins (Mato Grosso and Pará, respectively). Other biased areas included the Tocantins River (Maranhão), Branco River (Roraima), and along the Amazon River (from the Negro-Solimões confluence to its Atlantic estuary). In Colombia, bias was detected in the south-east (Vaupés Department), while in Guyana, it occurred in the Berbice and Essequibo River basins. Additional biases were observed in north-west and eastern French Guiana, north-west Suriname, and northern Venezuela (Figure 6).

Conversely, vast areas of the Amazon remain under-sampled, representing "Biodiversity Blind Spots" (sensu Ball et al. 2025)—regions lacking data collection, digitisation, or publication. These gaps are widespread but concentrated in: Brazil: central-west and west (between the Negro and Purus River basins), south-east (middle/upper Xingu River), East Maranhão, and North (Amapá, Roraima, and Pará); Bolivia: Central and eastern regions; Peru: Eastern lowlands; Colombia: Central, northern, and southern regions and: Smaller gaps occurred in southern Suriname, French Guiana, and north-west Venezuela (Figure 6).

3.3 | Temporal Sampling Bias

Our temporal assessment of the dataset revealed a strong reversal in the effect of bias variables on amphibian sampling across historical periods in the Amazon (Appendix S1). Pre-1975: HIG were the most influential variable, followed by CIT and, to a lesser extent, navigable RIV (Figures S1 and S3). 1975–2008: The inclusion of hydroelectric projects (UHEs) in the Amazon shifted sampling efforts, elevating rivers as the primary bias variable, followed by cities and the hydroelectric plants themselves, while highways lost influence (Figures S4 and S6). Post-2008: The rapid expansion of hydroelectric projects in the Amazon, combined with data from wildlife monitoring programs, further altered sampling bias patterns. Rivers became overrepresented, hydroelectric plants surpassed highways and cities in influence, transmission lines and cities had reduced effects, and highways became negligible (Figures S7 and S9).

4 | Discussion

We identified significant biases related to amphibian sampling over time, taxonomic resolution, digitization, and public accessibility. A primary challenge is the frequent absence of geographical coordinates, which hinders precise georeferencing and limits our understanding of species distribution patterns (Hortal et al. 2015; Anderson et al. 2020; Stropp et al. 2020; Lima et al. 2023; Penhacek et al. 2024; Ball et al. 2025). Although our database encompasses over 11% of globally described amphibian diversity (Frost 2024), comprising more than 213,000 occurrence records, it represents just 20% of available data for Amazonian amphibians (Penhacek et al. 2024). This limitation stems primarily from the "Wallacean shortfall" (Lomolino 2004; Hortal et al. 2015), characterized by missing georeferencing in specimen records from biological collections (Stropp et al. 2020; Araújo et al. 2022; Lima et al. 2023), often resulting from failures to record coordinates during fieldwork.

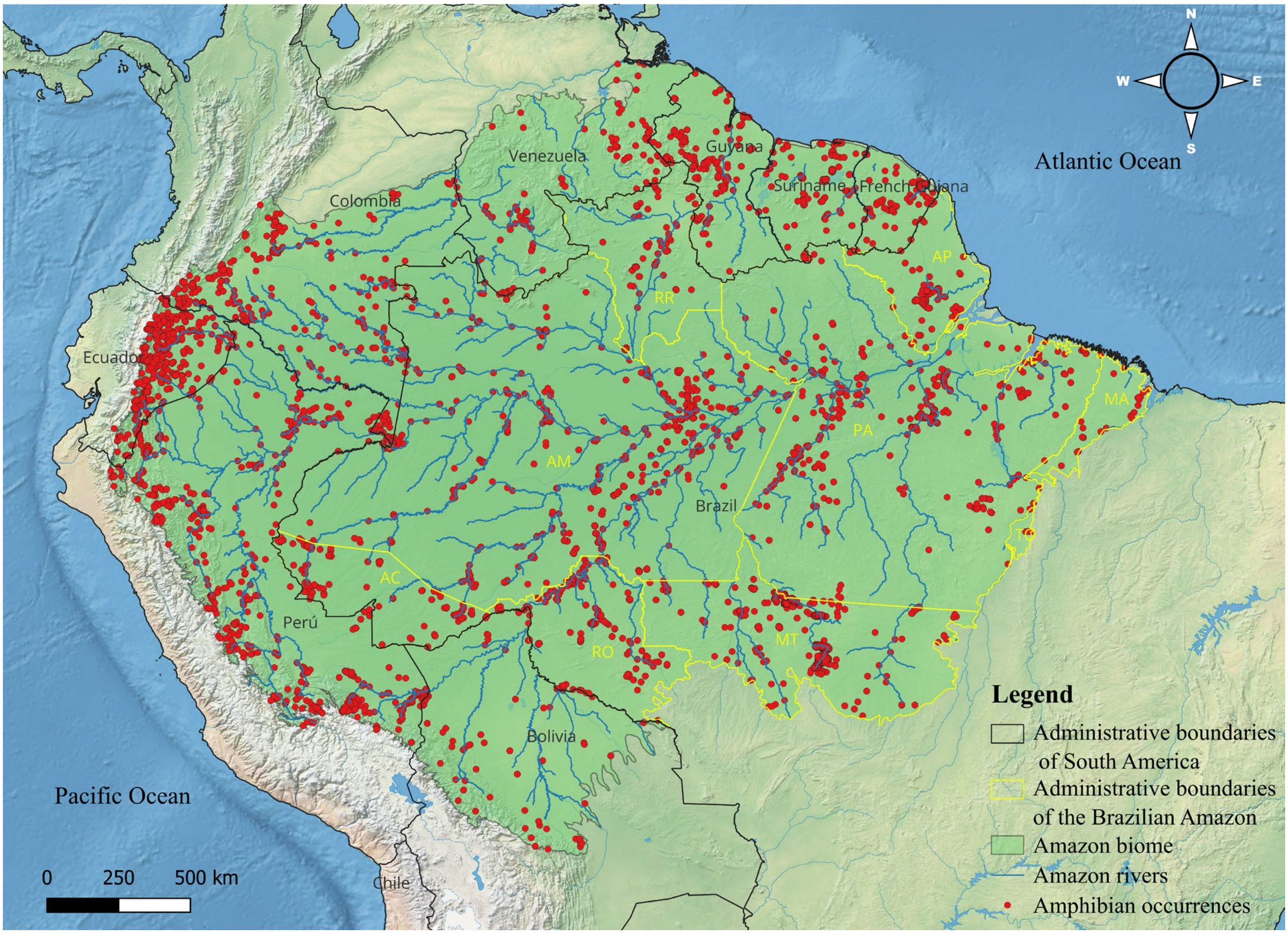

FIGURE 3 | Distribution of the 24,319 amphibian sampling points in the Amazon delimited according to WWF (2019).

A potential solution for utilizing non-georeferenced records involves computational approaches, such as the geographical dictionaries implemented in the plantR package (Lima et al. 2023), which enable coordinate recovery, correction, and validation. However, its effectiveness depends on sufficiently detailed textual descriptions of collection localities, which are often inadequate. An additional challenge is the "Linnean shortfall" (Brown and Lomolino 1998; Hortal et al. 2015), exacerbated by the Amazon's high diversity of cryptic species (Funk et al. 2012; Lima et al. 2023) and insufficient investment in taxonomic research and regional specialists (Lawton et al. 1998; Magurran and Queiroz 2010).

Even with the robust and extensive database used in this study, we observed that the Amazon has not been adequately sampled across all its regions. While we identified sampling concentrations in some areas, particularly along the western edges of the Peruvian and Ecuadorian Amazon, and near major rivers such as the Amazonas, Madeira, Tapajós, and the lower Xingu, among others, there are vast regions that are poorly sampled or entirely overlooked. These areas can be characterized as "biodiversity blind spots," according to Ball et al. (2025), and are distributed throughout the Amazon, with particular emphasis on the southeastern and central-western regions of the Amazon (Figure 6).

The vast territory of the Amazon, often surrounded by dense, nearly inaccessible forests, presents challenges for conducting biological surveys. This increases the sampling deficit "Wallacean deficits" (Lomolino 2004), leading to a concentration of sampling in easily accessible areas, population centers and areas of high interest such as parks and ecological reserves, while hard-to-reach areas are neglected, creating gaps in our understanding of biodiversity patterns (Teixido et al. 2020; Carvalho et al. 2023; Camacho-Rozo and Urbina-Cardona 2024). Overcoming these obstacles will require coordinated efforts, investments in research and monitoring, and the commitment of countries to the United Nations Sustainable Development Goal 15 ('Life on Land') of the 2030 Agenda for Sustainable Development, aiming at the conservation and sustainability of the region (ONU BR 2015).

Our results revealed significant sampling biases for Amazonian amphibians related to accessibility variables (especially rivers) and urban and industrial infrastructure. As expected, medium-sized and large rivers are the most important factors in amphibian sampling across the Amazon. Similar results have been observed for different taxonomic groups studied in the Amazon, including plants (Hopkins 2007; Stropp et al. 2020; Araújo et al. 2022), ants (de Albuquerque et al. 2021) and multi-taxa (Santos et al. 2015; Oliveira et al. 2016; Carvalho et al. 2023). Despite the differences

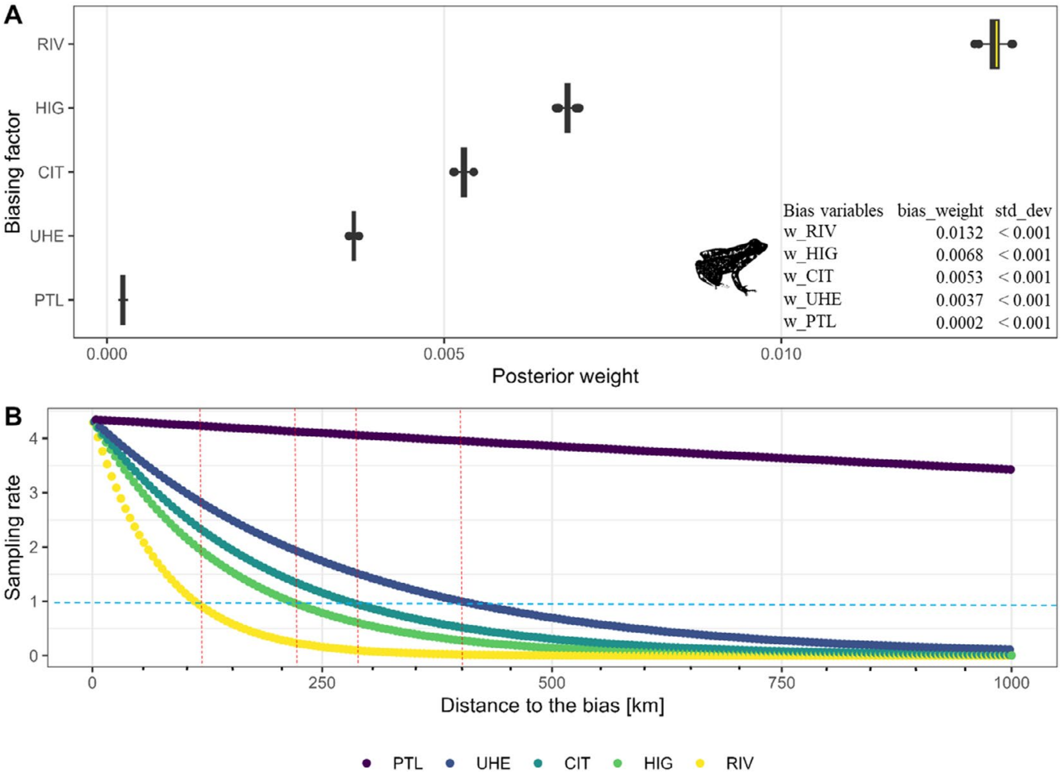

FIGURE 4 | Bias in amphibian occurrences in Amazonia related to accessibility and infrastructure variables. The bias weights (*w*) represent the influence of each bias variable, and the Factor Bias refers to the specific variable evaluated (A). Sampling rate as a function of the distance to the closest point of each bias variable (the expected number of occurrences) given the inferred sampbias model (B). At the study scale of 0.05° (about 5 × 5 km), sampbias identified the strongest polarization effect in proximity to rivers, highways, cities, hydroelectric plants, and transmission lines, respectively.

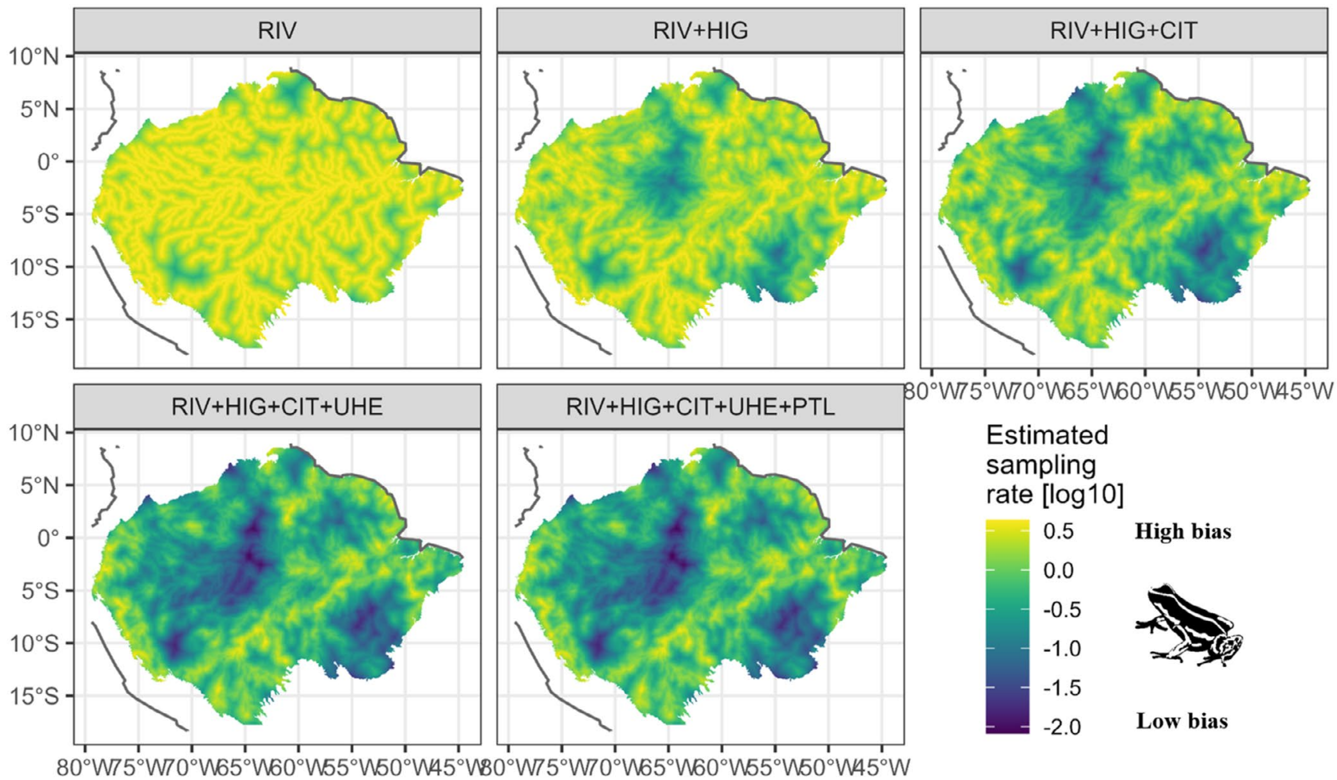

FIGURE 5 | Cumulative effect of bias source variables on amphibian sampling rates in the Amazon for accessibility and infrastructure variables, based on data from 1818 to 2022. CIT, cities; HIG, highways; PTL, power transmission lines; RIV, rivers; UHE, hydroelectric plants.

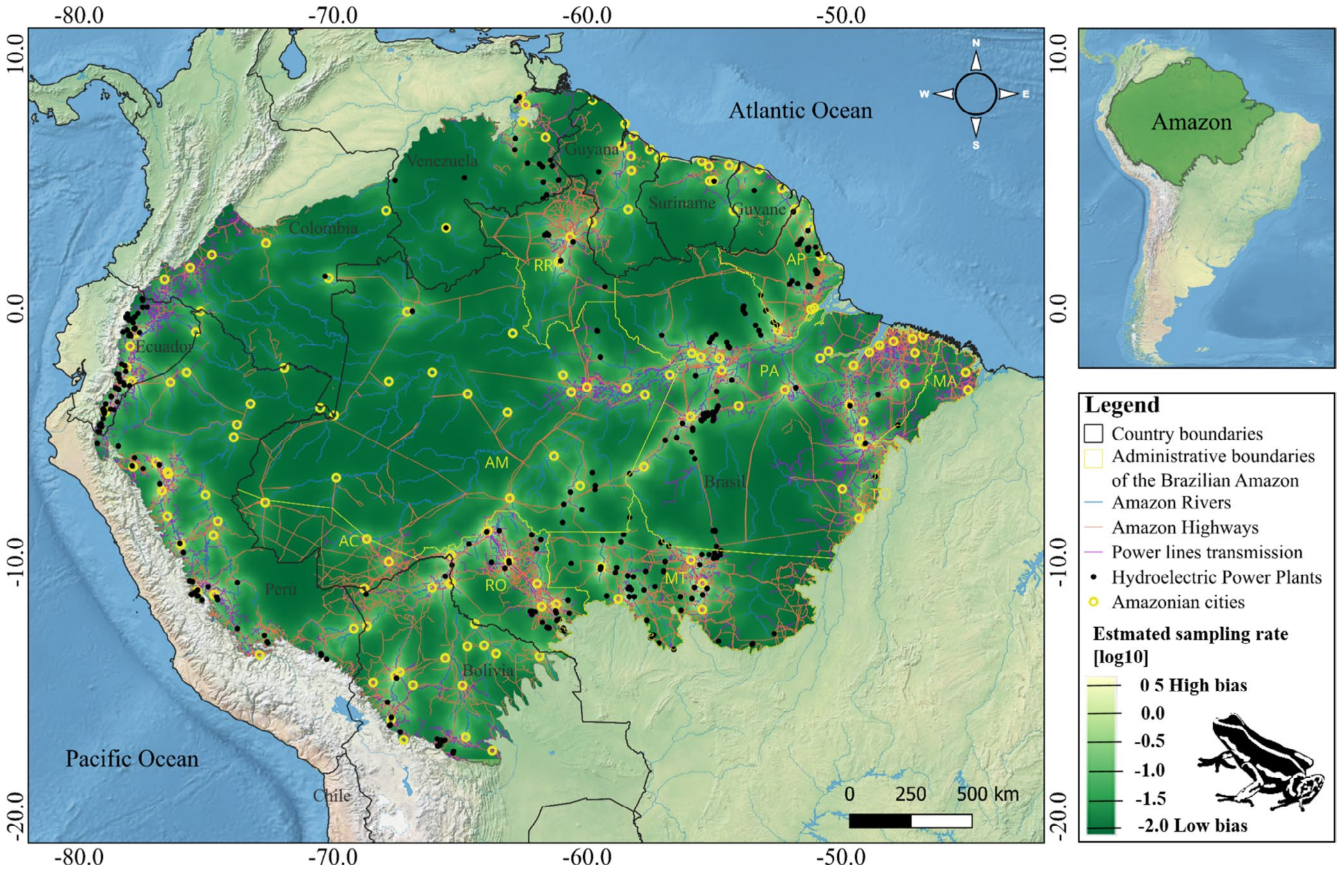

FIGURE 6 | Spatial variation in amphibian sampling intensity across the Amazon basin. Colors show the projection of log10-transformed sampling rates (i.e., number of sample occurrences per cell) when compared to null (stochastic) models. Values close to −3 indicate undersampled areas (gaps), while those near 1 indicate oversampled (biased). AC, Acre; AM, Amazonas; AP, Amapá; MA, Maranhão; MT, Mato Grosso; PR, Pará; RA, Roraima; RO, Rondônia; TO, Tocantins. Separate effects of the variables can be seen in Figure S1.

between taxonomic groups, well-sampled areas are consistently those close to rivers and cities. These biases may hinder our understanding of the distribution patterns of Amazonian biodiversity (Daru and Rodriguez 2023).

Due to the recent surge in road paving and construction projects across the Amazon, along with the consequent need for fauna surveys and impact assessments, we initially believed that highways could be predominant drivers of sampling bias, as observed in different taxonomic groups such as arthropods, vertebrates, and angiosperms (Oliveira et al. 2016; Andrade-Silva et al. 2022). However, investments in infrastructure in the interior regions of the Amazon are still relatively recent and sporadic (Araújo et al. 2023). Historically, rivers have been and remain the main means of transportation in the Amazon (Hernández-Fontes et al. 2021), especially in low-lying areas and along wide rivers. In these regions, road construction is significantly hindered by river flooding and soil types, creating substantial obstacles to travel during the rainy season. However, during this period, there is an increase in the vocalization, foraging, and mating activities of amphibian species (Ferrão et al. 2024). This leads herpetologists to prefer sampling during this time, due to the higher local aggregation of species and the increased efficiency in recording amphibian species richness (Ferrão et al. 2024). Therefore, river accessibility is fundamental to reaching remote areas of the Amazon, enabling the cataloging of species from these locations (Carvalho et al. 2023, This study).

The distance from cities (Carvalho et al. 2023) and Hydroelectric Power Plant (Dayrell et al. 2021) is also considered a driver of biodiversity sampling in the Amazon. However, in this study, the effect of these variables was smaller compared to that of navigable rivers and highways (Figure 4). Cities that act as regional hubs, such as those evaluated, tend to have better infrastructure, including airports, bus terminals, and research centers such as universities. Consequently, the number of researchers and research activities near these cities is typically higher, as observed by Hopkins (2007). Furthermore, sampling in remote and hard-to-reach locations is discouraged due to the high logistical costs and the limited financial resources allocated per km^2 in the Amazon, especially in Brazil (Fernandes et al. 2017; Barlow et al. 2018; Magnusson et al. 2016; Magnusson et al. 2018; Carvalho et al. 2023).

The construction of HPPs and SHPPs has significantly intensified in the Amazon over the past three decades (Brasil 2024). Due to their impacts on fauna and flora, and considering the high number of projects to be implemented in the Amazon (Cavalcante et al. 2021; Dayrell et al. 2021), the Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA) approved a normative instruction (IN 146, dated January 10, 2007). This regulation establishes the necessity for standardized monitoring criteria to assess potential impacts on biodiversity (MMA 2016). As a result, a large amount of data on biodiversity has been produced in recent years (e.g., Ávila and Kawashita-Ribeiro 2011; Vaz-Silva et al. 2015; Dayrell et al. 2021). These databases have significant potential for cataloging species and ecological data in previously unexplored or difficult-to-access regions, with considerable potential to fill gaps in our knowledge about biodiversity. However, a large portion of the data obtained during these projects is not adequately available, making it difficult for scientists and decision-makers to obtain and/or use it (Penhacek et al. 2024). Therefore, the correct identification and deposition of specimens in scientific collections, the standardization of collected data, and the dissemination of results as species lists by environmental agencies would improve the accessibility and usefulness of this information for researchers and environmental managers, thereby enhancing the effectiveness of decision-making and conservation efforts.

Is need caution when using data with large time intervals for current projections, as observed in our temporal analysis (Appendix S1). Although the general pattern of sampling bias has remained robust over historical time (Figures S3, S6, and S9), the weight of bias variables has reversed over time (Figures S1, S4, and S7). The excessive volume of data generated by the expansion of hydroelectric projects in a short period (e.g., 74,573 occurrence records collected between 2009 and 2022 from just five hydroelectric plants) introduced significant biases. Since hydroelectric plants are typically built in remote areas, far from roads and urban centers—to avoid flooding issues caused by reservoir formation—and since their biodiversity data are predominantly collected near rivers, their inclusion in our analysis overestimated the influence of rivers and underestimated the effect of roads and cities as sampling bias variables for Amazonian amphibians.

Our results also revealed regional variation in the effect of drivers contributing to sampling bias. Although rivers have shown the greatest influence on sampling biases across the Amazon, extensive sampling gaps remain in areas with high river density, particularly along the middle and upper Xingu basin in the southeastern Amazon, and in the basins of the Coari, Jutaí, Juruá, Napo, Solimões, Purus, and Putumayo rivers, among others, in the central-western Amazon region (Figure 6). This may arise from access barriers, such as the presence of Indigenous Lands that have restrictive laws on researcher access (Little 2005; Santos et al. 2015). Therefore, in each Amazonian subregion, different ecological and human factors—or their combination—may predominantly influence amphibian sampling rates.

Finally, this study revealed the predominance of a robust pattern in amphibian sampling across the Amazon, regardless of the temporal scope assessed (Figure 6; Figures S3, S6, and S9), highlighting gaps and challenges in biogeographic data collection and analysis. These biases, driven by proximity to navigable rivers, roads, urban centers, and hydroelectric plants, affect the interpretation of species distribution patterns and limit the usability of data for predictive modeling—a crucial tool for biodiversity conservation planning. Furthermore, they hinder our understanding of species dispersal, spatiotemporal occupancy patterns, and the impacts of human activities and climate change on biogeographic patterns. Thus, the identification of under-sampled regions, particularly in the southwestern and central-western Amazon, underscores the need for targeted efforts to fill these gaps, aiming for a more comprehensive and accurate representation of amphibian diversity in the region. Such initiatives are urgently needed in the face of growing threats from deforestation and climate change to Amazonian biodiversity.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data supporting the findings of this study are openly available at Mendeley Data, V1, doi: https://doi.org/10.3897/BDJ.12.e109785.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Appendix S1:** btp70079-sup-0001-AppendixS1.docx.