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Taxonomic Catalog of the Brazilian Fauna: Hydraenidae (Insecta: Coleoptera), diversity and distribution

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ABSTRACT. Taxonomic data about Brazilian hydraenids are currently available open access at the Taxonomic Catalog of the Brazilian Fauna (Catálogo Taxonômico da Fauna do Brasil – CTFB) website, an online database with taxonomic information on the animal species occurring in Brazil. Based on taxonomic contributions published until September 2023, a total of 34 valid Hydraenidae species have been recorded from Brazil, 27 (79%) of which are endemic. Foreign authors have dominated the description of Brazilian Hydraenidae species (eight out of 10), and Dr. P.D. Perkins from the United States has authored the highest number of species described from Brazil (20). While the primary type specimens of species described from Brazil are predominantly deposited in non-Brazilian institutions (65%), the collection of Museu de Zoologia, Universidade de São Paulo, Brazil, has the most Hydraenidae type species (11) in the country. So far, Hydraenidae have been recorded in 19 Brazilian states. The two states with the highest hydraenid biodiversity are Minas Gerais and Bahia, with 12 and seven species, respectively. Species distribution by Brazilian biomes reveals that the Atlantic Forest is the most diverse, with 24 species (21 endemic), followed by the Amazon rainforest, with nine species (five endemic). In this study we also analyzed the potential distribution of the four Hydraenidae genera occurring in Brazil using ecological niche modeling. Our results indicate that *Hydraena* Kugelann, 1794 and *Ochthebius* Leach, 1815 have a wide potential distribution, covering a large part of the country. Otherwise, *Adelphydraena* Perkins, 1989 would be restricted to the Amazon and *Parhydraenida* J. Balfour-Browne, 1975 to the mountains of the Brazilian Shield. The knowledge on the Brazilian hydraenid fauna is still very poor: There are significant knowledge gaps, and many areas have been under-sampled. This deficiency should be addressed in future studies.

KEY WORDS. Aquatic insects, ecological niche modeling, minute moss beetles, neotropics.

INTRODUCTION

Hydraenidae Mulsant, 1844 is a cosmopolitan family of small water beetles, commonly known as "minute moss beetles". It is considered a "predominantly aquatic" beetle family according to the water beetle classification of Jäch and Balke (2008). Hydraenids are also classified as "true water beetles" by Jäch (1998) because they stay submerged for most of their adult stage. The family is one of the most speciose among water beetles, with more than 1,600 described species (Short 2018) arranged in 40 genera worldwide (Perkins 2009, 2018, Jäch et al. 2016, Villastrigo et al. 2019, Bilton 2021).

Hydraenidae had long been considered close to Hydrophilidae or a subfamily of Hydrophilidae (e.g., Ganglbauer 1904), until Böving and Craighead (1931) suggested that Hydraenidae should be placed in Staphylinoidea (Jäch et al. 2016). Currently, most authors (Lawrence and Newton 1995, Bouchard et al. 2011) agree on the placement of Hydraenidae within Staphylinoidea, which has been corroborated by recent phylogenetic studies based on molecular (e.g., Korte et al. 2002) and integrative (Cai et al. 2022) data.

Four subfamilies are currently recognized in Hydraenidae: Orchymontiinae Perkins, 1997, Prosthetopinae Perkins, 1994, Hydraeninae Mulsant, 1844, and Ochthebiinae Thomson, 1859; the last two comprise more than 90% of the described hydraenid species (Jäch et al. 2016, Bilton et al. 2022). Much of the higher-level relationships of Hydraenidae remain untested and given that hydraenids have substantial ecological variability, major classification changes are likely (Short 2018).

Hydraenids occur in aquatic environments throughout the world. Due to their generally small size, hydraenids are able to inhabit a wide range of microhabitats, including very small water bodies. Although they are known as "minute moss beetles," only a small proportion of them are really associated with moss, and most species live among sand, mud, and vegetation in aquatic habitats (Delgado et al. 2018). Other microhabitats where we can find hydraenids include benthic gravels of streams and springs, banks of flowing waters, and stagnant waters near lotic biotopes (e.g., rock pools; Jäch et al. 2016). Some species, mainly those belonging to *Hydraena* Kugelann, 1794 and *Ochthebius* Leach, 1815, are found in pools, ponds, and lake margins, sometimes in great abundance (Benetti et al. 2021). Hygropetric habitats also play an important role in hydraenid ecology, so much so that most species of the Neotropical *Parhydraenida* J. Balfour-Browne, 1975 inhabit very thin layers of water flowing over rock faces (Balfour-Browne 1975, Perkins 1980, Jäch and Delgado 2018).

Hydraenidae represents one of the most widely distributed beetle families: its members are found on all continents and inhabit even some subantarctic islands, where only a few insects are able to cope with the harsh climatic conditions (Jäch and Balke 2008). Many genera are restricted to single geographical domains (e.g., the Neotropical *Adelphydraena* Perkins, 1989 and *Parhydraenida*). However, three genera (*Hydraena*, *Limnebius* Leach, 1815, and *Ochthebius*) are considered cosmopolitan. Furthermore, these genera are remarkably speciose, in fact, *Hydraena* (with about 550 species; see Jäch et al. 2000) is recognized as the most speciose water beetle genus throughout the world (Jäch et al. 2016). Most hydraenid species have a very small range, and the degree of endemism and the number of species with a restricted distribution (SORD) is unusually high in this family. Hydraenids are more common in temperate and tropical zones and are scarcely represented in cold regions. The greatest species diversities are probably found in tropical and subtropical montane forests (Jäch and Balke 2008). The exceptional diversity of hydraenids can likely be credited to their small size and limited dispersal ability. Paradoxically, there is evidence that large rivers can be effective barriers, even for running water species (Jäch et al. 2016).

Despite its high diversity, Hydraenidae is regarded as one of the least explored water beetle families. This is mainly due to their small size (most of the species are less than 2 mm long), their cryptic habits (many species live in tiny rainforest puddles, where they are difficult to detect), and the enormous degree of local endemism. This family probably contains a large number of undescribed species, with an estimated 4,000 extant species (Bilton et al. 2022), and it is the only water beetle family in which more than 1,000 species are expected to still be undescribed (Jäch and Balke 2008). A few of the least explored areas regarding Hydraenidae fauna include some of the Brazilian biodiversity hotspots (Myers et al. 2000), such as the Atlantic Forest and the Cerrado savanna, which are still very poorly studied, but probably host a high diversity of species. Recent studies (e.g., Jäch and Delgado 2018, Benetti et al. 2020, 2022) have revealed a high species richness, will all species endemic to Brazil.

Two subfamilies (Hydraeninae and Ochthebiinae) with nine genera and about 150 species have been reported from the Neotropical region (Hansen 1998, Delgado et al. 2018, Villastrigo et al. 2019). The fauna in this region is taxonomically quite well known, mainly thanks to the seminal contributions of Perkins (1980, 1989, 1997, 2011). Adults are generally much better known than the preimaginal stages, where only a few species have been studied or described so far (Delgado et al. 1997a, 1997b, Delgado and Archangelsky 2005, Deler-Hernández and Delgado 2017). Hydraenidae species from the Western Hemisphere were revised by Perkins (1980), who studied all species occurring in the Nearctic and Neotropical regions until that time. Later, Perkins (2011) published a comprehensive revision of *Hydraena* from South America including 54 species (seven from Brazil). Most recently, papers have included species descriptions of *Parhydraenida* (Jäch and Delgado 2018), *Adelphydraena* (Perkins and Ribera 2020), and *Hydraena* (Benetti et al. 2020, 2022).

The Taxonomic Catalog of the Brazilian Fauna (in Portuguese: Catálogo Taxonômico da Fauna do Brasil – CTFB), started in 2015, is a project focused on Brazilian fauna. The CTFB database is available as an online catalog that is constantly updated by over 500 zoologists, all of whom are experts in their respective animal taxa (e.g., Insecta, Trichoptera: Santos et al. 2020; Insecta, Neuroptera: Machado and Martins 2022). Currently, there are over 120,000 valid extant animal species represented in the CTFB, and information about them can be accessed on the website http://fauna.jbrj.gov.br. The section related to Hydraenidae is managed by the first author of this study and provides a checklist of the Brazilian species, as well as information such as the year of publication, the author's name, synonymic listing, endemism, and distribution for the Brazilian states and ecological biomes. In the near future, data on type specimens such as the type locality and museum repository and species additional information such as life form and environment are also expected to be added to this section of the CTFB.

The main objective of our study is to analyze data from the CTFB and (a) to determine the current state and evolution of knowledge of the Hydraenidae fauna in Brazil, since the first record of a species of this family in the country, 100 years ago, and (b) to estimate the potential distribution of the four Hydraenidae genera that occur in Brazil using ecological niche modeling (ENM) to discuss Brazilian hydraenids hotspots to support future research in areas with high diversity.

MATERIAL AND METHODS

Taxonomic data

We extracted the data analyzed in the present study from the CTFB website (http://fauna.jbrj.gov.br; Benetti 2023), which was last updated in September 2023. The data contained in the CTFB has been constantly updated and is based on available specialized taxonomic literature. The classification of Hydraenidae adopted in the CTFB follows Jäch et al. (2016), with modifications proposed by Villastrigo et al. (2019).

Our dataset is organized by subfamily, tribe, genus, subgenus, and species. For each species, the information compiled consists of: the author's name and nationality; year of description: year it was first reported from Brazil; the location of the primary type specimens; and whether it is endemic to Brazil. The location of the primary type specimens is denoted by collection abbreviations (see below). For the species distribution data, we considered the 26 Brazilian states plus the Federal District, as well as the six terrestrial Brazilian biomes: the Amazon rainforest, the Atlantic Forest, the Cerrado savanna, the Caatinga dry forest, the Pampas grassland, and the Pantanal wetlands (IBGE 2019). Graphics were generated in Excel and using the ggplot2 package in R. Distribution maps were made using Photoshop version 24.7 and QGIS version 3.22.14.

Collection acronyms

(BMNH) The Natural History Museum, London, United Kingdom; (CDM) Coll. Delgado, Universidad de Murcia, Spain; (CMP) Carnegie Museum, Pittsburgh, Pennsylvania, USA; (DZRJ) Coleção Entomológica Prof. José Alfredo Pinheiro Dutra, Departamento de Zoologia, Universidade Federal do Rio de Janeiro, Brazil; (FMNH) Finnish Museum of Natural History, Helsinki, Finland; (IBE) Institute of Evolutionary Biology, Barcelona, Spain; (INPA) Instituto Nacional de Pesquisas da Amazônia, Manaus, Brazil; (IRSNB) Institut Royal des Sciences Naturelles de Belgique, Brussels, Belgium; (MCZ) Museum of Comparative Zoology, Harvard University, Cambridge, Massachusetts, USA; (MZSP) Museu de Zoologia, Universidade de São Paulo, Brazil; (NMPC) National Museum (Natural History), Praha, Czech Republic; (NHMW) Naturhistorisches Museum, Wien, Austria; (USNM) National Museum of Natural History, Washington, D.C., USA.

Potential distribution analysis

For this study, we decided to model at the genus level rather than the species level, due to the lack of minimum occurrence records for most species. The approach of using higher taxonomic ranks (e.g., genus over species) has been validated and employed for several taxa (Ellis 1985, Souza et al. 2016, Vijapure and Sukumaran 2019, de Oliveira et al. 2020, Sroczyńska et al. 2021, Izabel-Shen et al. 2021, Chen et al. 2022).

In addition to CTFB data, we used three other different sources to obtain species records. First, we searched the specialized literature for Brazilian Hydraenidae (Balfour-Browne 1975, Perkins 1980, 2011, Jäch and Delgado 2018, Benetti et al. 2020, 2021, 2022), collecting 57 records. Secondly, we consulted the Global Biodiversity Information Facility (GBIF) to complement the records for Hydraenidae in South America, where we found 2,291 occurrences. These GBIF records undergone manual verification and we only retain entries provided by taxonomists. Finally, we included 25 new records obtained during comprehensive field campaigns in March 2019 and March 2020 from 97 sites (waterfalls and streams) covering an extension of 1,200 km in the Serra do Espinhaço region, in Brazil.

Additionally, we incorporated nine records of *Adelphydraena* species from nearby countries (Venezuela, Guyana, and Suriname) (Perkins 1989, Perkins and Ribera 2020). This was essential because the only record of *Adelphydraena amazonica* Perkins & Ribera, 2020 in Brazil is its type locality. By incorporating these records, we improve the modeling of this genus and the projections within Brazil. For the other genera, we only obtained records from Brazil, but they were sufficient to build models. We used the CELLSIZE occurrence thinning method as detailed by Fourcade et al. (2014) to mitigate sampling bias. From the initial 2,373 records, we reduced to 120 filtered records, comprising *Adelphydraena* (10 records), *Hydraena* (52 records), *Ochthebius* (25 records), and *Parhydraenida* (33 records). This method operates by randomly sampling a single occurrence within each grid cell, scaled twice the resolution of the environmental variables. We set this resolution to 2.5 arcminutes, which translates to a grain size of 5 arcminutes, approximately 9.0 km at the Equator (Fourcade et al. 2014, Velazco et al. 2019). After compiling all the records, we obtained the list of localities with some record to determine the current distribution of all Hydraenidae species in Brazil (Fig. 1). Supplementary file Table S1 includes a detailed description of the raw record sources.

Environmental data

We selected the following variables for our models based on their importance for modeling Hydraenidae distributions: (a) 19 bioclimatic variables from current conditions, offering crucial temperature and precipitation data derived from monthly values that depict annual trends, seasonality and extreme or limiting climatic factors (Fick and Hijmans 2017); (b) elevation (Fick and Hijmans 2017), serving as an indicator for mountainous regions where certain Hydraenidae species can be found; (c) the compound topographic index (CTI) (Amatulli et al. 2020), a measure of soil moisture potential taken from a digital elevation model. This index is commonly used in species distribution modeling, species richness studies, landslide susceptibility assessments, and soil carbon evaluations; (d) profile curvature (PCurv) (Amatulli et al. 2020), which reflects terrain complexity and has an impact on the rate of water flow across surfaces. These

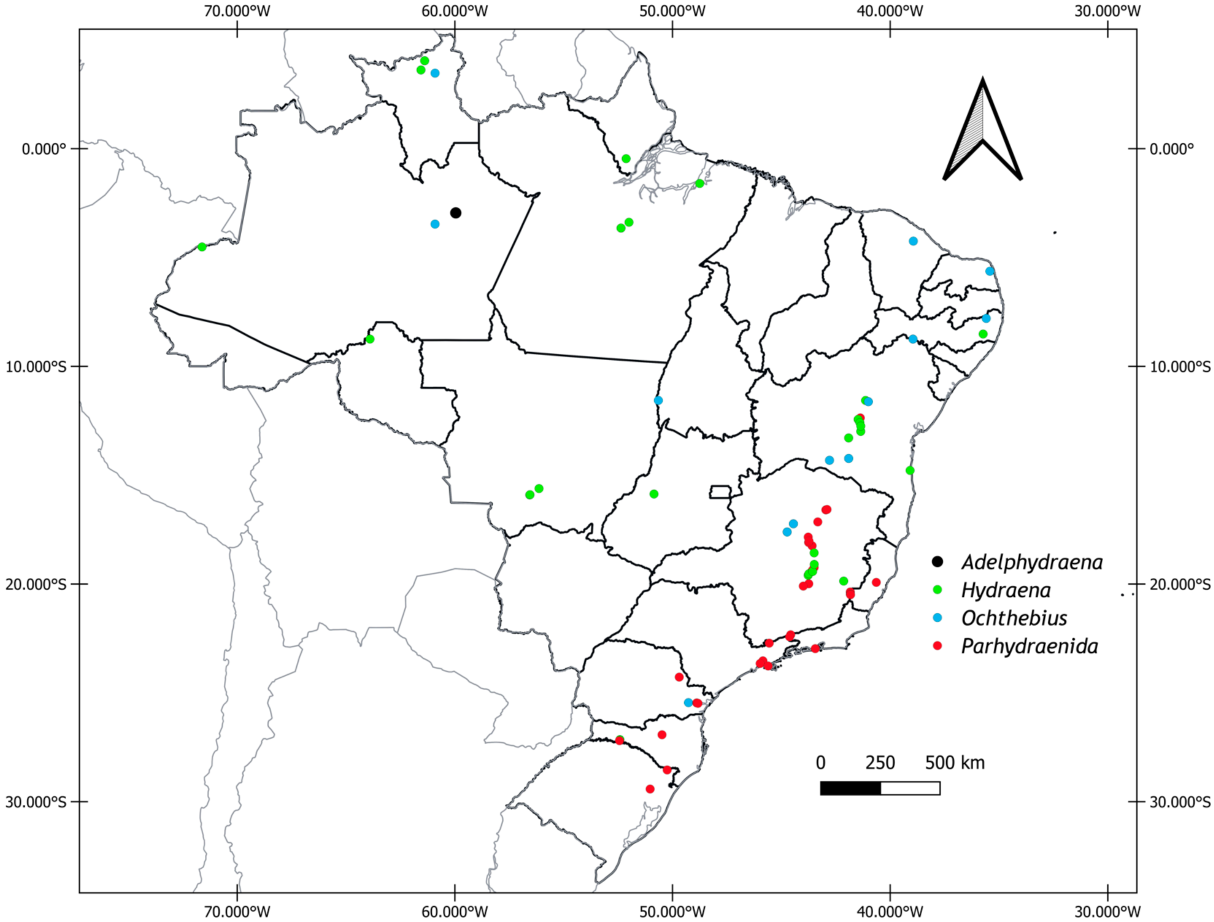


Figure 1. Known distribution of Hydraenidae species from Brazil.

selected variables play pivotal roles in processes such as erosion, soil composition, water accumulation, and infiltration, thereby indirectly influencing the presence and composition of both flora and fauna (Supplementary file Table S2). We standardized all spatial data to a 2.5-arcminute resolution. To counteract multicollinearity and minimize the variable count, we constructed models using the first eight axes of a principal component analysis (PCA), which represented more than 95% of the variance, as predictor variables (De Marco and Nóbrega 2018).

Ecological niche models

We included genera with a minimum of 10 verified records in the modeling. We delineated the "M area" (refer to Soberón and Peterson 2005) by creating a buffer around species occurrences, set to the greatest observed inter-occurrence distance (Barve et al. 2011, Peterson et al. 2011). We produced pseudo-absences and background data points within this accessible area, maintaining a 1:1 ratio of pseudo-absences to presence data, supplemented with 10,000 random background points. We constrained the selection of pseudo-absences to environmental zones predicted by the Bioclim model to have lower suitability (Engler et al. 2004).

We employed several algorithms to predict each genus' potential distribution area. These included maximum entropy, presences and background points (MXS), presences and background points (MXD), Support Vector Machine (SVM), generalized Additive Models (GAM), and generalized Linear Models (GLM), utilizing data like presence, absence, and background points. For the consensus model, we used the arithmetic mean of the top algorithms' suitability. Ensemble modeling, which integrates predictions from multiple algorithms, ensures enhanced accuracy in studies (Araujo and New 2007, Norberg et al. 2019, Thuiller et al. 2019). We only included models that exceeded the average true skill statistic (TSS) (Allouche et al. 2006, Velazco et al. 2019). By optimizing with the Jaccard metric, we binarized this consensus model, thus yielding a more dependable species distribution forecast. We employed k-fold cross-validation, specifically with five folds (Fielding and Bell 1997), to assess our models. We gauged performance based on the area under the curve (AUC) (Fielding and Bell 1997), the TSS (Allouche et al. 2006), and the Jaccard similarity index (Leroy et al. 2018). Given that the AUC and TSS can be influenced by species prevalence, possibly skewing evaluations, we incorporated the Jaccard index to counterbalance this potential bias. A score above 0.7 in any metric signifies commendable model performance. We applied the occurrence-based restriction technique to further refine the predictions, limiting the distribution area and reducing overpredictions by excluding suitable regions beyond the maximum inter-point distance (Mendes et al. 2020). We utilized the ENMTML R package (Andrade et al. 2020) for the modeling process, including pre- and post-processing.

RESULTS AND DISCUSSION

Diversity

Currently, there are 34 valid Hydraenidae species recorded in Brazil (September 2023) (Table 1). They belong to four genera: *Adelphydraena* (one species), *Hydraena* (19 species in two subgenera), *Ochthebius* (three species in two subgenera), and *Parhydraenida* (11 species) (Table 2). Two genera constitute 88% of the overall Brazilian diversity, *Hydraena* (56%) and *Parhydraenida* (32%), while *Ochthebius* includes 9% of the species and *Adelphydraena* contains 3%.

Adelphydraena (Fig. 2A) is a Neotropical genus with only five species confined to northern South America (mainly the Guiana Shield and only one species known in the Amazon River basin) (Perkins and Ribera 2020, Benetti et al. 2021). *Hydraena* (Fig. 2B) is the most speciose Hydraenidae genus with about 900 described species worldwide, including 85 recorded from South America (Perkins 2011, Benetti et al. 2020, 2022). *Ochthebius* (Fig. 2C) is a large cosmopolitan genus with 540 described species (Villastrigo et al. 2019) represented by only 18 species in South America (Perkins 1980, Benetti 2023). *Parhydraenida* (Fig. 2D) has 12 species that inhabit mountainous areas, mainly from the Brazilian shield, of which 11 are endemic to Brazil (Jäch and Delgado 2018).

Of the 34 species recorded in Brazil, 27 are endemic to the country (79%). The proportion of endemic species is also very high in three of the four genera recorded from Brazil (74% of endemic species in *Hydraena* and 100% in *Adelphydraena* and *Parhydraenida*). The last genus is worth mentioning because it is almost endemic to Brazil, with 11 species only recorded from the country and just one recorded from Ecuador. The high number of Hydraenidae species endemic to Brazil is not surprising. Despite the uneven collection efforts, endemism of hydraenid fauna in Brazil is remarkably high: About 79% of recorded species are endemic, a proportion much higher compared with other insect groups – e.g., 68% in Trichoptera, Santos et al. (2020); 49% in Neuroptera, Machado and Martins (2022).

Considering the current numbers, Brazilian hydraenid fauna represents about 2% of the global diversity of Hydraenidae species. This percentage is much lower than that

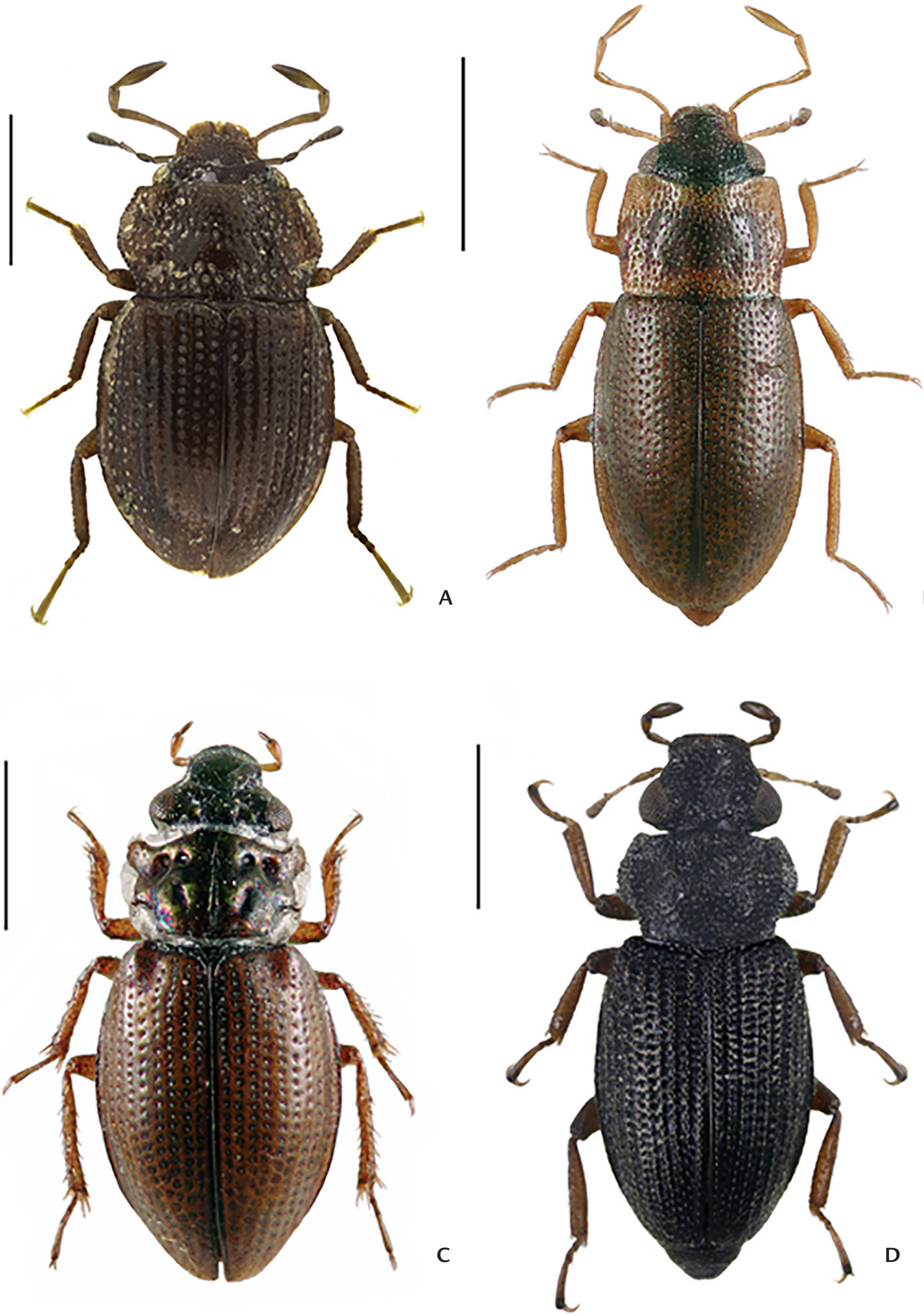


Figure 2. Hydraenidae adult habitus, dorsal view: (A) *Adelphydraena*; (B) *Hydraena*; (C) *Ochthebius*; (D) *Parhydraenida*. Scale bars: 500 µm.

Table 1. List of Hydraenidae species recorded from Brazil.

Species	Brazilian States	Distribution
Adelphydraena amazonica Perkins & Ribera, 2020	AM	Brazil
Hydraena alterra Perkins, 1980	MG	Brazil
H. anaphora Perkins, 1980	MT	Brazil, French Guiana
H. bahiana Benetti, Valladares, Delgado & Hamada, 2022	BA	Brazil
H. browni Perkins, 1980	PA	Brazil, Venezuela
H. curvosa Perkins, 2011	PA	Brazil, Peru
H. hintoni Perkins, 2011	RO	Brazil
H. hyalina Perkins, 1980	BA, MT, RR	Bolivia, Brazil, Colombia, Guyana, Venezuela
H. josefinae Benetti, Valladares, Delgado & Hamada, 2020	AP	Brazil
H. nanoscintilla Perkins, 2011	MT	Brazil
H. orcula Perkins, 1980	GO	Brazil
H. pantanalensis Perkins, 2011	MT	Brazil
H. pernambucana Benetti, Valladares, Delgado & Hamada, 2020	PE	Brazil
H. plaumanni Orchymont, 1937	SC	Brazil
H. punctilata Perkins, 2011	AM	Brazil
H. sahlbergi Orchymont, 1923	MG	Brazil
H. scintillutea Perkins, 1980	MG	Brazil
H. terralta Perkins, 1980	MG	Brazil
H. unita Perkins, 2011	MT	Brazil, Paraguay
H. xingu Perkins, 2011	PA	Brazil
Ochthebius (*Ochthebius*) *attritus* LeConte, 1878	PE	Brazil, Colombia, Cuba, Dominican Republic, Mexico, Puerto Rico, Venezuela, U.S.A. (Florida, Texas)
O. (*Gymnochthebius*) *compactus* Perkins, 1980	PR	Brazil
O. (*G.*) *fossatus* (LeConte, 1855)	BA, CE, MG, PE, RN, RR, TO	Argentina, Bolivia, Brazil, Colombia, Cuba, Guatemala, Honduras, Jamaica, Mexico, Nicaragua, Puerto Rico, Venezuela, U.S.A. (Arizona, Florida, Idaho, Kansas, New Mexico, Oklahoma, Texas)
Parhydraenida alida J. Balfour-Browne, 1975	RJ	Brazil
P. bubrunipes Perkins, 1980	SC	Brazil
P. effeminata J. Balfour-Browne, 1975	RS	Brazil
P. hygropetrica Perkins, 1980	ES, RJ	Brazil
P. lambda Perkins, 1980	PR	Brazil
P. paralonga Perkins, 1980	SP	Brazil
P. plesioformis Jäch & Delgado, 2018	MG	Brazil
P. proboscis Jäch & Delgado, 2018	ES, MG	Brazil
P. quadraticeps J. Balfour-Browne, 1975	PR	Brazil
P. reichardti J. Balfour-Browne, 1975	ES, RJ, SC, SP	Brazil
P. unicornis Jäch & Delgado, 2018	ES, MG	Brazil

Table 2. Number of total and endemic species of Hydraenidae genera occurring in Brazil.

Taxa	Species	Endemic species
Hydraeninae		
Adelphydraena	1	1
Hydraena	19	14
Hydraena (*Dnahydnaedna*)	2	2
Hydraena (*Hydraenopsis*)	17	12
Parhydraenida	11	11
Ochthebiinae		
Ochthebius	3	1
Ochthebius (*Ochthebius*)	1	
Ochthebius (*Gymnochthebius*)	2	1
Total	34	27

observed in other water beetle families, according to CTFB data and global estimates (Jäch and Balke 2008). For most of the water beetle families, the number of species of the Brazilian fauna in relation to the world's fauna is greater than 10%, reaching more than 20% in the case of Gyrinidae (Jäch and Balke 2008, Colpani et al. 2023).

We do not have an estimate for the real number of Hydraenidae species occurring in Brazil, but if we extrapolate the number of known and estimated species of different water beetle families for the Neotropical region and globally, the number of estimated species in Brazil would be double that currently known. On the other hand, if we consider the few Hydraenidae species records we have and the many knowledge gaps observed in Brazil (see Fig. 1) – in addition to the greater sampling efforts of recent sampling campaigns, which have yielded many new species records – we can assume that the estimated number of species is triple or quadruple of the currently known number.

Historical Hydraenidae data in Brazil

The first Hydraenidae species to be recorded from Brazil was *Hydraena sahlbergi* Orchymont, 1923. However, this is not the oldest name for a Hydraenidae from Brazil: It is actually *Ochthebius fossatus* LeConte described in 1855 from USA, but recorded for the first time from Brazil in 1943 (d'Orchymont 1943) as *O. nitiduloides* d'Orchymont, later synonymized with *O. fossatus* by Perkins (1980). The second oldest name from Brazil corresponds to *O. attritus* LeConte, described in 1878, but first recorded from Brazil in 1943 as *O. schubarti* d'Orchymont, later synonymized with *O. attritus* by Perkins (1980).

The peak of species description and records from Brazil was in 1980, when 12 species were first reported for the country (Fig. 3). The year with the second higher number of species reported is 2011 (7 records); both papers were published by Dr. Philip D. Perkins. The accumulation curve of species per year shows a significant rise in rates of Hydraenidae records in Brazil from 1980 onwards (Fig. 4). The curve has continued to rise with recent contributions (Jäch and Delgado 2018, Benetti et al. 2020, 2021, 2022, Benetti and Hamada 2022).

Until now, 10 different authors have participated in the description of Brazilian hydraenids (Table 3): six from Europe, two from the United States, and two from Brazil. Among all authors, Perkins has described the highest number of Hydraenidae species, 20 (all as first author), corresponding to 58% of the Brazilian Hydraenidae fauna.

Table 3. Name and nationality of authors, and number of Brazilian Hydraenidae species they participated on the original description.

Author's name	Nationality	Species described
P.D. Perkins	USA	20
J.A. Delgado	Spain	6
F. Balfour-Browne	UK	4
C.J. Benetti	Brazil	3
L.F. Valladares	Spain	3
N. Hamada	Brazil	3
M.A. Jäch	Austria	3
A. d'Orchymont	Belgium	2
J.L. Leconte	USA	2
I. Ribera	Spain	1

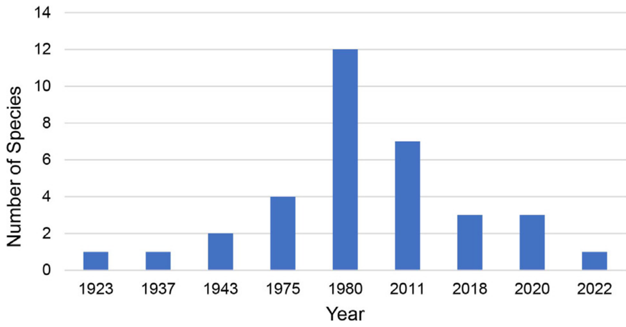


Figure 3. Number of Hydraenidae species recorded from Brazil by year (1923–2022).

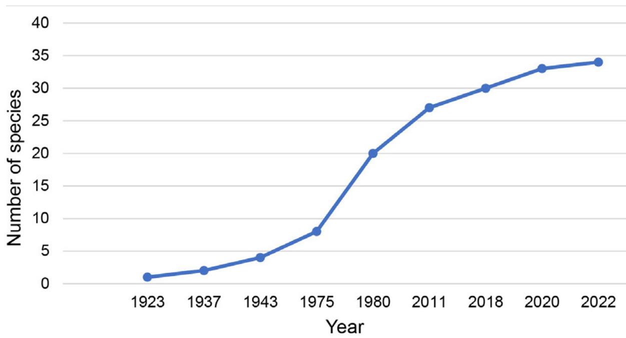


Figure 4. Accumulation curve of Hydraenidae species recorded from Brazil by year (1923–2022), based on the first record of each species to the country.

Dr. Juan. A. Delgado from Spain has described six Hydraenidae species from Brazil (all as co-author), followed by Dr. Francis Balfour-Browne (four species, all as first author). Until 2020, no Brazilian had participated in the description of any Hydraenidae species from Brazil, as either the first author or co-author. In this year, Brazilian and foreign authors described two *Hydraena* species (Benetti et al. 2020). Among the 10 authors who have described Hydraenidae species from Brazil, only one is a woman, Dr. Neusa Hamada, from Instituto Nacional de Pesquisas da Amazônia, who has participated in the description of three species. Historically, few women have authored papers providing the description of insect species, spotlighting an extensive gender gap that needs to be addressed in future research endeavors.

All primary type species (holotypes and paratypes) of Hydraenidae from Brazil are deposited in scientific collections in Brazil, Europe, and United States (Table 4). Eighteen primary types are deposited in Brazil (35%), 18 in European institutions (35%), and 15 in U.S. institutions (30%). The institution that houses the largest number of Hydraenidae type species from Brazil is MZSP (São Paulo, Brazil) (11 type species), followed by USNM (Washington, D.C.) with 10 and NHMW (Wien, Austria) with five. As already pointed out by different authors (e.g., Machado and Martins 2022), such a high number of primary types in foreign institutions could represent a taxonomic impediment for local researchers, primarily because accessing these specimens via travel or loans can often be very difficult.

Table 4. Collections where the primary types of Hydraenidae species recorded from Brazil are deposited; location (country) and number of type specimens deposited.

Collection	Country	Types deposited
BMNH	UK	4
CDM	Spain	1
CMP	USA	1
DZRJ	Brazil	3
FMNH	Finland	1
IBE	Spain	3
INPA	Brazil	4
IRSNB	Belgium	3
MCZ	USA	4
MZSP	Brazil	11
NMPC	Czechia	1
NHMW	Austria	5
USNM	USA	10

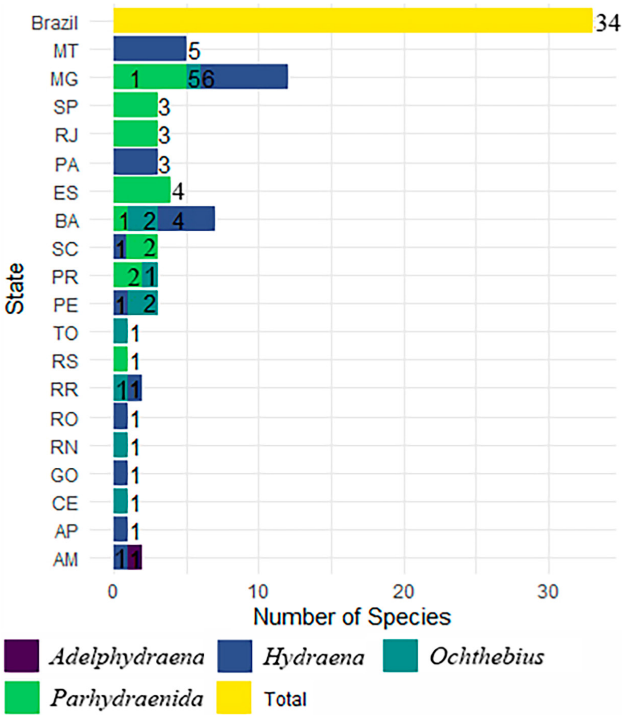


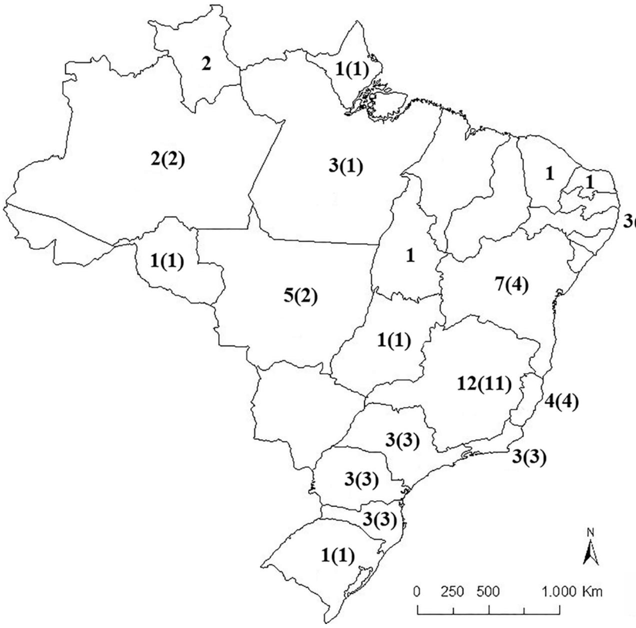
Figure 5. Number of Hydraenidae species recorded for each state of Brazil by genus.

Hydraenid distribution across Brazil

Information about the distribution of animals is usually biased due to unequal collection efforts (the "Wallacean shortfall"; Hortal et al. 2015), and hydraenids are not an exception. As we can see in Fig. 1, the knowledge on the Brazilian hydraenid fauna still has significant gaps, with many under-sampled areas. This lack of records is probably due to the few studies that have focused on regional and local biodiversity, especially in some areas, such as parts of the northeast, west, and north of the country. To try to reduce these gaps, sampling campaigns should be carried out in little-explored areas, which will surely yield new records and the discovery of new species. An example is the fieldwork that was carried out in 2019 and 2020 in the Serra do Espinhaço mountains in Bahia and Minas Gerais states. This fieldwork produced some new records and significantly increased the number of species from these states, including some possible new species.

Minas Gerais is the richest state in terms of hydraenids, currently with 12 species recorded, followed by Bahia with seven species, and Mato Grosso with five species. Other states have from one to three species currently recorded (Fig. 5). There are no records of Hydraenidae species in seven states as well as the Federal District. Minas Gerais is also the state with the highest number of endemic species: 11 of the 12 species recorded for the state are endemic (92%). The next states with the most endemism are Bahia and Espírito Santo with four species recorded; in the latter state, all known Hydraenidae species are endemic. It should also be noted that in 10 states all recorded species are endemic (Fig. 6). Curiously, there are no hydraenid species records for the state of Mato Grosso do Sul. This finding that is unusual when considering that other groups of water beetles are relatively well represented in the state. These species have been identified mainly by fieldwork carried out in the Corumbá area. We speculate that there may be undetermined Hydraenidae specimens deposited in the scientific collections, mainly those in Europe. The study of undetermined material deposited in the different institutions (Brazilian and foreign) will certainly provide us with very interesting data, be it new records or new species, and would contribute to reduce the knowledge gap on Hydraenidae fauna in many parts of Brazil.

Among the six Brazilian terrestrial biomes, there are Hydraenidae species records in five (no species has been recorded so far for the Pampas biome) (Fig. 7). The Atlantic



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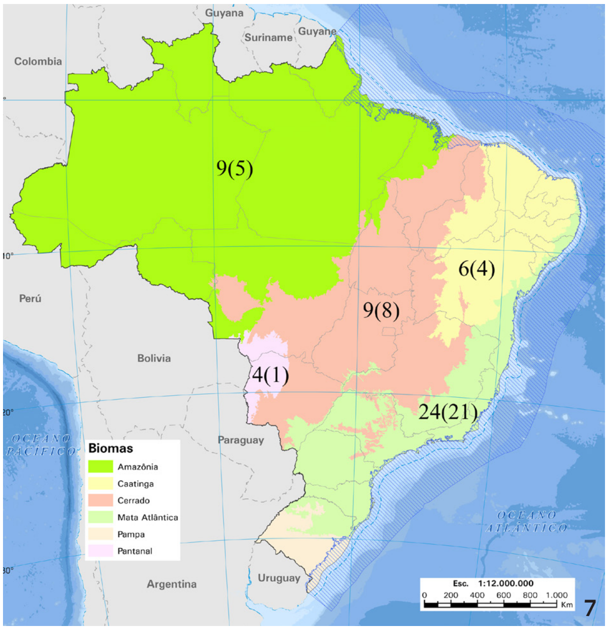

Figures 6–7. (6) Map of Brazil showing the 26 states plus the Federal District and the respective number of Hydraenidae species recorded for each, total and endemic (in brackets). (7) Map of Brazil showing the six continental biomes and the respective number of Hydraenidae species recorded for each, total and endemic (in brackets).

Forest is the richest biome with 24 species records, 70% of all Brazilian hydraenids, followed by the Amazon rainforest (9 species), Cerrado (7), and Caatinga and Pantanal (each with 4). The Atlantic Forest also presents the highest proportion of endemism, with 21 endemic species; 77% of Brazil's endemic species occurring in this biome. The Cerrado and Amazon rainforest have the next highest number of endemic species (5 each).

Potential distributions of Hydraenidae genera in Brazil

We used ENM to investigate the potential distribution of the four Hydraenidae genera occurring in Brazil, as described below. We conducted a PCA of the environmental variables. The first eight components explained 96.61% of the total variance, with the initial two components accounting for 64.7%. The primary component indicated a uniform representation across all variables without any dominant one. Conversely, the second component emphasized that precipitation seasonality is the predominant eigenvector. Performance metrics of the consensus models for genera within the Hydraenidae family are delineated in Table 5. The model exhibited commendable accuracy, with an AUC of 0.611–0.992, a TSS of 0.500–0.971, and a Jaccard coefficient of 0.633–0.971. The table also presents the number of validated records for each genus. The consistency in the high values of these metrics underscores the model's robustness in predicting the distribution of the specified genera based on the incorporated environmental variables.

Table 5. Performance metrics for consensus models across the different genera of Hydraenidae. Metrics displayed include the area under the curve (AUC), true skill statistic (TSS), and the Jaccard similarity coefficient for each genus. Standard deviations (SD) for each metric are also provided.

Genus	N records	AUC	TSS	Jaccard
Adelphdraena	10	0.611 ±0.079	0.500 ±0.236	0.633 ±0.047
Hydraena	52	0.926 ±0.028	0.827 ±0.042	0.848 ±0.037
Ochthebius	25	0.848 ±0.191	0.720 ±0.303	0.804 ±0.160
Parhydraenida	33	0.992 ±0.018	0.971 ±0.064	0.971 ±0.064

Within Brazil, Hydraenidae genera exhibit distinct distribution patterns. By utilizing current records and model projections, we have delineated areas of habitat suitability for each genus. The ensuing sections present a meticulous breakdown of these distributional characteristics for the four genera under consideration.

The Neotropical endemic genus *Adelphydraena* is currently represented in Brazil by one species, *A. amazonica*, so far present in only one locality in the Amazon (Ducke Reserve, Manaus, Amazonas state). The model projections suggest a potential distribution for this genus across parts of other northern Brazilian states. Specifically, areas of high to medium suitability are projected across most of the Amazonas state, except for some areas in the extreme west. The potential range also includes most of Pará, Amapá, Roraima, and Acre states, with isolated patches in the northern parts of Mato Grosso and Rondônia states (Fig. 8A).

The widespread genus *Hydraena* is also widely distributed in Brazil, with records from 11 states: Amapá, Amazonas, Bahia, Goiás, Mato Grosso, Minas Gerais, Pará, Pernambuco, Rondônia, Roraima, and Santa Catarina. The model projections indicate a potential distribution for this genus across all Brazilian states. However, the model also identifies environmentally unsuitable patches in the drier areas of the Cerrado and Caatinga biomes; the extreme west of the Amazonas state; the west of Rio Grande do Sul and Santa Catarina states; the east of Minas Gerais, Rio de Janeiro, and Espírito Santo states; and in northern Brazil, from Bahia to Ceará states (Fig. 8B).

Ochthebius is also widely distributed in Brazil, as it has been recorded in eight states: Bahia, Ceará, Minas Gerais, Paraná, Pernambuco, Rio Grande do Norte, Roraima, and Tocantins. The model projections suggest a broad potential distribution for this genus across nearly all Brazilian states. However, in some states such as Amapá, Pará, Paraná, Rio Grande do Sul, and Santa Catarina, more than 50% of the area is deemed unsuitable for this genus (Fig. 8C).

The Neotropical genus *Parhydraenida*, the members of which are found in hygropetric habitats and nearly exclusively endemic to Brazil, is currently distributed across eight Brazilian states: Bahia, Espírito Santo, Minas Gerais, Paraná, Rio de Janeiro, Rio Grande do Sul, São Paulo, and Santa Catarina. The model projections hint at a potential range for this genus spanning parts of the Brazilian Shield, from the northeast to the south of Brazil. Notably, there is occasional high to medium suitability within the Goiás state (Fig. 8D).

Our study provides significant insight into the diversity of hydraenids and their distribution patterns in Brazil. Our data show that the potential distribution of each genus diverges, but there is significant overlap in some. *Parhydraenida* is limited to the Brazilian Shield (apart from one species from Ecuador, endemic to Andean region) and *Adelphydraena* is limited to Amazon basin and Guiana Shield, which may indicate they are endemic to these areas. On the other hand, *Hydraena* and *Ochthebius* seem to have a wider distribution, throughout all of Brazil, although *Ochthebius* may not be present in part of the Amazon.

For genera *Hydraena* and *Ochthebius*, the model identifies environmentally unsuitable patches in some areas of Brazil. However, our projections do not exclude the possibility that some species of these genera may be present in these areas. Due to the lack of a more comprehensive set of environmental variables, including microhabitat preferences, our technique was deliberately conservative. This approach was chosen to avoid excessive extrapolations and to minimize many intrinsic biases of the modeling process. Some species within the *Hydraena* and *Ochthebius* inhabit a variety of habitats, such as temporary pools and streams. Furthermore, most of these species are widely distributed throughout northern South America (e.g., *Ochthebius fossatus* and *Hydraena hyalina* Perkins, 1980). Therefore, their presence in extensive areas of Brazilian territory is highly probable and cannot be discounted.

Some highlighted areas of high suitability in Brazil also present gaps in our understanding of the current biodiversity. More studies are necessary to comprehensively understand the distribution patterns of Hydraenidae species in Brazil and could also potentially lead to the discovery of new species, as highlighted by Short (2018) and foster a more complete comprehension of their ecological roles and conservation needs. In this sense, faunal inventories in areas identified as knowledge gaps are essential for expanding our understanding of hydraenid diversity and validating the models presented here. Investment in biological collections and the availability of data on digital platforms (such as CTFB, GBIF) are also vital for the advancement of both basic and applied science regarding freshwater biodiversity in Brazil.

Future studies

Future field research efforts should focus on less-explored areas, such as the northeast, parts of the west and north, where there is a lack of records of Hydraenidae species and thus large knowledge gaps. In addition, biomes that have been historically under-sampled, including the Caatinga, Cerrado, Pantanal, and Pampas, need to be targeted in future biodiversity projects. Future field work should also explore unique microhabitats such as hygropetric, temporary rocky pools, and phytotelmata: They have not been sampled extensively in Brazil, but they have shown high richness of water beetles (e.g., Alencar et al. 2022a, 2022b, Hájek at el. 2023, Santana et al. 2023) and could host an interesting hydraenid fauna.

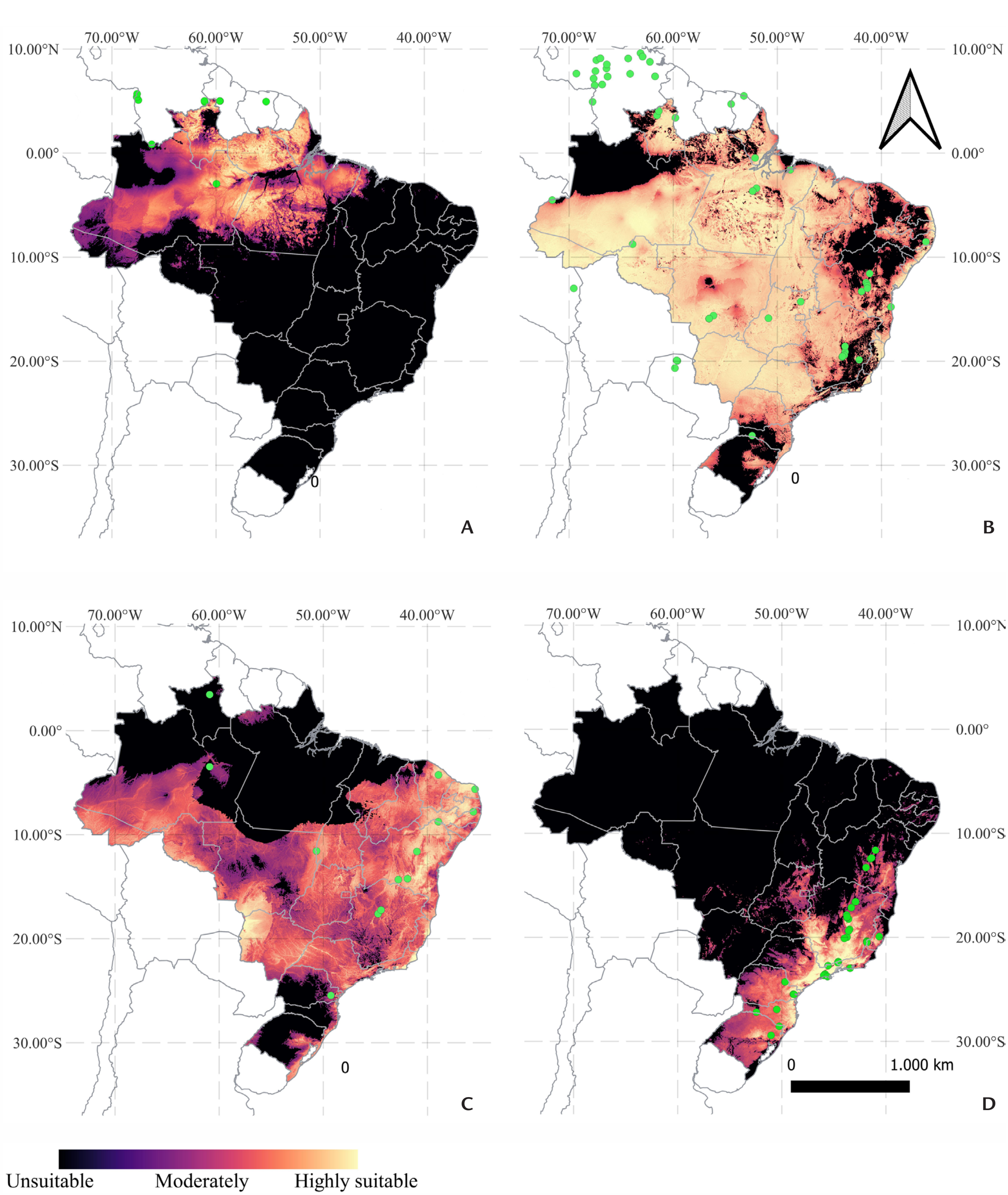

Figure 8. Occupied distributions and suitability areas for Hydraenidae genera: (A) *Adelphydraena* spp. (n = 10 records); (B) *Hydraena* spp. (n = 52 records); (C) *Ochthebius* spp. (n = 25 records); (D) *Parhydraenida* spp. (n = 33 records). Dots represent specimen records for each genus.

Another important aspect that should be addressed in future studies is the lack of taxonomic and biological data on the immature stages of hydraenids. The current data in the Hydraenidae section of CTFB is based entirely on adult records. In fact, none of the species recorded for Brazil have had their respective larva described. To achieve this goal, we should first increase the sampling efforts in the habitats where larvae live, which have been little explored – most likely the main reason why hydraenid larvae are very little studied. Most hydraenids are riparian in their larval stage, and the habitats in which they are found range from truly terrestrial to aquatic, including moist soil among stones, wood, and decaying leaves (Jäch et al. 2016).

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Competing Interests

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Supplementary material 1

Table S1. Sources of raw data (records).

Authors: CJ Benetti, JBR Alencar, N Hamada

Data type: species data.

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Supplementary material 2

Table S2. Principal component analysis (PCA) loadings of 22 environmental variables.

Authors: CJ Benetti, JBR Alencar, N Hamada

Data type: statistical results of environmental variables.

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