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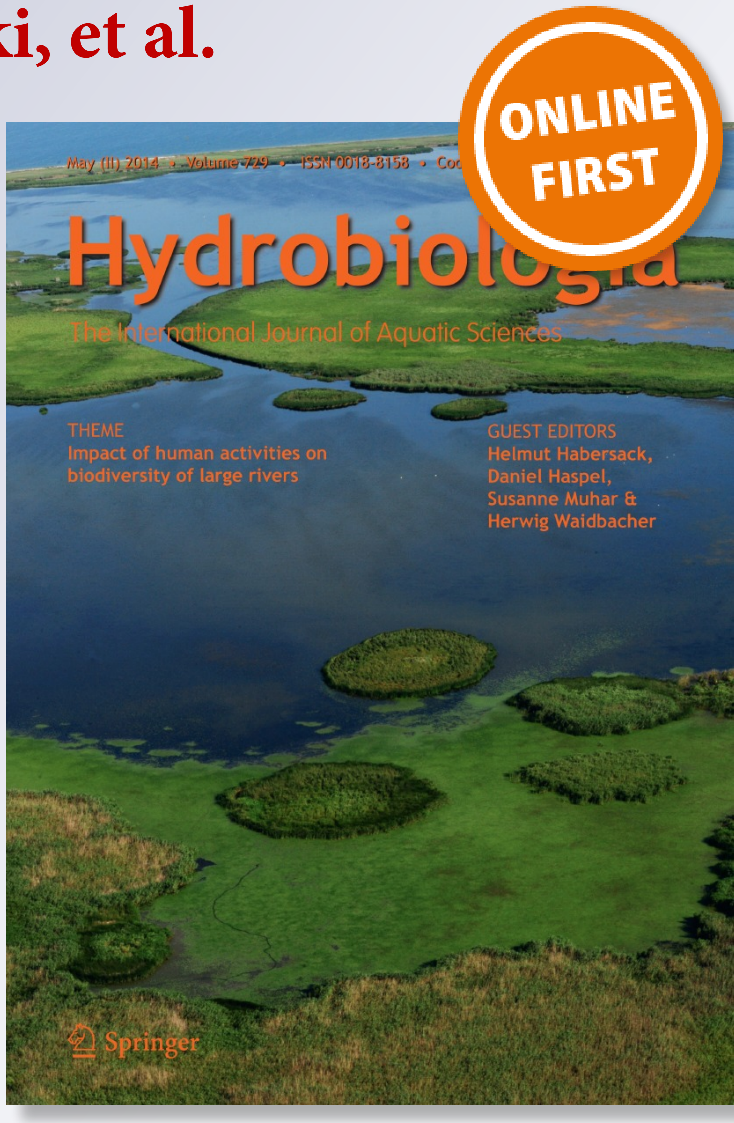

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PRIMARY RESEARCH PAPER

Fish-AMAZBOL: a database on freshwater fishes of the Bolivian Amazon

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Abstract The Bolivian part of the Amazon Basin contains a mega diverse and well-preserved fish fauna. Since the last decade, this fish fauna has received an increasing attention from scientists and the national authorities as fishes represent one of the most important sources of proteins for local human communities. However, this fish fauna still remains poorly documented. Here, we present a database for fishes from the Bolivian Amazon. To build the database, we conducted an extensive literature survey of native and non-native (exotic) fishes inhabiting all major sub-drainages of the Bolivian Amazon. The database, named Fish-AMAZBOL, contains species lists for 13 Amazonian hydrological units, covering 100% of the Bolivian Amazon and approximately 65% (722,137 km^2) of the all territory. Fish-AMAZBOL includes 802 valid species, 12 of them being non-native, that have been checked for systematic reliability and consistency. To put this number in perspective, this represents around 14% of the all Neotropical ichthyofauna and around 6% of all strictly freshwater fishes inhabiting the planet. This database

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is currently the most comprehensive database of native and non-native fish species richness available so far for the Bolivian Amazon.

Keywords Freshwater fishes · Checklist · South America · Amazon River basin · Madera River · Bolivia

Introduction

Bolivian fishes are diverse and abundant. However, despite of their importance for local livelihoods, little attention has been paid so far to this vertebrate group (Van Damme et al., 2009). Consequently, fishes remain the least known vertebrates group in Bolivia and information on their distribution and biology is scarce and dispersed. In the last decade, the Bolivian government and the scientific community have both focused their attention on this important natural resource that could be affected in a near future by increasing threats such as water pollution, dams, and species introductions (Carvajal-Vallejos et al., 2011; Van Damme et al., 2011; Van Damme & Carvajal-Vallejos, 2012).

The present data paper focused exclusively on the Bolivian part of the Amazon River basin. Lists of fish species records for the Bolivian Amazon started with Pearson's (1924) pioneering work describing 26 new species and presenting a longitudinal and altitudinal distribution of 160 species collected mainly in the Beni River basin and in some parts of the Mamoré River basin. Later, this same author published a list of 275 fish species for the Beni and Mamoré basins (Pearson, 1937).

More than five decades after this groundbreaking work, Lauzanne et al. (1991), based on an extensive sampling survey, published a provisional list of 389 fish species for the Bolivian Amazon to which Sarmiento (1998), Chernoff & Willink (1999), Lasso et al. (1999), and Chernoff et al. (2000) and added respectively an additional 21, 91, and 3 species, bringing the total to 504 species.

More recently, Pouilly et al. (2010), Carvajal-Vallejos & Zeballos Fernández (2011), and Hablützel et al. (2013), bringing together information on fish species present in the lowlands of the Bolivian Amazon (principally <300 m above sea level—m.a.s.l.), recorded between 721 and 994 species for this portion of the basin.

Based on this short review, it is clear that the number of new fish records for the Bolivian Amazon is in constant increase but remains highly variable depending on the authors. The reasons for this variability are multiple but mostly come from partial compilation of available data, inclusion of doubtful species, and the absence of systematic verification for species synonymies. The aim of the present study is thus to try, as far as possible, to avoid these previous drawbacks in order to provide a much comprehensive fish database for the Bolivian part of the Amazon basin. This has been done by including information available in published articles, books, the gray literature, online databases, foreign (22, listed in Pouilly et al. (2010) and Jégu et al. (2012)) and national (2) museums and universities, and by checking for systematic reliability and consistency for each species recorded.

Materials and methods

Spatial coverage

The Bolivian Amazon covers 722,137 km^2 (65.7% of the Bolivian territory) and is situated, from West to East, between the Andes and the southwestern border of the Brazilian Shield. While composed primarily by the Madera River basin (called Madeira River in Brazil), which covers alone an area of 720,057 km^2 (65.5% of the Bolivian territory), the Bolivian Amazon also contains a small portion of the Purus River Basin (i.e., the Acre River), covering an area of 1 851 km^2 (0.2% of the Bolivian territory) and located in the northwestern corner of the country (Fig. 1).

The Madera River basin was divided in 12 hydrological units corresponding, respectively, to the Abuná, Orthon, Madre de Dios, Beni, Yata, Mamoré, Grande, Parapetí and Iténez (or Guaporé) sub-basins and Beni-Madre de Dios-Orthon (B-MD-O), Mamoré-Iténez (MM-I), and Madera River main channel portions (Fig. 1). Hydrological units were defined following the hydrographic chart (level 5) of the Bolivian Ministerio de Medio Ambiente y Agua – Vice Ministerio de Recursos Hídricos y Riego (2010), and the water bodies map of the Sistema de Información Territorial de Apoyo a la Producción – SITAP (2009) (available at the Digital Center of Natural Resources of Bolivia, Department of Ecosystem Science and Management, Texas University (http://essm.tamu.edu/bolivia).

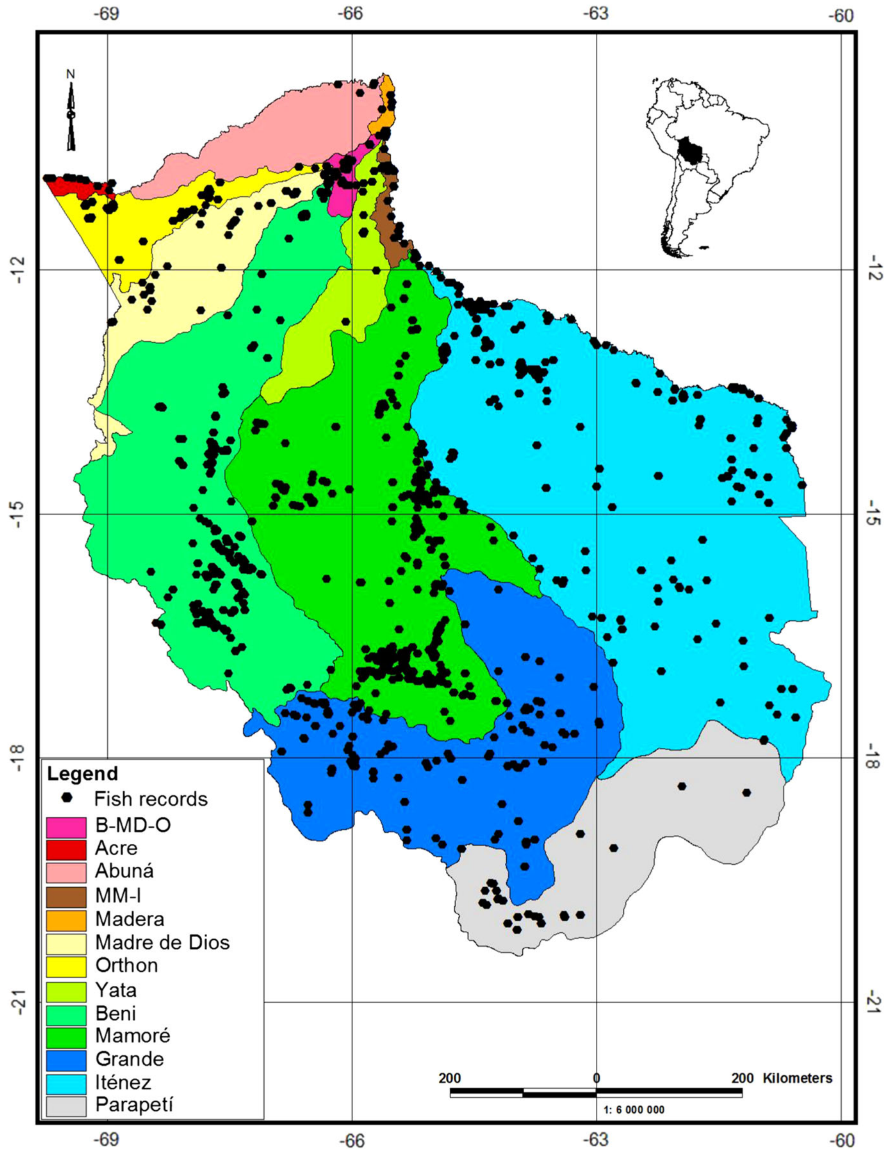

Fig. 1 Map of the Bolivian Amazon showing the 13 hydrological units and the sampled localities (*dots*) considered in the Fish-AMAZBOL database. *Dots* can represent more than one locality (closely related localities)

Latitude and longitude of hydrological units were collected from the literature, Google Earth Pro version 4.2 Beta, and from a demographic map of Bolivia (INE 2001, available at http://essm.tamu.edu/bolivia). We further calculated the altitudinal range, length of the main river stem, and surface area of each hydrological unit (Table 1).

Data collection

Data were collected as a joint collaboration between three institutions: the Unidad de Limnología y Recursos Acuáticos (ULRA) of the Universidad Mayor de San Simón (UMSS) – Cochabamba (Bolivia), FAUNAGUA (Institute for Applied Research on Aquatic Resources) – Cochabamba (Bolivia), and the Institute de Recherche pour le Dévelopement (IRD) – Marseille (France). We conducted an extensive survey of the literature published from 1855 to 2013 on native and non-native fish species of the Bolivian Amazon.

The database was gathered from 146 bibliographic sources including published papers, books, thesis, and gray literature (reports and unpublished data). The complete list of references used to compile the Fish-AMAZBOL database is given as online

Table 1 General description of the Fish-AMAZBOL database for each of the 13 hydrological units (see text for variables explanation)

Hydrological unit	Area (km^2)	Length (km)	Altitudinal range [m a.s.l.]	Fish species richness			
				Total	Native	Non-native	Exclusive
Acre	1,851.24	267.54	184–343	38	38	0	4
Abuná	23,559.83	1066.44	90–308	72	70	2	4
Madera	1,399.62	234.81	90–233	149	148	1	9
Orthon	18,387.88	1041.43	144–360	245	244	1	3
Madre de Dios	30,924.38	1442.94	105–3,117	353	351	2	5
Beni	119,205.99	2295.21	103–6,404	419	416	3	31
Yata	19,849.83	1030.21	99–225	32	31	1	0
Mamoré	129,955.18	2229.76	116–4,666	556	554	2	51
Grande	102,059.60	2070.91	158–5,141	133	127	6	13
Iténez	206,432.61	2843.20	108–919	520	519	2	73
Parapetí	60,686.07	1463.34	254–3,713	30	30	0	6
B-MD-O	3,652.88	363.68	105–217	141	139	2	4
MM-I	3,602.62	570.62	107–184	143	142	1	1
Total	721,567.73	-	90–6,404	802	790	12	203

supplementary material (see Appendix 1—Supplementary material), and the original bibliography is stored at ULRA and at FAUNAGUA. We also included, if valid (see below), fish records deposited in the Colección Boliviana de Fauna (CBF) in La Paz, Bolivia; in the Ichthyological Collection UMSS – D'Orbigny Museum, Cochabamba, Bolivia; and in foreign Museums and international databases (see below).

Fish species records were included in the Fish-AMAZBOL database according to the following criteria: (a) occurrence in a taxonomic revision or species description that includes material from the Bolivian Amazon, (b) occurrence in the Ichthyological Collection UMSS – D'Orbigny Museum where the material could be reviewed, (c) occurrence in the database and fish collection of the CBF, (d) occurrence in foreign museums and Universities cited in Pouilly et al. (2010) and Jégu et al. (2012) (i.e., the American Museum of Natural History of New York, USA; the Philadelphia Academy of Natural Sciences, USA; the Auburn University, Department of Zoology-Entomology, USA; the California Academy of Sciences, USA; the Cornell University Museum of Vertebrates, USA; the Florida Museum of Natural History, USA; the Field Museum of Natural History, Chicago, USA; the University of Kansas, USA; the Museum of Zoology of the University of Michigan, USA; the Smithsonian Institution, the National Museum of Natural History, Washington, USA; the British Museum of Natural History, United Kingdom; the Museo de Ciencias Naturales, Caracas, Venezuela; the Pontificia Universidade Catolica do Rio Grande do Sul, Museu de Ciencias, Porto Alegre, Brazil; the Museu Nacional da Universidade Federal do Rio de Janeiro, Brazil; the Museu de Zoologia da Universidade de São Paulo, Brazil; the Fundação Universidade Federal de Rondônia (UNIR), Rondônia, Brazil; the Instituto Nacional de Pesquisas da Amazônia, Manaus, Brazil; the Museum National d'Histoire Naturelle, Paris, France; the Swedish Museum of Natural History, Stokholm, Sweden; the Royal Ontario Museum, Canada; the Forschungsinstitut und Naturmuseum Frankfurt, Germany; the Zoological Museum of the Amsterdam University, the Netherlands), (e) occurrence in international online databases (i.e., the Global Biodiversity Information Facility (GBIF); the Neotropical Biodiversity Database (NEODAT); and the Rapid Assessment Program Biodiversity Survey Database (RAP), and f) occurrence in a fish list elaborated for a portion of the Bolivian Amazon.

For each record, the distribution and current status (valid species name or synonym) were reviewed using preferentially as nomenclature authority file the

California Academy of Science's Catalog of Fishes—CAS (online version fish database, Eschmeyer, 2013), updated December 10, 2013, and incidentally FishBase version October 2013 (Froese & Pauly, 2013). When the presence of a taxon was inconsistent with its actual known distribution and when there was no possibility to review the material, the record was classified as doubtful. In some cases, taxa identified at the genus level (4% of the total species list) were included in the database but only when no other species of the same genus was already recorded.

Some discrepancies in some taxa names were identified between CAS and FishBase. When a conflict was noted between the databases, we retained the name proposed by CAS. Conflicts appeared for the species *Ageneiosus valenciennesi* Bleeker 1864 (CAS) vs. *Ageneiosus militaris* Valenciennes 1835 (FishBase), *Cheirodon stenodon* Eigenmann 1915 (CAS) vs. *Odontostilbe stenodon* (Eigenmann 1915) (FishBase), *Galeocharax goeldii* (Fowler 1913) (CAS) and *Galeocharax gulo* (Cope 1870) (FishBase). However, three exceptions were made: (1) Following Weitzman & Palmer (1997) we retained *Hyphessobrycon megalopterus* (Eigenmann 1915) instead of *Megalamphodus megalopterus* Eigenmann 1915 (CAS), (2) following Britto (2003) *Brochis* genus was considered a synonym of *Corydoras* genus, and, therefore, we retained *Corydoras multiradiatus* (Orcés V. 1960) instead of *Brochis multiradiatus* (Orcés V. 1960) (CAS and FishBase), and (3) following Lundberg et al. (2011) and Carvajal-Vallejos (2013), we retained *Platynematichthys notatus* (Jardine 1841) instead of *Brachyplatystoma notatus* (Jardine 1841) (CAS).

Three diversity descriptors were retained for each hydrological unit: native, non-native, and total richness. Native richness is the number of species that currently occur in the unit but excludes non-native species that either directly or indirectly have been introduced in the basin. Non-native or "exotic" richness is the number of established non-native species occurring in each hydrological unit. We considered as non-native species: (a) species that did not naturally occur in a given hydrological unit and (b) that is apparently successfully established, e.g., maintains self-reproductive populations. Total richness takes into account the total number of species established in a given hydrological unit and is, therefore, the sum of native and non-native richness. The non-native status of each species was verified by using the specific literature on introductions (e.g., Welcomme, 1988; FAO web site www.fao.org, accessed July 2013).

Families are arranged in systematic order following the criteria proposed by Reis et al. (2003), who presented the family name positions based on evolutionary history inter-relationships. In the interest of simplification, we decided to use the Reis et al. (2003) most commonly accepted classification, although new relationships and classification based on molecular and morphological evidences have been proposed for members of the Characidae family (e.g., Mirande, 2009, 2010; Oliveira et al., 2011; Netto-Ferreira et al., 2013). Genera and species within a family are listed in alphabetic order.

Fish fauna similarity among hydrological units

Using our matrix of species (presence-absence) we calculated, for each pair of hydrological units, the turnover component of the Jaccard Dissimilarity Index as defined by Baselga (2012). This index is formulated as $\beta_{jtu} = 2\min(b, c)/a + 2\min(b, c)$; where a is the number of species common to both hydrological units, b is the number of species occurring in the first unit but not in the second, and c is the number of species occurring in the second unit but not in the first. By using the minimum value of assemblage dissimilarity, the β_{jtu} accounts for species replacement, while minimizing the influence of differences in species richness (Leprieur & Oikonomou, 2014), a highly desirable property in our case, as species richness varies greatly between hydrological units. This index goes from 0 to 1, and is minimum (no dissimilarity) when the poorest assemblage is fully nested in the richest assemblage and maximum when the two assemblages have no species in common ($a = 0$). We further applied a hierarchical clustering analysis to our dissimilarity matrix using an average link (UPGMA) method and a Kelley–Gardner–Sutcliffe (KGS) penalty function (Kelley et al., 1996) to determine the optimal number of groups of hydrological units.

Results

Fish-AMAZBOL contains 802 species (among which 145 valid species described from the Bolivian Amazon, over an initial number of 160), distributed in 15 orders, 50 families and 326 genera (Appendix 2—Supplementary material). The fish fauna is dominated by Characiformes (CHA, 331 spp.), Siluriformes (SIL, 312 spp), Perciformes (PER, 68 spp.), and Gymnotiformes (GYM, 46 spp.). The most important families in term of number of species are Characidae (177 spp.—CHA), Loricariidae (71 spp.—SIL), Cichlidae (63 spp.—PER), Callichthyidae (46 spp.—SIL), Pimelodidae (45 spp.—SIL), and Curimatidae (31 spp.—CHA).

Following our methodology, the presence of 45 species was for now considered doubtful. These species belong mainly to Characiformes (25) and Siluriformes (14) orders (See Appendix 2—Supplementary material).

We recorded 38 species for the Bolivian part of the Purus River (Acre) and 798 species for the all Upper Madera basin. In the Upper Madera, the Mamoré River unit contains the greatest number of species (556), while the Parapetí unit contains the fewest number (30). The Iténez (520 species), Beni (419), Madre de Dios (353), and Orthon (245) units, also show an important fish richness. The hydrological unit with the highest exclusive records is the Iténez (73 species), followed by the Mamoré (51), the Beni (31), and the Grande (13) units (Table 1). Note that these exclusive species do not represent necessarily endemic species (i.e., species restricted to one hydrological unit), as they may eventually be present in other parts of the Amazon Basin.

Twelve non-native species, corresponding to seven orders, were also recorded in Fish-AMAZBOL. Among these orders, Cyprinodontiformes alone have three non-native representatives (*Poecilia reticulata* Peters 1859, *Gambusia affinis* (Baird & Girard 1853), and *G. holbrooki* Girard 1859). Other notable introductions concern the Rainbow trout *Onchorhynchus mykiss* (Walbaum 1792) and the Brook trout *Salvelinus fontinalis* (Mitchill 1814) (Salmonidae, Salmoniformes) that were recorded in the Andean portion of the Beni and Mamoré units, and the giant Amazonian Osteoglossiform *Arapaima* aff. *gigas* that was recorded in the lowlands of northern Bolivia (see Appendix 2—Supplementary material).

To assess the influence of sampling effort on hydrological units native species richness, we plotted the relationship between native species richness and the number of records, after controlling for the size of our hydrological units (i.e., using residuals of (1) the relationship between native species richness (log) and the surface area of the hydrological units (log) and (2) the relationship between the number of records (log) and the surface area of the hydrological units (log)). Results show that after taking into account the size of the units, native species richness increases linearly with the number of records with a significant level off for higher number of records. This means that some of our units are under sampled and should host a greater number of species that currently known (i.e., Parapetí, Yata, Abuná, Acre, and Grande hydrological units), while species richness of the others (i.e., Madre de Dios, Mamoré, Iténez, Madera, Beni, Orthon, MM-I, and B-MD-O) seems more accurate as being independent of the number of records (Figs. 1, 2).

This result leads us to conclude that the number of species in the Bolivian Amazon is larger that we can document at present and that more field studies are needed to get a reliable picture of the ichthyofauna of the region and more specifically in the Parapetí, Yata, Abuná, Acre, and Grande hydrological units (see Fig. 2).

Results of hierarchical clustering analysis highlight a clear separation of the southernmost hydrological units (i.e., Parapetí and Grande units) from the remaining ones, indicating a distinct fish fauna for

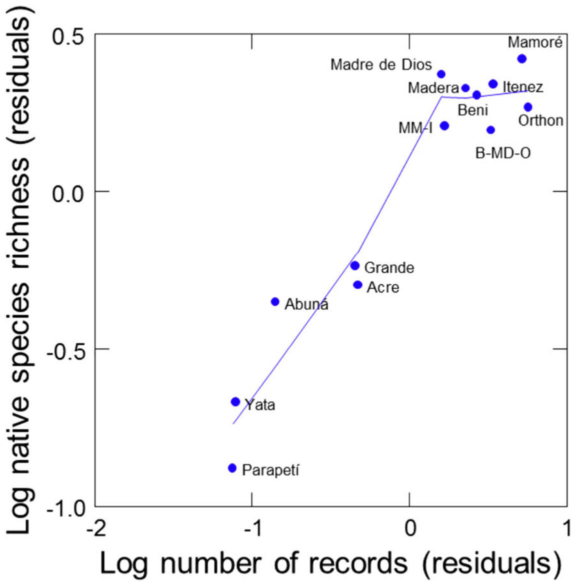

Fig. 2 Relationship between native species richness and the number of records, after controlling for the size of the hydrological units (see "Results" section for further details). Lowess curve (tension = 0.8)

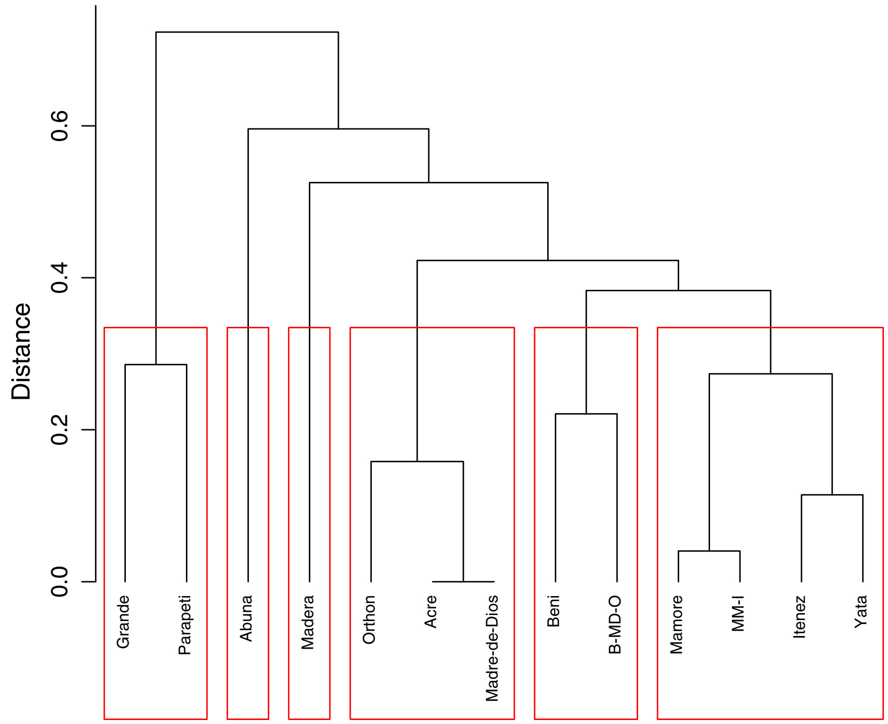

Fig. 3 Dendrogram of the hydrological units according to compositional (dis)similarity in their ichthyofauna. The hierarchical cluster analysis was performed using the average link (UPGMA) method. The *rectangles in red* correspond to the optimal groups of hydrological units according to the KGS penalty function (see text for further details)

this area. Furthermore, the Abuná and Madera units seem both to host distinct fish fauna. In contrast, our results show faunal similarities between (1) Grande and Parapetí hydrological units, (2) Orthon, Acre and Madre de Dios units, (3) Mamoré, Iténez, Yata and MM-I units, and (4) Beni and B-MD-O units; the last two groups being close from each other. The overall pattern of faunal (dis)similarity seems to follow a gradient of geographical proximity from northwestern to eastern Bolivia (or the reverse) (Fig. 3).

Discussion

Following a general taxonomic composition pattern previously observed in the major systems of the Neotropical realm (Reis et al., 2003; Buckup et al., 2007), Characiformes, Siluriformes, Perciformes, and Gymnotiformes dominate the fish diversity of the Bolivian Amazon.

The greatest levels of fish diversity were recorded in the Mamoré, Iténez, Beni, and Madre de Dios hydrological units, which are the largest in terms of areas, as well as being the most studied in the Bolivian Amazon. Other smaller hydrological units (e.g., Yata, Grande, Parapetí, Abuná, Acre, and MM-I), clearly need special attention and more field assessments to improve knowledge on their fish fauna.

The Bolivian part of the Amazon Basin is mostly represented by the Upper Madera basin, a semi-isolated sub-basin due to rapids and cataracts in the area upstream from Porto Velho, Brazil. The Upper Madera basin contributes around 25% of the discharge of the Madera River basin as a whole, the latter contributing 10% of the discharge of the Amazon River (Carvalho & Albert, 2011). The FISH-AMAZBOL database contains information on 802 (12 non-native) fish species inhabiting the 13 hydrological units of the Bolivian Amazon. To put this number in perspective, the ichthyofauna of the Bolivian Amazon represents around 14% of the Neotropical ichthyofauna (Albert & Reis, 2011) and around 6% of all strictly freshwater fishes inhabiting the planet (Lévêque et al., 2008). This value of 802 species falls between values proposed earlier by Pouilly et al. (2010) and Carvajal-Vallejos & Zeballos Fernández (2011) for the same area. These authors found 973 and 714 species, respectively. The difference in species richness between the present study and the two previous ones comes from 1) inclusion of doubtful species and the absence of systematic check for species synonymies and 2) partial compilation of available data in these previous works. Here we undertook a detailed revision taking into account specialized bibliography and two digital online databases (Catalog of Fishes-CAS and FishBase), for generating the most comprehensive and accurate fish list records. In this sense, Fish-AMAZBOL intends to be a reference baseline that could be completed progressively with new field data and new bibliography.

The Bolivian Amazon remains relatively intact (Josse et al., 2013) compared to other South American countries sharing the Amazon basin (e.g., Brazil, Peru, Colombia). Human pressure remains low and still has not become a serious threat for aquatic resources, although some fish stocks begin to show signs of overexploitation (e.g., *Colossoma*, Carvajal-Vallejos et al., 2009). The most apparent threat in the short term for Bolivian Amazon fishes and fisheries seems to be hydropower dam projects at the Bolivian border with Brazil and in the Brazilian portion of the Upper Madera basin. Because over 99% of the Bolivian Amazon drains into the Madera River, it is necessary to predict the potential effects that these dams and their associated impoundments could produce on fish communities and fisheries. In this sense, FISH-AMAZBOL database will help to develop regional conservation programs and contribute to large-scale aquatic ecosystem management.

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