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ARTICLE

The ichthyofauna of the Rio Carinhanha basin, one of the main tributaries of the Rio São Francisco

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Abstract. The ichthyofauna of the Rio São Francisco basin is relatively well-documented. However, most of this knowledge is concentrated at the upper stretch of its catchment area. In this study, we compile a list of species encompassing almost the entire length of the Rio Carinhanha, an important tributary from upper-middle section of the Rio São Francisco, including a comprehensive diversity of environments. A total of 99 species from 8 orders and 27 families were recorded. Five species are considered non-native, six classifieds as long distance migrants, and three as vulnerable. The orders with the greatest richness of native species were Characiformes and Siluriformes. Characidae was the most represented family, followed by Loricariidae. The main river channels were the richest environments sampled, followed by floodplain lagoons, *veredas,* and streams. The Carinhanha basin has important lotic remnants, thus it has several migratory fish populations as well as endangered species. This study demonstrates the importance of cataloguing the still poorly explored tributaries of the upper-middle section of the Rio São Francisco basin.

Key-Words. Cerrado; Freshwater; Checklist; Rio Itaguari; Rio Cochá; Grande Sertão Veredas National Park.

INTRODUCTION

The ichthyofauna of the Rio São Francisco has been studied since the eighteenth century, when *Prochilodus marggravii* was first described by the naturalist Johann Julius Walbaum (Britski *et al.,* 1988). After more than a century, the basin has one of the most well-known ichthyofauna in the Neotropical region with 241 recorded native species, 70% of them with confirmed occurrences in the state of Minas Gerais (Alves & Pompeu, 2010; Alves *et al.,* 2011; Barbosa *et al.,* 2017). Despite the significant knowledge about the fish assemblages within the catchment, the distribution of studied areas is uneven, with the greatest concentrations of research occurring around the most populous regions (Alves *et al.,* 2011). Surveys of species in highland rivers (Casatti & Castro, 1998, Vieira *et al.,* 2005; Alves & Leal, 2010; Alves & Pompeu, 2010; Domingos *et al.,* 2013), some reservoirs (Silva *et al.,* 2006; Prado & Pompeu, 2014; Sanches *et al.,* 2014), and some floodplain lagoons of the upper and upper-middle sections of the Rio São Francisco (Sato *et al.,* 1987; Pompeu & Godinho, 2003; Luz *et al.,* 2012) are available. However, the fish assemblages of some of the main tributaries of the upper-middle section of the Rio São Francisco remains poorly known (Alves *et al.,* 2009), as is the case of the Rio Carinhanha basin.

The great regional importance of the Rio Carinhanha contrasts with the scarcity of knowledge concerning the basin's ichthyofauna. The Carinhanha constitutes one of the most preserved tributaries of the Rio São Francisco basin, running through well-preserved areas including some important protected zones such as Grande Sertão Veredas National Park (Borges & Santos, 2009). The river also is one of the largest perennial rivers in the central section of the São Francisco basin, a region of notorious water stress (Pereira *et al.,* 2007; Mendes *et al.,* 2015). Despite its importance, there has only been one systematic survey of the ichthyofauna in the basin (IBGE, 2007). However, that survey did not consider all its richness due to the

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restricted area sampled, nor did it evaluate the distribution of the species in the catchment's different habitats.

The Carinhanha is considered a priority area for fish fauna conservation in the central area of the Rio São Francisco basin (Drummond *et al.,* 2005; Rosa *et al.,* 2003) because it represents an important lotic remnant of the basin. However, all of the basic requirements for adequate conservation strategies are lacking, especially because the species composition remains unknown. Therefore, in this study we compile a list of species, encompassing the full extent of the catchment and record the diversity of the basin's habitats.

MATERIAL AND METHODS

Study area

The Rio São Francisco basin is one of the largest river basins in Brazil, covering five Brazilian states (Alagoas, Bahia, Minas Gerais, Pernambuco, and Sergipe), and is divided into four sections: upper, upper-middle, lower-middle, and lower (Drummond *et al.,* 2005; Paiva, 1982; Sato & Godinho, 2003). The main tributaries of the Rio São Francisco flow into the upper-middle section (Godinho & Godinho, 2003) and include the Rio Carinhanha, which divides states of Minas Gerais and Bahia (Fig. 1).

The Rio Carinhanha is 468 km long. Its basin exhibits an elongated shape (Viglio *et al.,* 2011), running in an easterly direction, and covering an area of 1.7 million hectares (Borges & Santos, 2009). Although it occupies 2.7% of the total area of the Rio São Francisco basin, the Rio Carinhanha drainage contributes 6.5% of the average flow of the main river (Pereira *et al.,* 2007). This can be explained by the types of soils in the region: urucuia sandstone and deposits containing lateritic detritus, superimposed by Quartzarenic Neosols (Borges, 2009), have relatively high rates of rainwater infiltration compared to other types of soils (Gaspar *et al.,* 2007).

There are many protected areas in the Carinhanha basin (MMA/IBAMA, 2003). Six of them are part of a set of protected areas called Mosaico Sertão Veredas-Peruaçu (Moraes, 2011), which cover approximately 30% of the Carinhanha drainage basin. The Grande Sertão Veredas National Park is one of the largest protected area in the region and is part of this integral protection group. The other protected areas, Porto Cajueiro, Cochá-Gibão, Veredas do Caraíba, Gibão-Flexeiras, and Triângulo I, are classified into sustainable use (Dudley, 2008).

The predominant biomes along the course of the Rio Carinhanha are the Brazilian savanna *(cerrado)* and the tropical dry forest *(caatinga).* Its leads to great variability to the mean of the annual rainfall along the basin, being closer that observed in *cerrado* on its headwaters (near to

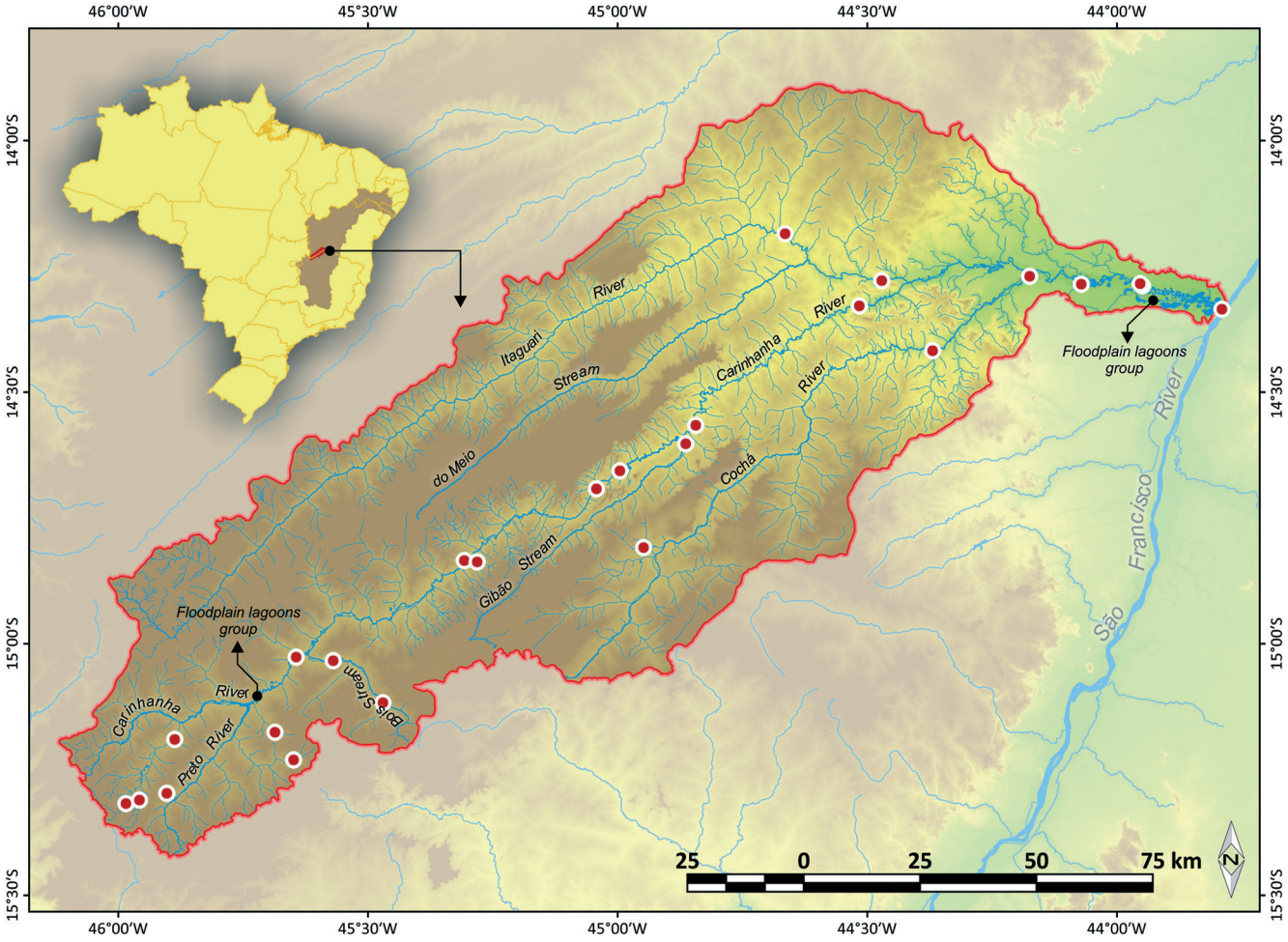


Figure 1. Distribution of the sampled sites across the Rio Carinhanha basin.

1,500 mm), and closer to the caatinga on its mouth (near to 700 mm/year) (Borges, 2009; EMBRAPA, 2012; Silva *et al.,* 2018). *Veredas* (Brazilian palm swamp) and floodplain lagoons are both abundant along the Carinhanha basin. The first formation occurs mainly along the upper portion of the basin. There are numerous floodplain lagoons near the mouth of the Rio Preto (more than 130 floodplain lagoons with an average size of 0.2 ha), and in the lower river (120 floodplain lagoons with an average size of 8.2 ha). Furthermore, there are also permanent ponds, a lentic environment isolated from the river channel.

Fish Sampling and Identification

Sampling was undertaken at 25 sites in the Rio Carinhanha basin (Fig. 1) from September 2014 to April 2015. The sampled water bodies included 3 streams, 6 *veredas,* 2 floodplain lagoons, 2 permanent ponds, and 12 points along the main channels of the Rio Carinhanha as well as 2 of its tributaries: the Rio Itaguari and Rio Cochá (Figs. 2 and 3; Supplementary Materials 1). We considered *veredas* (palm swamps) to be all streams classified as Strahler third order which flowed into hydromorphic ground and had a poorly defined channel surrounded by *buritis (Mauritia flexuosa)* palm trees (Silva & Bates, 2002). We differentiated floodplain lagoons from permanent ponds by its position in the drainage basin. While floodplain lagoons are located near the Rio Carinhanha channel and are directly influenced by its flood pulses, permanent ponds are lentic environment away from the floodplains and lacking flood pulse influence (Costa, 2002; Tavares-Júnior *et al.,* 2020).

The main river channel of the Carinhanha (Figs. 2A and 2B) and Itaguari (Fig. 2C) as well as one floodplain lagoon (Fig. 3C) were sampled using gillnets with mesh sizes ranging from 3 to 16 cm (between opposing knots) at each sampling site. The gillnets were set up in the af-

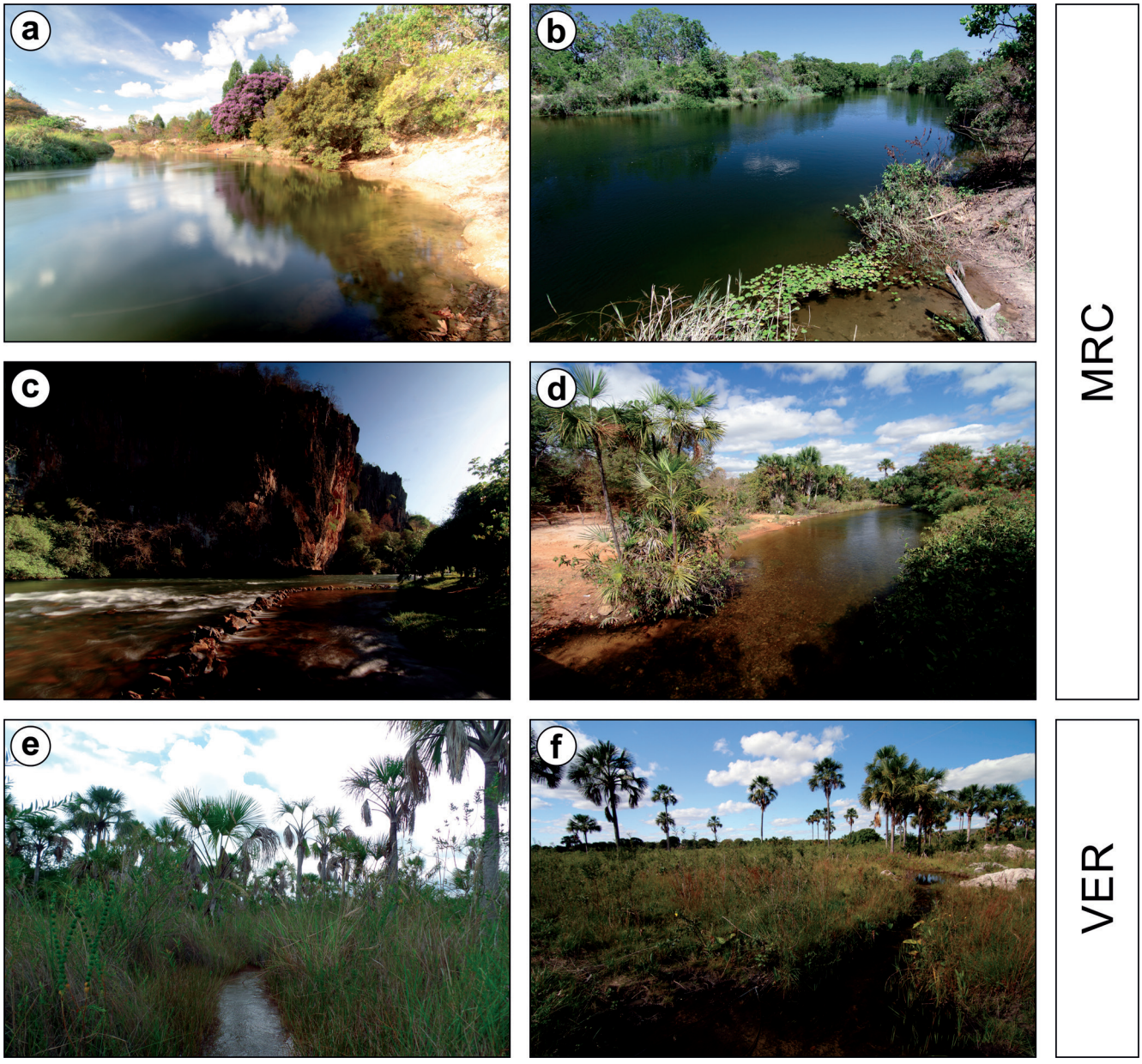


Figure 2. Aquatic habitats [main river channels (MRC) and *veredas* (VER)] at the Rio Carinhanha basin.

ternoon and removed the following morning, staying approximately 15 hours submerged. At each of these three locations, two seinings and an additional 15 sieve samplings were carried out as supplementary methodology. The seine was 3 m long by 1.5 m high, and the sieve had a diameter of approximately 0.2 m^2; both with mesh size 0.5 mm. In the main channel of the Rio Cochá (Fig. 2D) and in another floodplain lagoon (Fig. 3D), only sieve samplings were done due to environmental conditions; at the permanent ponds (Figs. 3E and 3F), only seining was undertaken.

To sample fish communities in streams and *veredas* (Figs. 3A, 3B, 3E and 3F), a 150 m long section was delimited in each study site. Fish collections were undertaken against the water-flow (*i.e.,* from downstream to upstream) with hand nets (80 cm in diameter, 1 mm stretched mesh size). Two hand nets were used for sampling, and collection time was standardized (12 minutes per cross-section, 120 minutes for each stream). Hand nets were used because of their efficiency in lower-order streams. The sampling effort was the same in all streams.

After capture, the fish were euthanized with lethal doses of anesthetic and then fixed in 10% formalin solution. In the laboratory, we transferred the fishes to 70% ethanol and identified them to the species level through dichotomous keys from Britski *et al.* (1988) and recent literature on the ichthyofauna of the São Francisco basin. The scientific names followed Fricke *et al.* (2020). Voucher specimens were deposited in the ichthyological collections of the Museum of Natural Sciences of PUC-Minas (MCNIP) and the Laboratory of Fish Ecology of the Federal University of Lavras (UFLA) (Supplementary Materials 2).

Data analysis

All analyses were undertaken using qualitative data from this field sampling. The species were classified ac-

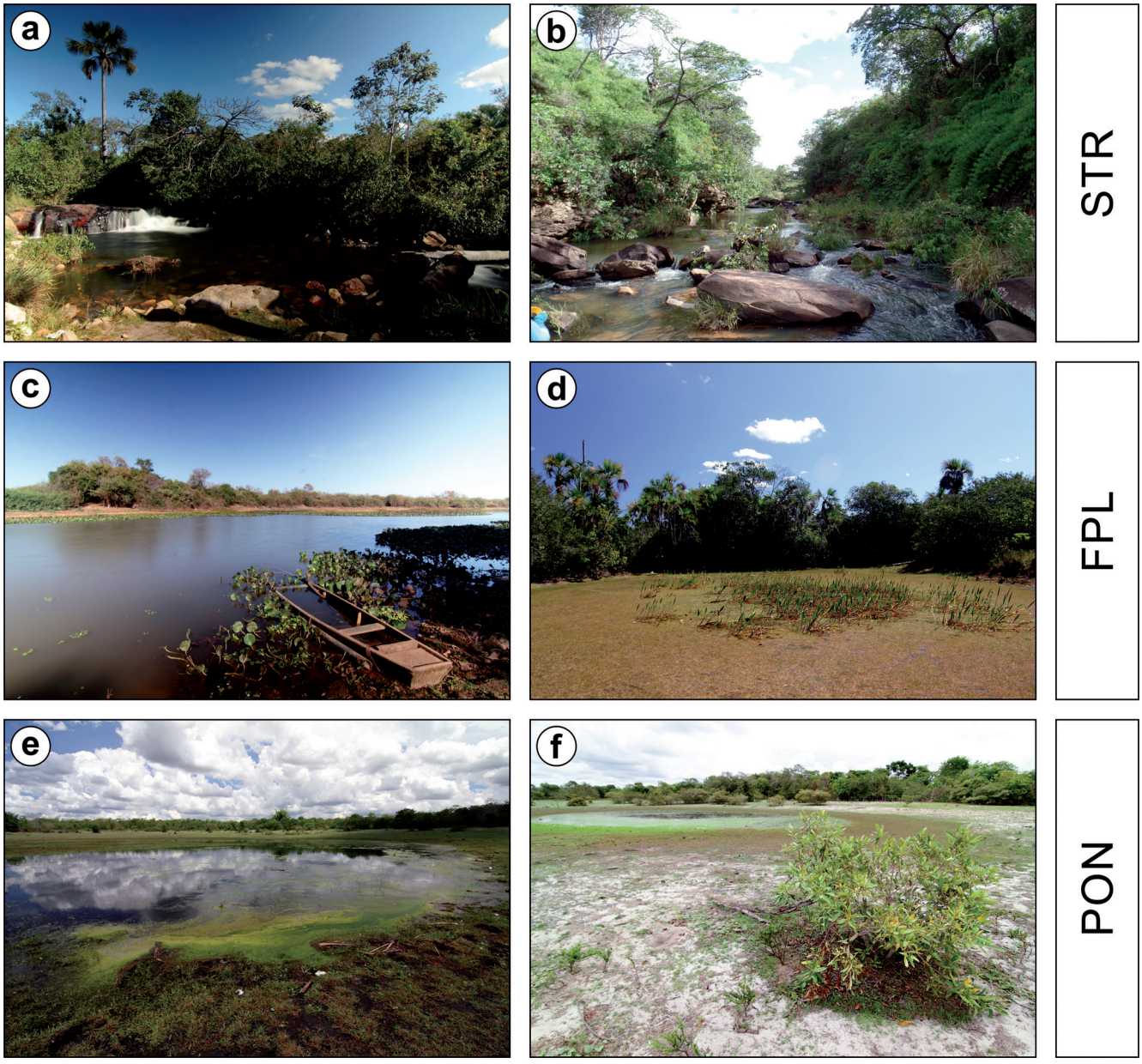


Figure 3. Aquatic habitats [streams (STR), floodplain lagoons (FPL), and permanent ponds (PON)] at the Rio Carinhanha basin.

cording to their original distribution (native or non-native; Alves & Leal, 2010), their reproductive characteristics, sedentary or migratory (Sato & Godinho, 2003), and their conservation status (Vieira *et al.,* 2008; MMA, 2014; IUCN, 2015).

Individuals were classified into orders and families following Van der Laan & Fricke (2020). The relative richness of native species in each order and family was considered. The distribution of species in the following five different habitats within the basin were also evaluated: the main river channel (MRC) of Carinhanha and its tributaries, Itaguari and Cochá, streams (STR), *veredas* (VER), floodplain lagoons (FPL), and permanent ponds (PON). As a complement to our list, we incorporated species that were not recorded in our study, by checking the basin's voucher species. Subsequently, a Jaccard matrix was calculated and served as the basis for a principal coordinate analysis (PCoA) to evaluate the similarity of ichthyofauna among the five different habitats.

In order to test whether sampling was adequate, a species accumulation curve was generated through the rarefaction of the data obtained by sampling site and to estimate total basin richness, the mean of Jackknife values were used, both using Vegan package in R (Oksanen *et al.,* 2013; R Core Team, 2015).

RESULTS

A total of 99 species distributed across 8 orders and 27 families were recorded for the Rio Carinhanha basin (Table 1; Fig. 4). Characiformes was the order with the highest richness of native species (56%), followed by the Siluriformes (33%), and then both Cichliformes and Gymnotiformes (3% each) (Fig. 5). This pattern was similar in four of the five sampled habitats, with minor variations principally between the first two orders. The exception occurred in PON, in which the only two species recorded were Characiformes. Characidae was the most representative family with 23% of recorded species, followed by Loricariidae (11%), and Anostomidae (7%) (Fig. 6). Of all the families recorded in the Carinhanha basin, 70% had a richness of less than three species. The habitat MRC was the richest environment among the sampled species with 82% of the species recorded for the entire basin, followed by FPL (41%), VER (33%), and STR (20%). Of the two species recorded in PON, one is probably new to science (*Characidium* sp.). No single species was recorded in all habitats, but 16% were recorded in three or four sites, and 84% of the species showed a restricted distribution to just one or two habitat types (Table 1).

Five of the sampled species are considered introduced in the basin, one characiform *(Metynnis lippincottianus),* one siluriform *(Hoplosternum littorale),* and three cichliforms *(Astronotus ocellatus, Cichla piquiti,* and *Coptodon rendalli)*. The distribution of the introduced species was restricted to the MRC and FPL in the lower section of the Rio Carinhanha. Six species *(Brycon orthotaenia, Megaleporinus obtusidens, Prochilodus argenteus, Prochilodus costatus, Salminus franciscanus,* and *Pseudoplatystoma corruscans)* are classified as long-distance migrators and occurred in MRC and FPL. *Brycon orthotaenia, S. franciscanus,* and *P. corruscans* were recorded only in the FPL close to the confluence of the two rivers, while the other migratory species were only recorded in the MRC of Carinhanha and Itaguari. Three species are classified as vulnerable: *Brycon orthotaenia* (Characiformes) (IUCN, 2015), *Bagropsis reinhardti* (MMA, 2014), and *Lophiosilurus alexandri* (MMA, 2014). *Bagropsis reinhardti* was recorded only in the upper section of the two MRC (Rio Carinhanha and Rio Itaguari), while *B. orthotaenia* and *L. alexandri* occurred in both MRC and FPL habitats and were restricted to the lower section of the Rio Carinhanha.

MRC and FPL sampling sites formed a group based on their similarities, which was distinct from the group represented by VER, STR, and PON. Among the sites belonging the different habitats, those of VER showed the highest variation (Fig. 7). The species accumulation curve stabilized (Fig. 8), and the observed richness (99 species) represented 97% of the richness estimated by Jackknife 1 (102 ± 2 species).

DISCUSSION

The Rio Carinhanha basin can be considered one of the richest tributaries of the Rio São Francisco basin, with around 40% of the known fish species for the entire São Francisco (Alves & Pompeu, 2010; Barbosa *et al.,* 2017). With 99 species, including *Hysteronotus megalostomus,* which was recorded only in the literature (Menezes *et al.,* 2016), the Rio Carinhanha basin has the second-highest richness, second only to the Rio das Velhas basin (Alves & Leal, 2010). However, important tributaries, such as the Paracatu, Urucuia, and Corrente rivers still lack detailed fish surveys, although some localized studies have been carried out (*e.g.,* Belei *et al.,* 2016). With the increase of knowledge about the fish fauna of those tributaries, we believe that some may have a similar fish richness to the Carinhanha.

The predominance of otophysians Characiformes and Siluriformes species, a pattern observed in the present study, are known to be the rule in the Neotropics (Lowe-McConnell, 1987; Reis *et al.,* 2016) and have already been observed in different studies in the Rio São Francisco basin (*e.g.,* Britski *et al.,* 1988; Alves & Leal, 2010). Similarly to what was found in the present study, this pattern can also be found both in small tributaries (*e.g.,* Casatti & Castro, 1998), and large rivers (*e.g.,* Alves & Leal, 2010; Belei *et al.,* 2016).

The record of a larger number of species at the main river channel is in accordance with the River Continuum Concept, which predicts an increase in species richness from the headwaters towards the mouth (Vannote *et al.,* 1980) due to the increase in habitat diversity and availability (Karr & Schlosser, 1978). The lowest richness was recorded in PON, with only two species. It can be explained by the instability of those water bodies, which almost dry out completely during the dry season (Costa,

Table 1. Species recorded in the Rio Carinhanha basin, one of the main tributaries of the Rio São Francisco. The species identified with (*) are classified as endangered. Species followed by (*θ*) are classified as non-native and (+) are classified as long-distance migratory species. Habitats: main river channel (MRC), streams (STR), *veredas* (VER), floodplain lagoons (FPL), and permanent ponds (PON).

Taxon	HABITAT				
	MRC	STR	VER	FPL	PON
ORDER CLUPEIFORMES					
Family Engraulidae					
Anchoviella vaillanti (Steindachner 1908)	X			X	
ORDER CHARACIFORMES					
Family Crenuchidae					
Characidium cf. *fasciatum* Reinhardt 1867			X		
Characidium zebra Eigenmann 1909	X	X	X		
Characidium sp.					X
Family Erythrinidae					
Hoplerythrinus unitaeniatus (Spix & Agassiz 1829)			X		
Hoplias intermedius (Günther 1864)	X		X	X	
Hoplias malabaricus (Bloch 1794)	X				
Family Parodontidae					
Apareiodon hasemani Eigenmann 1916	X			X	
Apareiodon sp.A (following Britski *et al.*, 1988)	X				
Family Serrasalmidae					
Metynnis lippincottianus (Cope 1870)	X				
Myleus micans (Lütken 1875)	X				
Pygocentrus piraya (Cuvier 1819)	X				
Serrasalmus brandtii Lütken 1875	X			X	
Family Anostomidae					
Leporellus vittatus (Valenciennes 1850)	X				
Leporinus marcgravii Lütken 1875	X				
Leporinus piau Fowler 1941	X			X	
Leporinus taeniatus Lütken 1875	X				
Megaleporinus obtusidens (Valenciennes 1837) +	X				
Megaleporinus reinhardti Lütken 1875	X			X	
Schizodon knerii (Steindachner 1875)	X			X	
Family Curimatidae					
Curimatella lepidura (Eigenmann & Eigenmann 1889)	X			X	
Steindachnerina elegans (Steindachner 1875)	X			X	
Family Prochilodontidae					
Prochilodus argenteus Spix & Agassiz 1829 +	X			X	
Prochilodus costatus Valenciennes 1850 +	X			X	
Family Triportheidae					
Triportheus guentheri (Garman 1890)	X			X	
Family Bryconidae					
Brycon orthotaenia Günther 1864 +*	X			X	
Salminus franciscanus Lima & Britski 2007 +	X			X	
Salminus hilarii Valenciennes 1850	X				
Family Iguanodectidae					
Bryconops sp.	X	X	X	X	
Family Acestrorhynchidae					
Acestrorhynchus britskii Menezes 1969	X			X	
Acestrorhynchus lacustris (Lütken 1875)	X			X	
Family Characidae					
Astyanax bockmanni Vari & Castro 2007	X	X	X		
Astyanax fasciatus (Cuvier 1819)	X	X	X	X	
Astyanax lacustris (Lütken 1875)	X	X	X	X	
Astyanax rivularis (Lütken 1875)		X	X		
Compsura heterura Eigenmann 1915			X		
Hasemania nana (Lütken 1875)	X				X
Hemigrammus cf. *gracilis* (Lütken 1875)	X				
Hemigrammus marginatus Ellis 1911	X	X	X	X	
Hyphessobrycon micropterus (Eigenmann 1915)	X			X	
Hyphessobrycon santae (Eigenmann 1907)			X		
Hysteronotus megalostomus Eigenmann 1911	X				
Knodus moenkhausii (Eigenmann & Kennedy 1903)	X				
Lepidocharax burnsi Ferreira, Menezes & Quagio-Grassiotto 2011	X	X			
Moenkhausia costae (Steindachner 1907)	X			X	
Moenkhausia sanctaefilomenae (Steindachner 1907)			X		
Orthospinus franciscensis (Eigenmann 1914)	X			X	
Phenacogaster franciscoensis Eigenmann 1911	X	X	X	X	
Piabarchus stramineus (Eigenmann 1908)	X			X	
Piabina argentea Reinhardt 1867	X	X	X		
Roeboides xenodon (Reinhardt 1851)	X				
Serrapinnus heterodon (Eigenmann 1915)	X	X	X		
Serrapinnus piaba (Lütken 1875)	X	X	X	X	
Tetragonopterus chalceus Spix & Agassiz 1829	X			X	
ORDER SILURIFORMES					
Family Auchenipteridae					
Centromochlus bockmanni (Sarmento-Soares & Buckup 2005)			X		
Trachelyopterus galeatus (Linnaeus 1766)	X			X	
Family Doradidae					
Franciscodoras marmoratus (Lütken 1874)				X	
Family Heptapteridae					
Cetopsorhamdia iheringi Schubart & Gomes 1959			X		
Imparfinis minutus (Lütken 1874)	X		X		
Phenacorhamdia tenebrosa (Schubart 1964)			X		
Pimelodella laurenti Fowler 1941	X				
Rhamdia quelen (Quoy & Gaimard 1824)	X	X	X		
Pimelodella lateristriga (Lichtenstein 1823)			X		
Family Pimelodidae					
Bagropsis reinhardti Lütken 1874*	X				
Pimelodus fur (Lütken 1874)	X			X	
Pimelodus maculatus Lacepède 1803	X			X	
Pimelodus pohli Ribeiro & Lucena 2006	X			X	
Pseudoplatystoma corruscans (Spix & Agassiz 1829) +	X				
Family Pseudopimelodidae					
Cephalosilurus fowleri Haseman 1911	X				
Lophiosilurus alexandri Steindachner 1876*	X				
Family Trichomycteridae					
Stegophilus insidiosus Reinhardt 1859	X				
Family Callichthyidae					
Corydoras garbei Ihering 1911			X		
Corydoras lymnades					
Tencatt, Vera-Alcaraz, Britto & Pavanelli 2013	X				
Corydoras multimaculatus Steindachner 1907	X				
Hoplosternum littorale (Hancock 1828) *θ*	X				
Family Loricariidae					
Harttia longipinna Langeani, Oyakawa & Montoya-Burgos 2001		X			
Hisonotus vespuccii Roxo, Silva & Oliveira 2015		X	X		
Hisonotus sp.	X		X		
Hypostomus margaritifer (Regan, 1908)	X				
Hypostomus cf. *lima* (Lütken 1874)	X	X	X		
Hypostomus francisci	X		X		
Hypostomus velhochico Zawadzki, Oyakawa & Britski 2017	X				
Otocinclus xakriaba Schaefer 1997	X				
Pterygoplichthys etentaculatus (Spix & Agassiz 1829)	X			X	
Rineloricaria sp. (similar to *R. lima*)		X			
Megalancistrus barrae (Steindachner 1910)	X				
ORDER GYMNOTIFORMES					
Family Gymnotidae					
Gymnotus gr. *carapo* Linnaeus 1758			X	X	
Family Sternopygidae					
Eigenmannia besouro Peixoto & Wosiacki 2016	X		X	X	
Sternopygus macrurus (Bloch & Schneider 1801)	X	X	X		
ORDER CYPRINODONTIFORMES					
Family Poeciliidae					
Pamphorichthys hollandi (Henn 1916)	X			X	
ORDER SYNBRANCHIFORMES					
Family Synbranchidae					
Synbranchus sp.	X	X	X	X	
ORDER PERCIFORMES					
Family Sciaenidae					
Pachyurus francisci (Cuvier 1830)	X			X	
Pachyurus squamipennis Agassiz 1831	X				
ORDER CICHLIFORMES					
Family Cichlidae					
Astronotus ocellatus (Agassiz 1831) *θ*	X				
Cichla piquiti Kullander & Ferreira 2006 *θ*	X			X	
Cichlasoma sanctifranciscense Kullander 1983	X		X		
Coptodon rendalli (Boulenger 1897) *θ*	X				
Crenicichla lepidota Heckel 1840	X			X	
Geophagus brasiliensis (Quoy & Gaimard 1824)		X			

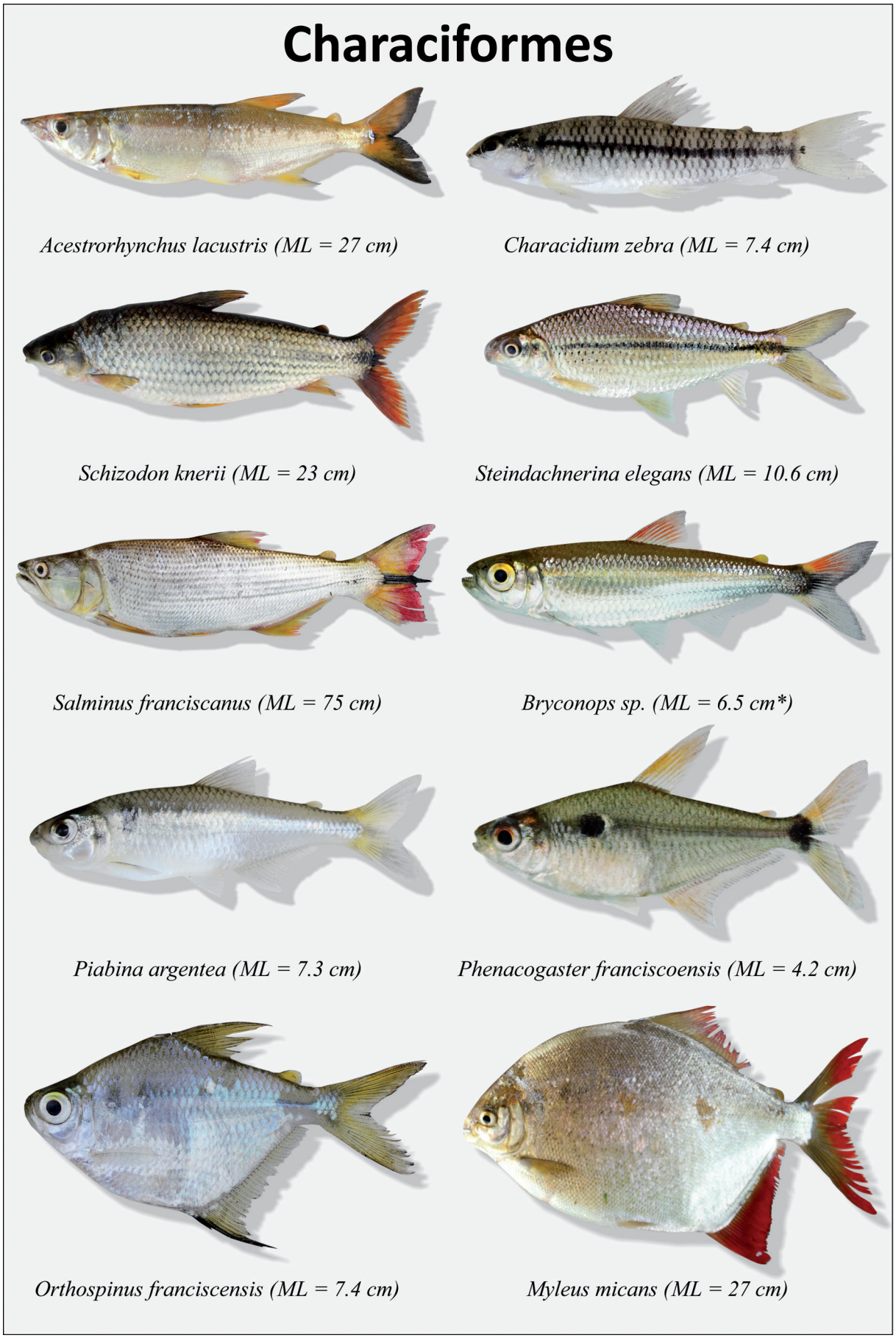
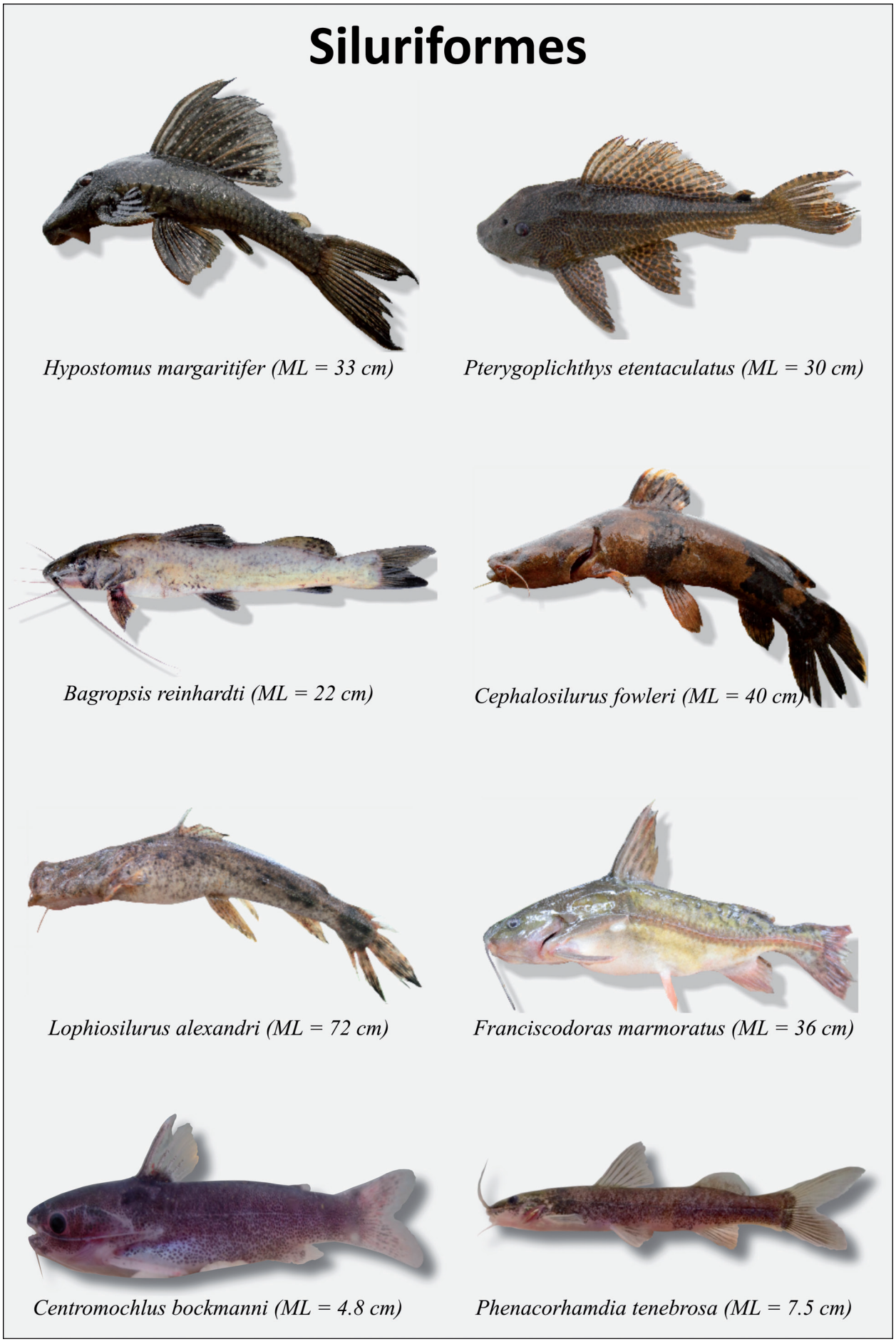


Figure 4. Representative species belonging to the Characiformes, Siluriformes, Gymnotiformes, Cichliformes and Synbranchiformes orders from the Rio Carinhanha basin. ML = Maximum length recorded by Froese & Pauly (2020). * Maximum length of *Bryconops* sp. was obtained by measuring specimens collected in the Rio Carinhanha basin. Photos: Gilberto N. Salvador and Ruanny Casarim.



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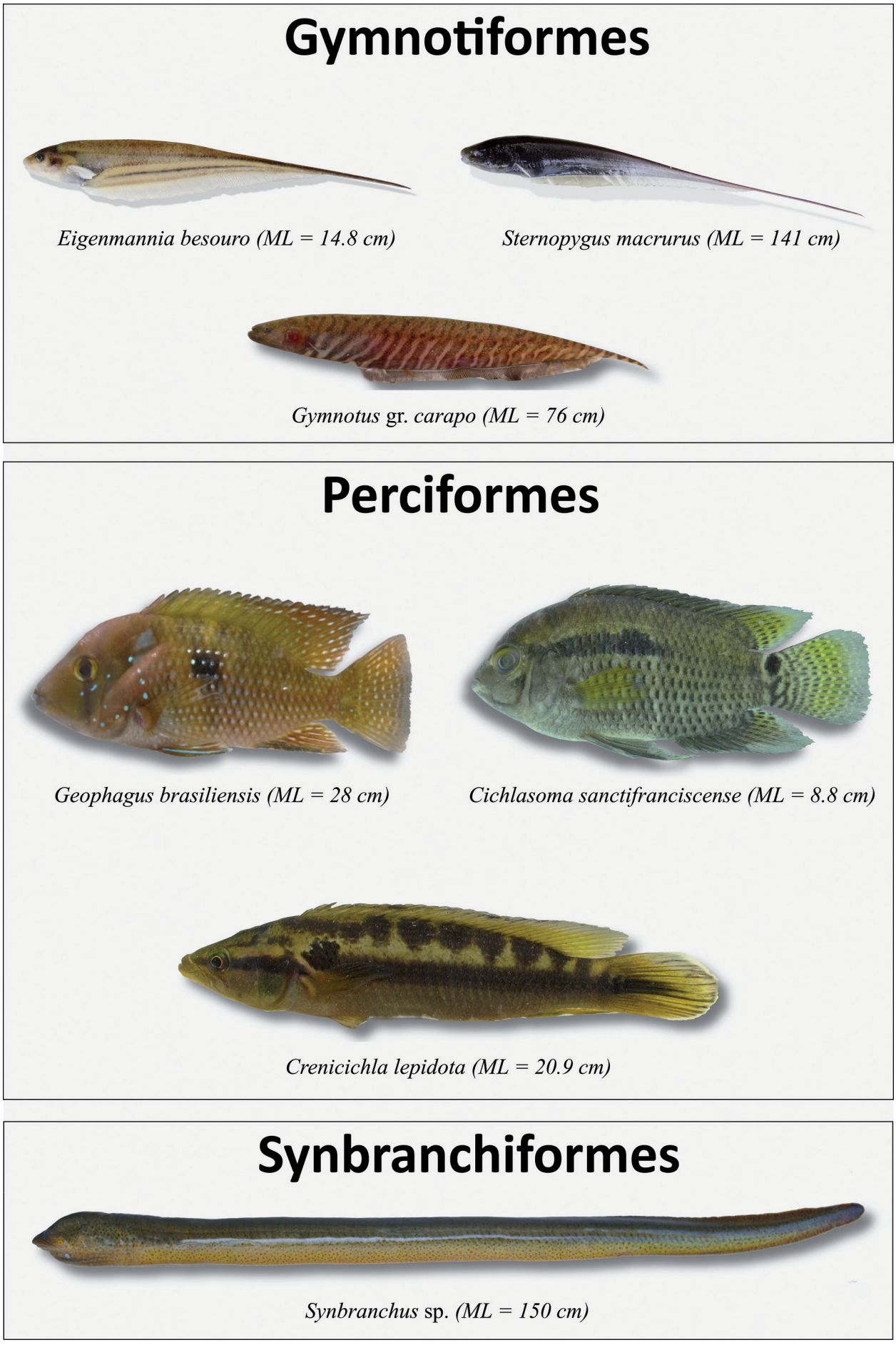

Figure 4. Continued.

2002). The undescribed *Characidium* has, so far, only been recorded for the Lagoa Bonita, a water body that is connected with the surrounding *veredas* only during the peak of the rain season. Therefore, preservation of the area in which the species has been recorded, and the identification of new potential sites where it may occur, are necessary for description and conservation of this undescribed species.

Despite recording a similar number (five species) of non-native species to the average observed in other tributaries of the Rio São Francisco (Alves & Leal, 2010), their occurrence in the Rio Carinhanha was restricted to the lower section of the basin. The introduction of these species have occurred at different points in the São Francisco basin (Alves & Leal, 2010; Pompeu & Godinho, 2003; Salvador-Jr. & Silva, 2011). The area where this group of species was recorded coincides with the most anthropogenic disturbed section of the basin (Borges & Santos, 2009), which increases the probability of introduction. However, natural dispersal, which is a further step in establishing viable populations in the invaded environment (Blackburn *et al.,* 2011), may also be the source of non-native species in the basin.

Of the great migratory fish species of the Rio São Francisco, only *Conorhynchos conirostris* was not registered in this study, and there are no recent records of such species for the section close to the Rio Carinhanha (Alves & Bockmann, 2008). *Prochilodus* spp. were found in practically the entire length of the Rio Carinhanha, indicating the absence of natural barriers. These species, which represent a large part of the fish biomass of the Rio São Francisco (Sato & Godinho, 2003), were recorded from the Grande Sertão Veredas Park area to the region near the mouth. However, records of *P. corruscans, B. orthotaenia,* and *S. franciscanus* were restricted to the lower section of the basin.

The Rio Carinhanha basin is home to 27% of the threatened fish species of the Rio São Francisco (Vieira

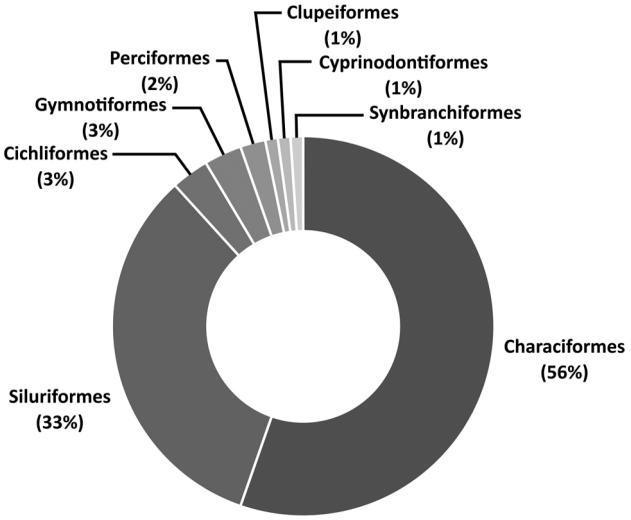

Figure 5. Distribution of ichthyofauna richness by order in the Rio Carinhanha basin.

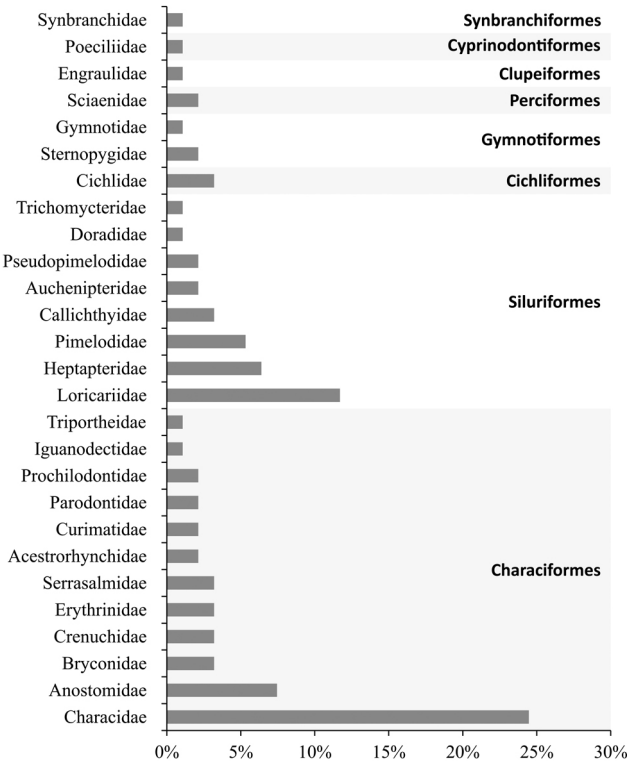

Figure 6. Distribution of ichthyofauna richness by family in the Rio Carinhanha basin.

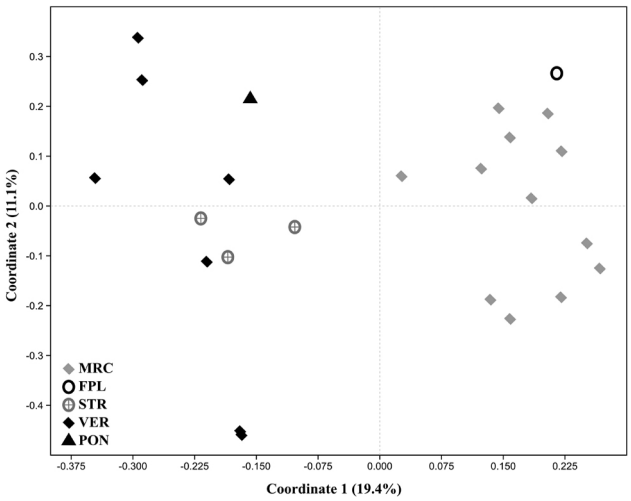

Figure 7. Ordination using PCoA based on Jaccard distance of the habitat groups showing the difference between main river channel and floodplain lagoons (MRC+FPL) and *veredas,* streams, and permanent ponds (VER+STR+PON) in coordinate 1.

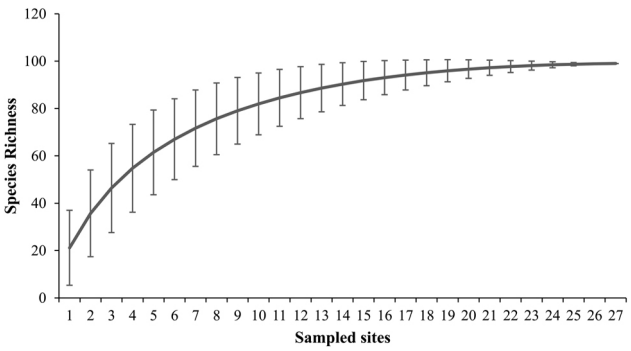

Figure 8. Rarefaction of the observed richness by sample.

et al., 2008; MMA, 2014; IUCN, 2015) (excluding rivulid fishes), a value close to that observed for the Rio Pandeiros and Rio Paraopeba basins, but lower than that observed for the Rio das Velhas (Alves & Leal, 2010). The catfish *B. reinhardti* was the only threatened species recorded in the most conserved section of the basin (Borges & Santos, 2009). The preference for larger environments may be the main reason for the absence of other endangered species in the upper section. Spatial segregation between the two *Brycon* species is commonly observed in the Rio São Francisco basin, with *B. orthotaenia* tending to occupy the lower sections of the tributaries and the main river channel (Lima, 2017). On the other hand, *L. alexandri* inhabits more lentic environments (Santos *et al.,* 2013), which are more common in lower sections.

The observed similarity between the main river channel and floodplain lagoons can be explained by the connectivity between these two environments during the flood pulses. Moreover, a similarity between streams and *veredas* is expected, since *veredas* are generally associated with smaller water bodies (Boaventura, 1981). The *veredas* have an important ecological significance, but they have been heavily impacted by human action (Drummond *et al.,* 2005). Their conservation in the Carinhanha basin can allow the protection of an important portion of the basin's fish species, since there is a high intraspecific variation in the ichthyofauna in this habitat. The segregation of the ichthyofauna from Lagoa Bonita, a permanent pond, is due to its low richness and the recording of an undescribed species (*Characidium* sp.), which is so far only known for this habitat.

The fish species richness recorded during the present study represents 97% of the estimated richness for the Carinhanha basin by Jackknife methodology, reflecting the stabilization of the species accumulation curve. This reflects the sampling effort in different habitats, like the main river channel, floodplain lagoons, and streams. However, we expect an increase in the number of species with additional collections in the basin, especially in poorly sampled habitats, like floodplain lagoons and streams. The absence of collections in streams located in the lower section of the basin should also be highlighted, where there is a predominance of tropical dry forest. In this region, located in the north of the Minas Gerais state, many streams are intermittent (Paiva, 1982) and there was no flow during the period when the surceys were done.

This study provides evidence for the importance of inventorying the still poorly explored tributaries in the upper-middle section of the Rio São Francisco. In addition to presenting a rich fish fauna, this region may harbor species new to science, as was observed in this study. Because there are important lotic remnants, this area still contains important populations of migratory fish, as well as species threatened with extinction. Knowledge of the ichthyofauna in a key for more sound discussions about the conservation of fishes in the Rio Carinhanha basin, expanding alternatives to maintain fish biodiversity in the upper-middle section of the Rio São Francisco.

AUTHOR CONTRIBUTIONS

Gilberto Nepomuceno Salvador conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the paper, and approved the final draft. *Gustavo Ribeiro Rosa* analyzed the data, authored or reviewed drafts of the paper, and approved the final draft. *Ruanny Casarim* conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the paper, and approved the final draft. *Yuri Malta Caldeira* conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the paper, and approved the final draft. *Paulo Santos Pompeu* conceived and designed the experiments, analyzed the data, authored or reviewed drafts of the paper, and approved the final draft.

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SUPPLEMENTARY MATERIALS

Supplementary Materials 1

Sampled sites along the Rio Carinhanha basin grouped by habitat. For each site, the table shows its geographic coordinates, altitude, and Strahler order.

Group	Latitude	Longitude	Alt. (m)	Order
Main river channel (MRC)	15°01'35"S	45°38'38"W	695	5
	14°46'23"S	45°13'53"W	675	5
	14°41'41"S	45°2'44"W	628	5
	14°39'57"S	44°59'51"W	619	5
	14°32'34"S	44°50'44"W	569	5
	14°19'40"S	44°30'59"W	489	5
	14°17'06"S	44°4'18"W	451	6
	14°17'19"S	43°56'55"W	449	6
	14°10'37"S	44°45'12"W	539	4
	14°16'40"S	44°28'16"W	496	5
	14°25'05"S	44°27'55"W	453	5
	14°16'10"S	44°10'29"W	520	5
veredas (VER)	14°50'14"S	45°16'52"W	684	3
	15°17'49"S	45°54'10"W	753	2
	15°11'24"S	45°53'13"W	725	2
	15°10'33"S	45°41'10"W	745	2
	15°13'50"S	45°38'56"W	750	3
	15°07'01"S	45°28'12"W	726	4
Streams (STR)	15°18'38"S	45°57'27"W	760	3
	14°36'08"S	44°51'49"W	605	3
	15°19'03"S	45°59'05"W	787	3
Floodplain lagoons (FPL)	14°17'03"S	43°57'12"W	450	
	14°19'13"S	43°47'30"W	439	
Permanent ponds (PON)	14°48'31"S	44°56'52"W	691	
	15°02'01"S	45°34'10"W	706	

Supplementary Materials 2

Species vouchers of fishes caught in the Rio Carinhanha basin. Acronyms: MCNIP (Museu de Ciências Naturais da PUC Minas); CI-UFLA (Universidade Federal de Lavras); ZUEC (Museu de Zoologia da Universidade de Campinas); ANSP (The Academy of Natural Sciences of Drexel University – from Menezes *et al.,* 2016).

Species	Voucher
Acestrorhynchus britskii	MCNIP 1576
Acestrorhynchus lacustris	MCNIP 1736
Anchoviella vaillanti	MCNIP 1575
Apareiodon hasemani	MCNIP 1764/1766
Apareiodon sp.A	MCNIP 1765
Astyanax cf. *bockmanni*	CI-UFLA 0929
Astyanax fasciatus	CI-UFLA 0930
Astyanax lacustris	CI-UFLA 0931
Astyanax rivularis	CI-UFLA 0932
Bagropsis reinhardti	MCNIP 1561
Bryconops sp.	MCNIP 1745
Brycon orthotaenia	ZUEC 9189
Centromochlus bockmanni	CI-UFLA 0935
Cephalosilurus fowleri	MCNIP 1734
Cetopsorhamdia iheringi	CI-UFLA 0936
Characidium sp.	MCNIP 1629
Characidium cf. *zebra*	CI-UFLA 0937/MCNIP 1579
Characidium fasciatum	CI-UFLA 0938
Cichlasoma sanctifranciscense	MCNIP 1573/CI-UFLA 0939
Compsura heterura	MCNIP 1772
Coptodon rendalli	MCNIP 1767
Corydoras garbei	CI-UFLA 0940
Corydoras lymnades	MCNIP 1567
Corydoras multimaculatus	MCNIP 1568
Crenicichla lepidota	MCNIP 1572/1578
Curimatella lepidura	MCNIP
Eigenmannia besouro	CI-UFLA 0941
Franciscodoras marmoratus	MCNIP 1753
Geophagus brasiliensis	CI-UFLA 0942
Gymnotus gr. *carapo*	CI-UFLA 0943
Harttia longipinna	MCNIP 1749
Hasemania nana	MCNIP 1769
Hemigrammus cf. *gracilis*	MCNIP 1746/1768
Hemigrammus marginatus	CI-UFLA 0946
Hisonotus vespuccii	MCNIP
Hisonotus sp.	CI-UFLA 0947
Hoplerythrinus unitaeniatus	MCNIP 1750
Hoplias intermedius	MCNIP 1559
Hoplias malabaricus	MCNIP 1739
Hoplosternum littorale	MCNIP 1735
Hyphessobrycon micropterus	MCNIP 1741
Hypostomus margaritifer	MCNIP 1562
Hypostomus cf. *lima*	MCNIP 1773
Hypostomus francisci	MCNIP 1569
Hypostomus velhochico	MCNIP 1570
Hysteronotus megalostomus	ANSP 170504 (Menezes *et al.,* 2016)
Imparfinis minutus	CI-UFLA 0949
Lepidocharax burnsi	CI-UFLA 0950/MCNIP 1742
Leporinus marcgravii	MCNIP 1553
Leporinus piau	MCNIP 1551
Leporinus taeniatus	MCNIP 1552/1556
Lophiosilurus alexandrii	MCNIP 1737
Megaleporinus obtusidens	MCNIP 1752
Megaleporinus reinhardti	MCNIP 1555
Moenkhausia cf. *costae*	MCNIP 1748
Moenkhausia sanctaefilomenae	CI-UFLA 0952
Myleus micans	MCNIP 1546/1547
Orthospinus franciscensis	MCNIP 1747
Otocinclus xacriaba	MCNIP 1744
Pachyurus francisci	MCNIP 1738
Pachyurus squamipennis	MCNIP 1560
Pamphorichthys hollandi	MCNIP 1743
Phenacogaster franciscoensis	CI-UFLA 0954
Phenacorhamdia tenebrosa	CI-UFLA 0955
Piabarchus stramineus	MCNIP 1763
Piabina argentea	CI-UFLA 0956
Pimelodella lateristriga	CI-UFLA 0957
Pimelodella laurenti	MCNIP 1770
Pimelodus fur	MCNIP 1771
Pimelodus maculatus	MCNIP 1566
Pimelodus pohli	MCNIP 1733
Prochilodus argenteus	MCNIP 1548
Prochilodus costatus	MCNIP 1549
Pterygoplichthys etentaculatus	MCNIP 1564
Rhamdia aff. *quelen*	CI-UFLA 0958
Rineloricaria sp.	CI-UFLA 0959
Roeboides xenodon	MCNIP 1582
Salminus franciscanus	MCNIP 1751
Salminus hilarii	MCNIP 1557
Schizodon knerii	MCNIP 1550/1577
Serrapinus heterodon	CI-UFLA 0960
Serrapinus piaba	CI-UFLA 0961
Serrasalmus brandtii	MCNIP 1580
Steindachnerina elegans	MCNIP 1558
Sternopygus macrurus	MCNIP 1574
Sternopygus macrurus	CI-UFLA 0962
Synbranchus sp.	CI-UFLA 0963
Tetragonopterus chalceus	MCNIP 1740
Trachelyopterus galeatus	MCNIP 1571
Triportheus guentheri	MCNIP 1581

Species	No voucher
Astronotus ocellatus	***
Hyphessobrycon santae	***
Knodus moenkhausii	***
Leporellus vittatus	***
Megalancistrus barrae	***
Metynnis lippincottianus	***
Pseudoplatystoma corruscans	***
Pygocentrus piraya	***
Cichla piquiti	***

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