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Deep barcode divergence in Brazilian freshwater fishes: the case of the São Francisco River basin

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Abstract

Background and aims. The application of DNA barcoding as a global standard for fish identification is probing diverse worldwide realms (Nearctic, Australian and the Neotropics) and environments (e.g. marine and freshwater). Comparing the patterns of sequence divergence among conspecific and congeneric taxa between realms can provide valuable information on recent evolutionary histories of lineages as barcode data accumulates. **Materials and methods.** Herein, we have analyzed over 100 species (around 50%) of the Neotropical fish fauna from the São Francisco River, in southeast Brazil. Our aims were to test the performance of DNA barcoding in this biodiversity-rich region, and to compare patterns of genetic divergence with previous studies. **Results.** The mean Kimura two-parameter distances within species, genera, families, orders, and classes were 0.5, 10.6, 21.0, 22.7, and 24.4%, respectively, with 100% of the species examined successfully differentiated by barcoding. With the exception of *Astyanax bimaculatus lacustris*, *Piabina argentea*, and *Bryconamericus stramineus*, all other species yield a single, cohesive cluster of barcode sequences. The average 'nearest-neighbor distance' was 11.12%, 21-fold higher than the mean within species distance of around 0.54%. In a few instances, deep lineage divergences among conspecifics (up to 10%) and congeners (up to 22.9%) taxa were revealed. **Conclusions.** Reflecting possible cases of cryptic speciation and the deeper phylogeographic history of São Francisco fish fauna, with some higher clades extending back into the late Cretaceous and Cenozoic (90 mya), when much of the diversification of the Neotropical region apparently took place. In addition, barcodes also highlighted misidentifications and helped to document range extensions for known species.

Keywords: neotropical, fishes, phylogeography, cytochrome oxidase c subunit I, São Francisco River, cryptic species

Introduction

Neotropical fishes represent 13% of all vertebrates' biodiversity, occurring in less than 0.003% of the world's water (Vari and Malabarba 1998). Brazil alone has around 25% of the described freshwater fish species, with over 2587 known species (Buckup et al. 2007). However, it is estimated that 30–40% of the Neotropical fish fauna has not yet been described (Reis et al. 2003). The Neotropical fish fauna thus

offers a challenging group to test the performance of DNA barcoding as universal system for species identification.

The mitochondrial DNA cytochrome *c* oxidase subunit I gene (*COI*) has been advocated as a universal tool for the identification of animal species (Hebert et al. 2003; Hebert and Gregory 2005) and community uptake has been diverse. Applications have included tracking invasive species population sources (Corin et al. 2007), wildlife forensics

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investigations (Dawnay et al. 2007; Nelson et al. 2007), ecology of cryptic communities (Corin et al. 2007; Pfenninger et al. 2007), and identification of prey from stomach contents (Pons 2006). Reliance on mitochondrial DNA in molecular taxonomy has been criticized because of numerous concerns ranging from introgressive hybridization and pseudogene ontogenesis to retention of ancestral polymorphisms (e.g. Rubinoff 2006), all of which could potentially mislead barcoding. However, the examination of species assignment failures typically does not exceed 5–10% (Hebert and Gregory 2005; Ward et al. 2005; Hubert et al. 2008; Valdez-Moreno et al. 2009) and indeed are often much lower, suggesting such problems are the exception rather than the norm.

Given the socioeconomic importance of fishes, combined with a solid taxonomic framework against which to validate the performance of barcoding, they were an obvious choice for a large-scale initiative. A global effort to assemble a standardized barcode reference sequence library for all fishes known as FISH-BOL (the Fish Barcode of Life Campaign; Ward et al. 2009) was initiated in 2005. Briefly, FISH-BOL aims to highlight cases of range expansion for known species, flag previously overlooked species, facilitate species identification, and enable identification where traditional methods cannot be applied (Ward et al. 2009).

Previous barcode studies involving freshwater fishes have detected similar values of sequence divergence within species and among congeners as those involving marine species (Hubert et al. 2008; Valdez-Moreno et al. 2009). However, the more fragmented environment found in freshwaters when compared with marine habitats is expected to promote a greater genetic structuring among populations and also promote deeper divergences among haplotypes (Ward et al. 1994). The lack of strong genetic structure reported in previous studies (Hubert et al. 2008; Valdez-Moreno et al. 2009) could be due to either a more recent colonization, which occurred after glacial retreats at the end of the Pleistocene (Bernatchez and Wilson 1998; Hubert et al. 2008), or to a more recent origin of freshwater species (Valdez-Moreno et al. 2009).

The São Francisco River basin (SFR), the fourth largest river in Brazil, has a fish fauna of at least 205 species, excluding diadromous species (Alves et al. 2007), from which 22 species are considered threatened due to pollution, damming, overfishing, and introduced species (Lins et al. 1997). The development of a Barcode database for Brazilian fishes will add new data for the taxonomic identification of Neotropical fishes regardless of lifestage or sex. Also, because there is evidence that cryptic species are prevalent in tropical regions, efforts to document species richness are critical (Hebert et al. 2004; Beheregaray and Caccone 2007).

We conducted an examination of *COI* diversity within and among over 100 fish species of the SFR (around 50% of its ichthyofauna) to test whether the divergence of barcode sequences within conspecifics will be lower than within congeneric species, and to evaluate the efficiency of species discrimination by Barcoding. We also test the null hypothesis of a greater genetic structure and divergence among haplotypes when compared with marine species or recent colonized freshwater habitats. As Brazilian freshwater fishes probably have an old evolutionary history (Lundberg et al. 1998), a deeper lineage divergence within taxa is expected.

Materials and methods

Samples

Fishes were sampled mainly from the medium course of the SFR, ranging from headwaters to floodplains. Five major tributaries were targeted (Velhas, Paraopeba, Pandeiros, Verde Grande, and Urucuia). Samples were also obtained from one reservoir (Três Marias), small tributaries, and from the main river. In the present study, we did not target marine nor annual fishes. All specimens were photographed and georeferenced. More details on coordinates, collecting localities and dates can be obtained within the project file 'Brazilian Freshwater Fishes—The São Francisco Basin Population' (BSB) on the Barcode of Life Data System (BOLD; Ratnasingham and Hebert 2007). All specimens have been preserved as reference vouchers at the Museum of Science and Technology, Pontifícia Universidade Católica do Rio Grande do Sul (PUC-RS), and at the fish collection of the Laboratório de Biologia e Genética de Peixes, Universidade Estadual Paulista, UNESP/Botucatu. Morphological identifications were conducted based on the literature, and also by taxonomy specialists at PUC-RS and UNESP collections.

DNA extraction, PCR amplification, and sequencing

Tissue subsamples were isolated from fragments of muscle, fin, and eyes (small voucher species) of 105 fish species from the SFR (one nonindigenous species—*Leporinus macrocephalus*) and stored in 90% ethanol. Numbers of specimens per species ranged from 1 to 23 with a mean of 4.34 (SD = 2.97). Sequencing was carried out at the Canadian Centre for DNA Barcoding using standard protocols (Hajibabaei et al. 2005). An automated proteinase K protocol (Ivanova et al. 2006) was used to obtain DNA extracts from prepared tissue subsamples (1 mm³). A fragment of approximately 658 bp *COI* was amplified using different combinations of primers: FishF1, FishR1 (Ward et al. 2005), or the M13-tailed primer cocktails C_Fish F1t1—C_FishR1t1 and

C_VF1LFt1—C_VR1LRt1 (Ivanova et al. 2007) as noted for each entry in BOLD. The 12.5 µl PCR mixes included 6.25 µl of 10% trehalose, 2 µl ultrapure water, 1.25 µl of 10 × PCR buffer, 0.625 µl MgCl₂ (50 mM), 0.125 µl each primer (0.01 mM), 0.0625 µl each dNTP (0.05 mM), 0.0625 µl *Taq* polymerase (5 U/µl), and 2.0 µl DNA template. Amplification protocols consisted of 94°C for 2 min, 35 cycles of 94°C for 30 s, 52°C for 40 s, and 72°C for 1 min, with a final extension at 72°C for 10 min. The most intense PCR products, visualized on pre-cast agarose gels (E-Gels; Invitrogen, Carlsbad, CA, USA), were selected for sequencing. Sequences were determined bi-directionally using the BigDye Terminator v3.1 Cycle Sequencing Kit (Applied Biosystems, Inc., Foster City, California, USA) as described before (Hajibabaei et al. 2005) using an Applied Biosystems Inc. 3730 or 3130 capillary sequencer.

Data analysis

Sequences were edited and aligned using CodonCode Aligner (v3.5.6; Codon Code Corp., Edham, MA, USA). All data (i.e. electropherograms, trace files, primer details, photographs, and collection localities) for each specimen were deposited within the project 'Brazilian Freshwater fishes—The São Francisco Basin Population' file on BOLD (<http://www.boldsystems.org>) and the assembled DNA sequences were also submitted to GenBank (accession numbers included in Appendix A). Online tools implemented on BOLD were used to estimate pairwise sequences divergences using the Kimura two-parameter (K2P) distance model (Kimura 1980), as well as to calculate nearest-neighbor distance (NND) values and neighbor-joining phenograms (for a clear graphic representation of the divergence values, see Appendix B).

Results

A total of 431 *COI* barcodes were obtained, for 101 species in 75 genera and 22 families, constituting around 50% of all known fauna of the SFR. All amplified sequences were larger than 600 bp, and no insertions, deletions, or stop codons were observed, therefore reducing the possibility of nuclear DNA sequences originating from mitochondrial DNA. Only four species failed to amplify, even after trying different primer combinations: *Acestrorhynchus britskii* ($n = 1$), *Corydoras garbei* ($n = 1$), *Leporinus obtusidens* ($n = 1$), an unidentified genus and species from the family Characidae ($n = 4$). Accession numbers to BOLD and GenBank sequences for each specimen are provided in Appendix A.

With the exception of two species (*Bryconamericus stramineus* and *Piabina argentea*) and one subspecies (*Astyanax bimaculatus lacustris*), all species analyzed were monophyletic (Appendix B), confirming that

barcoding is an efficient method for species-level identification. Moreover, the mean intra-specific distance was less than 1% for 86% of all species (Figure 1a). Mean K2P distances within species, genus, family, order, and class were 0.5, 10.6, 21, 22.7, and 24.4%, respectively (Table I). A 21-fold greater difference among congeneric species than among conspecific specimens was observed. The distributions of mean K2P distances among conspecific individuals and among congeneric species overlapped (K2P distances ranged from 0 to 10.5% among conspecifics and from 0 to 22.9% among congeneric species; Table I). Deep intra-specific divergences and low sister-species divergence may originate overlapping in the distribution of the genetic distance between conspecifics individuals and congeneric species.

The lowest congeneric divergences were detected between *A. bimaculatus lacustris* and *A. bimaculatus* (0%), *Astyanax* cf. *fasciatus* and *Astyanax rivularis* (0.93%), and also between the commercial important species *Prochilodus argenteus* versus *Prochilodus costatus* (1.7%). In addition, the nonidentified specimens *Pamphorichthys* sp. (BSB361) and *Pseudopimelodus* sp. (BSB162) had small conspecifics divergence (0–0.15 and 0.33%, respectively), grouping within described species of the same genus. The specimen identified as *Brycon* sp. (BSB149) was closely related to *Oligosarcus* sp. (diverging only by 1.8%), possibly due to misidentification, because of their morphological similarity.

On the other hand, deep intra-specific divergences were detected within nine species, with the highest values observed for *Pimelodella vittata* (Table III). Some of the deep divergences between conspecific could be explained by phylogeographic patterns (e.g. *Synbranchus marmoratus* and *Gymnotus carapo* had exclusive lineages detected in the Paraopeba River), reflecting the broad range of sample sites. Other factors such as ancient clade splitting and cryptic speciation might also be related with high genetic intra-specific divergence observed in several small-size species (Table III).

The NND distribution analysis—that is, the minimum genetic distance between a species and its closest congeneric relative—showed that 9% (nine species) of the NND was lower than 1% (Table II and Figure 1b,c), whereas 89% (90 species) had NND values over 2.7% (Table II). The average NND was 11.12% (ranging from 0 to 25.89%), 21-fold higher than the mean within-species distance of around 0.54, while 88% of intra-specific divergences were less than 1% (Figure 1a).

When considering only the economically important species (large-sized fish [> 20 cm], $n = 20$), all species were monophyletic, with tight clusters (within-species divergences were lower than 1%). Therefore, they were clearly differentiated by barcoding (K2P tree—Appendix C). Only two species, *P. argenteus* and *P. costatus*, presented NND lower than 2.7% (Table II).

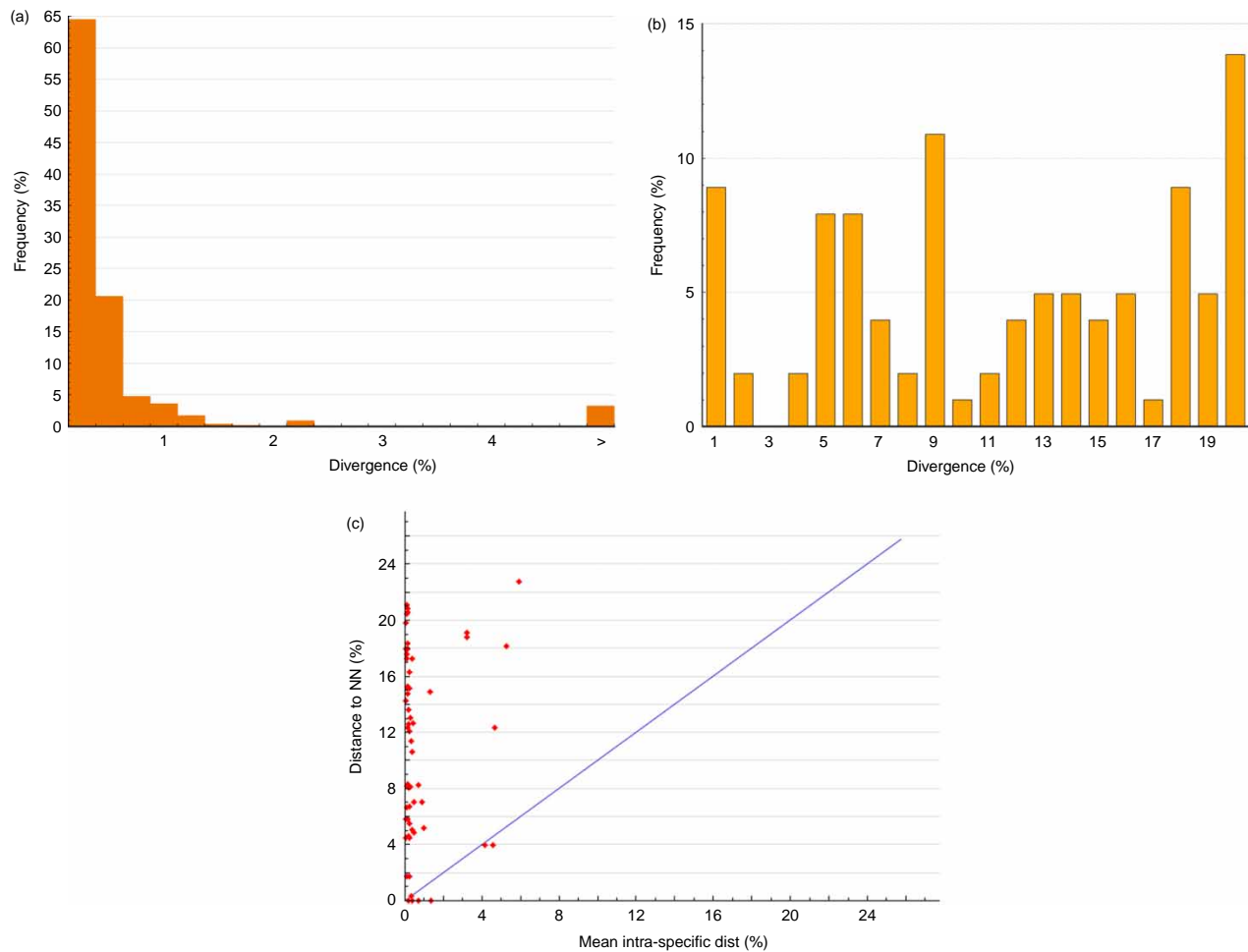


Figure 1. Summary of the genetic variability (K2P distances) distribution at *COI* sequences for 433 individuals and 101 species. (a) Mean intra-specific distribution of genetic distances. (b) Distribution of the genetic distances to the NN. (c) Pairwise percentage distance to NN versus mean intra-specific distance.

Discussion

Overall, the observed genetic distances between conspecifics (mean = 0.5%) and congenetics (mean = 10.61%) for the SFR fishes were higher than that previously reported in the marine (0.3 and 8.4%; Ward et al. 2009) or freshwater ecosystem (0.3/8.3% and 0.45/5.1%, respectively; Hubert et al. 2008; Valdez-Moreno et al. 2009). The mean NND value observed herein (11.12%) was also higher than that previously described for the Canadian (7.67%) and Mexican (8.86%) freshwater and Australian marine (9.14%) barcode surveys. Cryptic speciation, phylogeographic structure, and the old evolutionary history of the Neotropical fish fauna, with some higher clades extending back into the late Cretaceous and Cenozoic (90 mya; Lundberg et al. 1998) might explain the deep genetic divergence recovered for some SFR species. However, when analyzing commercially important fishes alone (larger species), divergences within species decreased considerably (ranging from 0 to 0.85%, mean = 0.13%) (Table I),

possibly reflecting the better taxonomic knowledge of larger species, when compared with small-sized fish.

Deep divergence for congeneric comparisons has been previously reported, with a maximum of 19.3% of divergence (Stoeckle 2003; DeSalle et al. 2005). Nonetheless, here we report even deeper divergences, with a maximum of 22.9% recovered within the genus *Moenkhausia*. Interestingly, only 0.1% of NND values were lower than 9% for SFR species (Table II and Figure 1c). In contrast, Hubert et al. (2008) reported that 27% of NND values were lower than 0.1%, presumably reflecting the more recent diversification of the freshwater Canadian fauna.

Several cases of possible cryptic speciation due to deep intra-specific barcode divergence were observed, ranging from 2.2 to 10% for several species—e.g. *Imparfinis minutus* (9%), *B. stramineus* (9%), *Pamphorichthys hollandi* (2.2%), *P. argentea* (6%), and *P. vittata* (10%)—and well-known species complexes—e.g. *Eigenmannia virescens* (9%), *G. carapo* (5%), and *S. marmoratus* (9%)—are likely to increase genetic divergence estimation (Table III). Biogeography

Table I. Summary of genetic divergences (K2P) within species, genus, order, and class.

| | Comparisons | Minimum distance (%) | Mean distance (%) | Maximum distance (%) | SE distance (%) |
|----------------|---------------|----------------------|-------------------|----------------------|-----------------|
| Within species | 1035 (311) | 0 (0) | 0.50 (0.13) | 10.54 (0.85) | 0.049 (0.01) |
| Within genus | 1006 (278) | 0 (1.67) | 10.61 (11.2) | 22.88 (17.34) | 0.185 (0.323) |
| Within family | 13,260 (678) | 1.875 (4.48) | 21.01 (19.0) | 30.50 (27.89) | 0.034 (0.251) |
| Within order | 23,353 (3164) | 15.32 (16.3) | 22.71 (21.8) | 31.59 (30.48) | 0.017 (0.061) |
| Within class | 53,145 (1674) | 17.34 (19.5) | 24.40 (24.0) | 37.82 (31.02) | 0.012 (0.061) |

Note: Data consist of 435 sequences of 101 species, with values in brackets consisting of divergence analysis only with the commercially important species ($n = 20$).

patterns alone are unlikely to explain all deep divergences observed, as pronounced intra-specific genetic divergence was recovered from specimens sampled in sympatricity. For instance, sympatric cryptic lineages diverging up to 10% were recovered from small fish species in the Velhas River Basin—e.g. *P. vittata* (BSB375–376), *B. stramineus* (BSB214), and *P. argentea* (BSB368) (Table III and Appendix A). Further integrative approaches, including nuclear markers, morphology, and broader range of sampling sites might shed some light on this issue.

Our screen for species splits, applying the threshold of 1% average divergence between conspecific individuals (as suggested by Hubert et al. 2008), was able to differentiate most species. Well known as a complex of species of controversial taxonomy (Reis et al. 2003), *Astyanax* specimens were divided into three major clusters, and therefore showed support from barcode data for at least three species: *A. bimaculatus*, *A. rivularis*, and *A. cf. fasciatus*. Even considering the small K2P divergences detected between *A. rivularis* and *A. cf. fasciatus* (0.93%),

probably indicating a case of recently derived species, a tight array of haplotypes was observed for each cluster (Appendix B). Several nonidentified *Astyanax* species were also assigned to one of the three clades. However, the subspecies *A. bimaculatus lacustris* had no divergence from *A. bimaculatus*; hence, barcodes do not support the hypothesis of divergence between these two subspecific lineages. In another interesting case, samples of *P. argentea* and *B. stramineus* could not be separated as expected. Among the seven specimens analyzed, four units were observed. These two genera are composed of several complex species (Javonillo et al. 2010; Pereira et al. 2010) and new specimens should be analyzed for a clearer picture of this problem, before a resolution could be presented.

Moreover, nine species (Table II) would be over-split due to deep divergence within conspecifics if only the 1% threshold was adopted, reinforcing the fact that while divergence thresholds are a useful heuristic tool, they must be applied judiciously. Hubert et al. (2008) reported that the 1% threshold would have overlooked 34 fish species.

Table II. Summary of the SFR freshwater fish diversity and distribution of genetic distance.

| Order | Family | Number of species | < 0.1 | 0.1–1.0 | 1.0–2.7 | > 2.7 |
|--------------------|-------------------|-------------------|-------|---------|---------|---------|
| Characiformes | Characidae | 33 | 4 | 1 | | 28 (6) |
| | Anostomidae | 6 | | | | 6 (5) |
| | Erythrinidae | 2 | | | | 2 (2) |
| | Parodontidae | 2 | | | | 2 |
| | Curimatidae | 3 | | | | 3 |
| | Acestrorhynchidae | 1 | | | | 1 (1) |
| | Crenuchidae | 3 | | | | 3 |
| | Prochilodontidae | 2 | | | 2 (2) | |
| | Loricariidae | 15 | | | | 15 |
| Siluriformes | Doradidae | 1 | | | | 1 |
| | Heptapteridae | 5 | | | | 5 |
| | Pimelodidae | 6 | | | | 6 (3) |
| | Pseudopimelodidae | 4 | 2 | | | 2 (1) |
| | Callichthyidae | 2 | | | | 2 |
| | Aspredinidae | 1 | | | | 1 |
| | Auchenipteridae | 1 | | | | 1 |
| | Trichomycteridae | 3 | | | | 3 |
| | Gymnotidae | 1 | | | | 1 |
| Gymnotiformes | Sternopygidae | 2 | | | | 2 |
| | Gymnotidae | 1 | | | | 1 |
| Cyprinodontiformes | Poeciliidae | 4 | 2 | | | 2 |
| Perciformes | Cichlidae | 3 | | | | 3 |
| Synbranchiformes | Synbranchidae | 1 | | | | 1 |
| Total | | 101 (20) | 6 (0) | 3 (0) | 2 (2) | 90 (18) |

Note: A total of 101 species were analyzed using the nearest-neighbor (NN) approach at *COI* (K2P distance). Values in brackets consist of NND analysis with only commercially important fish species ($n = 20$).

Table III. Species with deep intra-specific barcode divergence.

| Species | Distribution | Intra-specific divergence values (%) |
|----------------------|--------------|--------------------------------------|
| <i>B. stramineus</i> | Sympatric | 9 |
| <i>G. carapo</i> | Allopatric | 5 |
| <i>S. marmoratus</i> | Allopatric | 9 |
| <i>E. virescens</i> | Sympatric | 9 |
| <i>I. minutus</i> | Sympatric | 9 |
| <i>P. hollandi</i> | Allopatric | 2.2 |
| <i>P. argentea</i> | Sympatric | 6 |
| <i>P. vittata</i> | Sympatric | 10 |
| <i>Poecilia</i> sp. | Sympatric | 2.2 |

Note: Species names, their distribution and percentage of intra-specific genetic divergence are presented.

Deep intra-specific divergences recovered from *S. marmoratus* and *G. carapo* haplotypes might be related to phylogeographic history or geographic structure, as expected for freshwater fishes (Ward et al. 1994). Interestingly, both species had lineages exclusive from the Paraopeba River, suggesting a possible Evolutionary Significant Unit (ESU) for this tributary within the SFR. However, due to the few samples analyzed at each site and the lack of additional corroborating data, this result must be considered provisional, but the species are worthy of further phylogeographic investigation. Also *P. hollandi*, sampled from two different sites (Velhas River and Pandeiros), at least 500 km apart, had 2.1–2.51% within-species divergences. On the other hand, deeply divergent lineages recovered for several species were not always related with phylogeographic patterns. For instance, in *I. minutus* there was pronounced differentiation (10% sequence divergence) in sympatry (i.e. two lineages found in the Velhas River), which might suggest a possible case of cryptic speciation. Other highly divergent lineages were observed in sympatry: *E. virescens* had all specimens collected at Pandeiros River with high conspecific lineage divergence (9%) and *P. argentea*, with 6% of within species divergence, was detected in sympatry with conspecifics in the Curimataí River (tributary of Velhas River Basin). Also, *Poecilia* sp. presented two clades with 2.2% divergence in sympatry within species samples in the Velhas River. In one case, a young specimen of *B. stramineus*, which could not be taxonomically differentiated from adults and therefore was identified as *B. stramineus*, had conspecific divergence of 8.73%, flagging a possible new cryptic species.

Several unidentified small sucker-mouth catfish species (e.g. *Bunocephalus* sp., *Neoplecostomus* sp., *Pareiorhina* sp., *Microlepidogaster* sp., *Parotocinclus* sp., *Rineloricaria* sp., and *Hemipsilichthys* sp.) were each represented by a single cohesive array of barcode sequences, distinct from any other species, suggesting that each of these genera was represented in our collection by a single species. Interestingly, the specimens identified as *Hisonotus* sp. are a yet-to-be described genus and species for this river system (Carlos Lucenna personal communication). Other

nonidentified small fish species, such as *Pamphorichthys* sp. (BSB361) and *Pseudopimelodus* sp. (BSB162), could not be identified based only on morphology, but they were closely associated with known barcoded specimens, of the same genus, with low divergence values (0–0.33%; Appendix B).

Haplotypes of *Knodus* recovered from SFR species had 100% similarity with *Knodus moenkhausii* from the Paraná River Basin, as compared with other projects on BOLD, suggesting that these individuals belong to the same species. However, the genus *Knodus* has not yet been described for the SFR. In addition, *Knodus* is differentiated from *Bryconamericus* by a sole feature, the presence of scales on the basal portion of the caudal fin in *Knodus* (Ferreira and Carvajal 2007). We therefore suggest that the range of occurrence of *K. moenkhausii* should be extended to the SFR. These results are also supported by morphological data (Katiane M. Ferreira, personal communication). Hence, DNA barcodes were able to discriminate *Knodus* from *Bryconamericus* (13% of divergence between species), despite little morphological divergence, demonstrating that the barcode approach is valid for Neotropical fish identification. In fact, the species identified here as *Knodus* were initially misidentified as *Bryconamericus*; and after our barcode data flagged the likely mistake, their morphological identification was checked and corrected.

In summary, our study provides an example of the usefulness of barcoding for cataloging the diversity of Brazilian freshwater fishes from the SFR. Our barcode data support the discovery of several putative new species and genera (e.g. the '*Hisonotus* sp.' case), describe a case of range expansion for a known species (e.g. *K. moenkhausii*) and flagged previously overlooked species (e.g. *I. minutus*, *B. stramineus*, *P. hollandi*, *P. argentea*, and *Poecilia* sp.).

We have shown that the current knowledge of the SFR ichthyofauna, even in a well-studied Brazilian river system, is far from complete. The present study was not intended to solve taxonomic issues, but does flag taxa requiring further analyses, as well as providing baseline information on species that may represent good models for comparative phylogeographic surveys (Beheregaray 2008). Moreover, a deeper knowledge of the molecular systematics of species complexes of small-sized fishes (which are poorly studied in Brazil) may also help in the description of new species, contributing to improve local species richness estimates and to help delineate taxonomic units for conservation programs. As all commercially important fishes were clearly discriminated, we also foresee a great role of DNA barcode analysis in fish market certification and regulation by governmental agencies.

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