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BIODIVERSITY VIEWPOINT

Mind the (information) gap: the importance of exploration and discovery for assessing conservation priorities for freshwater fish

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Abstract

Biodiversity conservation often is aimed at areas of high species richness and endemism. Our understanding of freshwater fish diversity in the Neotropics is biased by lack of exploration within mountainous regions that historically have been difficult to access. These regions are particularly likely to contain high species endemism. The upper Mazaruni River drainage is hydrogeographically and climatically distinct from the rest of the Essequibo Basin. Recent ichthyological expeditions to the upper Mazaruni discovered up to 32 species previously unknown to science and a fish assemblage with perhaps the highest level of endemism in the Neotropics. This unique ichthyofauna is threatened by gold mining that has severely degraded aquatic habitats and therefore requires immediate protection.

Keywords

Endemism, gold mining, Guiana Shield, Guyana, Neotropics, taxonomy, upper Mazaruni River.

INTRODUCTION

Freshwater fish species represent roughly 25% of living vertebrates, while inhabiting < 1% of the earth's surface (Lévêque *et al.*, 2007). Freshwater biodiversity is increasingly impacted by human reliance on freshwater ecosystem services (Darwall *et al.*, 2011). Specific and interacting threats to freshwater species include: overexploitation, pollution, habitat destruction, flow modification and invasive species (Lévêque *et al.*, 2007; Strayer & Dudgeon, 2010). Nearly all freshwater biotas are more imperilled than their terrestrial counterparts (Strayer & Dudgeon, 2010; WWF, 2012). Conservation research, however, is often focused on terrestrial systems or charismatic species and relatively little is known about freshwater species distributions and conservation status (Darwall *et al.*, 2011).

Conservation efforts often target areas of high species richness, endemism, extinction risk or habitat degradation (Brooks *et al.*, 2006; Wilson *et al.*, 2007). Endemism is a particularly useful metric for biodiversity conservation because protecting areas of high endemism captures significantly more species than expected by chance (Lamoreux *et al.*, 2006). Around 40% of freshwater fish species occur in the Neotropics (nearly 5600 described species, Lévêque *et al.*, 2007; Albert *et al.*, 2011). However, accurately comparing freshwater fish richness and endemism within the Neotropics is difficult because species ranges are poorly understood and a large part of the fauna remains undescribed (Albert *et al.*, 2011). This is in part due to the richness of the fauna, size of river systems and inaccessible terrain. Current rates of species discovery and publication suggest there are likely more than 8000 Neotropical freshwater fishes (Reis, 2013). The large number of unknown species, along with historical sampling bias towards more accessible areas, limits our ability to interpret the biogeographical patterns of this fauna (Albert *et al.*, 2011) and also hampers our ability to set appropriate conservation priorities. Painfully few conservation initiatives are dedicated to protect Neotropical freshwater fishes (Reis, 2013), and many species may go extinct before being described (Stiassny, 2002; Fontaine *et al.*, 2012).

Geographic range is a primary determinant of extinction risk: species with small ranges have higher extinction rates (Harnik *et al.*, 2012). Most fish species in tropical South America are known to have small geographic ranges, with more than half limited to a single ecoregion (Albert *et al.*, 2011). Species with smaller ranges have a lower probability of being described than species with larger ranges, and in turn, undescribed species are likely at greater risk of extinction than known species (Blackburn & Gaston, 1995; Giam *et al.*, 2012). Together, small ranges and lack of formal

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taxonomic status mean that undescribed centres of freshwater fish endemism are disproportionately vulnerable. Identifying these faunas through targeted exploration and discovery is an essential first step towards their conservation.

There are several possible indicators that a poorly explored region may have higher species richness and more endemic fish species than previously recognized. These include high richness or endemism in neighbouring basins and climatic or physical isolation. High numbers of small-range species are known to occur in regions with rare climates that are colder and at higher elevations than surrounding areas (Ohlemüller *et al.*, 2008). North American endemic riverine fish species richness is related to historical biogeography and current climate (Oberdorff *et al.*, 1999) and patterns of fish species richness and endemism in Europe have been related to historical events including Pleistocene glaciations (Reyjol *et al.*, 2007). The history of hydrogeographic connections within and among river basins is reflected in the evolution of Neotropical fish lineages (Lundberg *et al.*, 1998; Albert & Reis, 2011). It follows that the hydrogeographic history, landscape and climate of a region, as well as the diversity in neighbouring regions, may be indicators of areas of undetected endemism and conservation risk.

The Essequibo ecoregion (Fig. 1, and see Abell *et al.*, 2008) appears to have lower fish species density than other portions of the Guiana Shield, likely as a result of poor sampling in headwaters given the region's location between the species-dense Amazonian and Guianan faunal provinces (Albert *et al.*, 2011). The Essequibo also appears to have significantly lower endemism than expected if species were randomly distributed (Tedesco *et al.*, 2012). However, the Guiana Shield has high climate rarity in comparison with neighbouring regions (Ohlemüller *et al.*, 2008) and many portions of the region are physically and hydrogeographically isolated from neighbouring areas (Lujan & Armbruster, 2011). The upper catchment of the Mazaruni River in Guyana runs through an ~500 m elevation region of rain forests and savannas before plunging into the Guyana lowlands through a series of rapids and waterfalls that prevent fishes from dispersing up stream or down stream (Fig. 2). Due to its relative inaccessibility, the upper Mazaruni had been poorly sampled until recently (Lujan & Armbruster, 2011). Climate uniqueness, hydrogeographic isolation from the rest of the Mazaruni-Essequibo basin and lack of exploration suggested that the drainage might harbour a highly endemic fish fauna. Moreover, discovery of *Mazarunia mazarunii* (a cichlid), *Skiotocharax meizon* (a crenuchid) and *Derhamia hoffmannorum* (a lebiasinid), from opportunistic collections in the late 20th century, indicated endemic fish taxa inhabit the basin. Considering these factors, we carried out three targeted ichthyological expeditions to the upper Mazaruni River.

We show (1) that the upper Mazaruni River drainage in Guyana is a centre of endemism in freshwater fishes, which has been seriously underestimated due to a lack of scientific exploration, and (2) that the fishes of the upper Mazaruni are under threat of extinction from expanding mining operations. Fish in this watershed represent a cross-section of the evolutionary lineages from the uniquely rich Neotropical freshwater fish fauna and are key to understanding the evolutionary history and historical biogeography of Neotropical fish diversity. The Mazaruni River demands immediate protection and it is a clear case of the need for exploration and discovery in hydrogeographically and climatically isolated regions with high endemism and dangerously underestimated diversity.

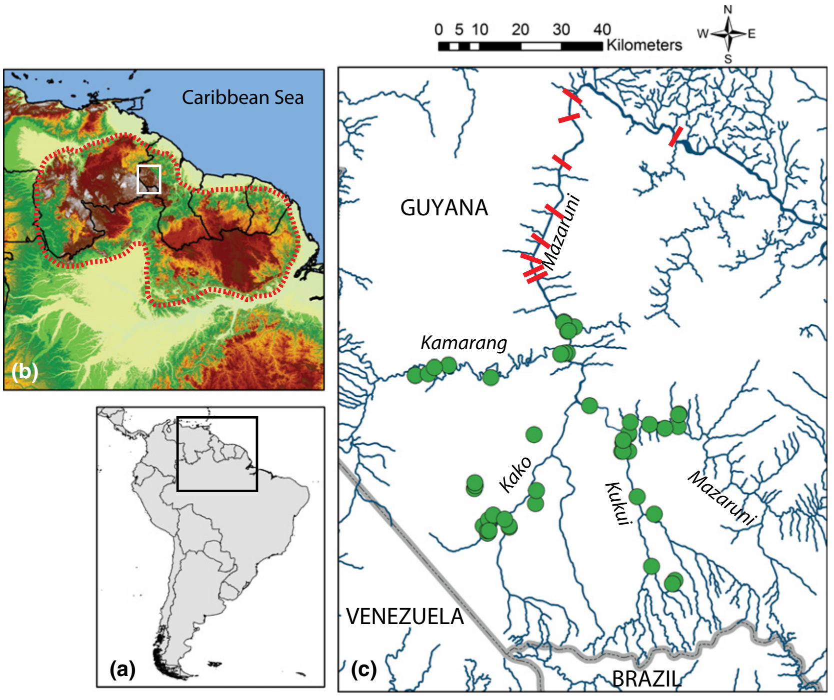

Figure 1 The location of the upper Mazaruni drainage basin within (a) South America, (b) the high elevation region of the Guiana Shield (outlined in red) and (c) a map of sampling locations in the upper Mazaruni drainage basin; red tick marks indicate the approximate location of rapids and waterfalls that limit dispersal of fishes between the upper and lower reaches of the Mazaruni River (see text).

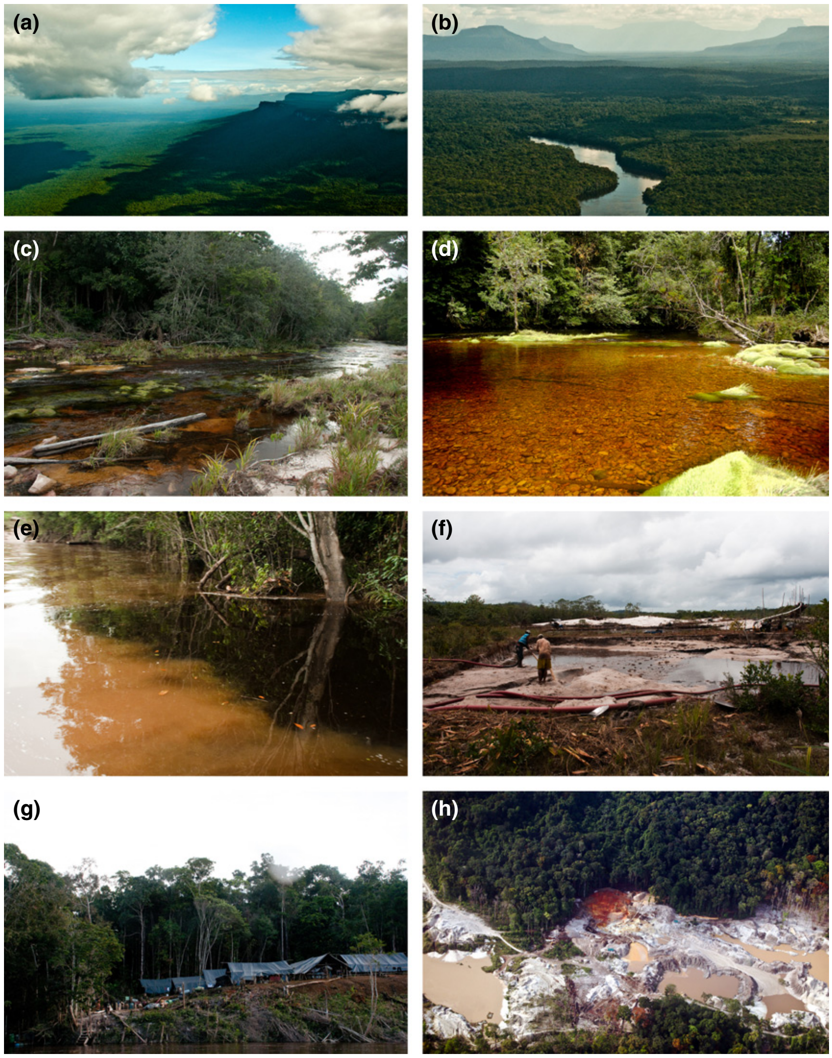

Figure 2 Habitats sampled and gold mining impact on the upper Mazaruni River. (a) The eastern edge of the western Guiana Shield in Guyana with the lowlands of the Essequibo basin (left side of image); the upper Mazaruni River is isolated from the lowland basin by a series of rapids and waterfalls that tumble down the escarpment's cliff. (b) The main channel of the upper Mazaruni (looking approximately west) with the Roraima highlands in the background. (c) Abbou Creek, a small, pristine tributary of the upper Mazaruni River. (d) A shallow reach of Waruma Creek, a small, pristine tributary of the Kako River. (e) Mouth of the pristine Abbou Creek as it meets the heavily silted main channel of the upper Mazaruni River; siltation results from sediment suspension and dumping from gold mining operations. (f) An overland mining operation uses high-pressure water to remove topsoil for gold mining; the removed sediment is directed to barges on the river where gold is extracted by mercury amalgamation and sediment is expelled into the Mazaruni River channel. (g) A mining camp on the left bank of the upper Mazaruni. (h) An overland mining station near the Mazaruni River bank as seen from the air.

A CASE STUDY: EXPLORATION AND DISCOVERY IN THE UPPER MAZARUNI RIVER

Fishes were sampled in three dry season surveys (April 2008, April 2011 and November 2011). A total of 98 sites were sampled in the main upper Mazaruni River channel and its three main tributaries, the Kukui, Kako and Kamarang, as well as some other minor tributaries (Figs 1 & 2). Fish samples were collected using straight and bag seines and gillnets. At each site, fish were collected until five consecutive seine hauls produced no new species for the site. Gill nets were used as a complementary capture method for fishes that were either too large or too fast to be captured with seines. Samples were complemented with fishes captured by members of the local community using traditional methods. Fishes were euthanized with an overdose of the anaesthetic clove oil and then fixed in a solution of 10% formalin. Collections were preserved in 70% ethanol and deposited and studied at the Royal Ontario Museum, Toronto, Canada. All holotypes and a representative portion of these collections are or will be deposited at the Ichthyology collection in the Centre for the Study of Biological Diversity (CSBD), University of Guyana, Georgetown.

Definitive taxonomic assignment of fish species from the upper Mazaruni is still ongoing because of the complexity of taxonomic analysis in the context of the exceptionally diverse and incompletely understood Neotropical fish fauna (Albert *et al.*, 2011; Reis, 2013), which contribute to delay species discovery and description (Fontaine *et al.*, 2012). Nevertheless, richness and endemism can be bracketed by making explicit assumptions based on current taxonomic understanding. To estimate richness and the proportion of species endemic to the drainage while accounting for the uncertain taxonomic position of several groups, we used two approaches. The 'conservative' approach (Table 1, see Appendix S1 in Supporting Information) assumed the fewest possible endemic species. This was carried out by identifying upper Mazaruni samples of unconfirmed identity as belonging to similar described species from neighbouring basins, assuming any morphological differences reflect intraspecific geographic variation (e.g. the cichlid *Krobia* cf. *potaroensis*, where cf, or confer, indicates an unconfirmed identification

Table 1 Species- and genus-level richness, proportion of endemic taxa and proportion in need of taxonomic description in the upper Mazaruni River basin according to our conservative and liberal estimates

	Conservative estimate		Liberal estimate	
	Number	%	Number	%
Species	36		39	
Endemic species	24	66.7	37	94.9
Genera	26		28	
Endemic genera	7	26.9	9	32.1
Species remaining undescribed	13	36.1	25	64.1

that upon further examination may reveal a currently unrecognized species). In contrast, the 'liberal' approach assumed the highest possible number of endemic species, such that samples of unconfirmed identity were assumed to be undescribed endemic species. This approach also assumed a finer subdivision of some groups (e.g. the catfish genus *Trichomycterus*, see Appendix S1).

There are three species that may be recent introductions into the upper Mazaruni basin for human consumption: *Cichlasoma bimaculatum*, *Hoplerythrinus* cf. *unitaeniatus* and *Megalechis* cf. *thoracata*. We obtained anecdotal confirmation that *C. bimaculatum* was recently introduced as a source of protein and it is cultivated in ponds near Amerindian villages; thus, we treated it as a non-native species under both approaches. Both *H. unitaeniatus* and *M. thoracata* are widespread in lowland Guyana and common in the local fisheries; therefore, under the conservative approach, we assumed these species were introduced to the upper Mazaruni. Under the liberal approach, we treated *H.* cf. *unitaeniatus* and *M.* cf. *thoracata* as endemic undescribed taxa given the isolation of the upper Mazaruni and the lack of conclusive evidence of their introduction.

Finally, the crenuchid species *Skiotocharax meizon* was described from the upper Mazaruni and, on the basis of one specimen, the lowland Berbice river of Guyana (Presswell *et al.*, 2000). We treated this species as non-endemic under the conservative approach, but because no further specimens of the species have been reported from the Berbice (H. López-Fernández *et al.*, unpublished data), we considered it a potential endemic under the liberal approach. Our conservative and liberal approaches provide estimates of the minimum and maximum proportion of endemic species in the upper Mazaruni River basin. The true rate of endemism is likely somewhere between these two values, but will only be known once the taxonomy of the upper Mazaruni fishes is further resolved. To test whether our surveys reflected the true fish diversity of the Mazaruni basin, we calculated a species accumulation curve (SAC) (see Appendix S2).

We collected 11,065 individuals distributed in 14 families (see Appendix S3). The SAC suggests that we sampled the vast majority of the basin's diversity (see Appendix S2). Nevertheless, a few undetected species may remain as suggested by the recent description of the annual killifish *Laimosemion paryagi* (Vermeulen *et al.*, 2012). Annual killifishes tend to live in extremely small creeks or in temporal pools on floodplains and are thus unlikely to be sampled in riverine habitats. Depending on whether we used conservative or liberal estimates, species richness in the basin varied between 36 and 39 species in 26–28 genera, and the proportion of endemic species ranged from 67 to 95% (Table 1). While we estimate between 33 and 64% of Upper Mazaruni taxa are still undescribed, exploration since 2008 has accelerated discovery, resulting in the description of a new endemic genus and eight endemic species with several others pending (Table 1, see Appendix S1).

A previously unrecognized centre of fish endemism

The fishes of the upper Mazaruni represent a clear example of a threatened endemic freshwater fauna in an underexplored and highly isolated region. Three ichthyological expeditions to the upper Mazaruni River uncovered a fauna, which was mostly unknown to science (see Appendix S1 and S3). By our liberal estimate, the upper Mazaruni has perhaps the highest proportion of endemic species of any freshwater fish fauna reported in the Neotropics. Lake Titicaca has the highest rates of fish endemism described in a Neotropical ecoregion: 92% of fish species are endemic (Albert *et al.*, 2011). It is likely that the upper Mazaruni has equivalent or higher endemism. Species endemic to the upper Mazaruni, however, occur in at least 11 of 14 families present in the basin, unlike the radiation of endemic pupfish species in Lake Titicaca, which all belong to the single genus *Orestias* (Albert *et al.*, 2011). This pattern of phylogenetic overdispersion suggests the fishes of the upper Mazaruni may represent a relict centre of palaeo-endemism (i.e. a refuge for fish lineages that differentiated in the past and have since become extinct elsewhere) rather than a recent *in situ* diversification. Recent study of the phylogeny and age of the endemic cichlid genus *Mazarunia* revealed it belongs to a Guiana Shield-restricted clade possibly originating between the Oligocene and Miocene (~11–32 Ma; López-Fernández *et al.*, 2013). This suggests the diversity of the region may date back to times when the Mazaruni River is thought to have exited to the Atlantic through its own mouth (Lujan & Armbruster, 2011). Relatively species-poor drainage basins, like the upper Mazaruni, have been noted to have a higher proportion of palaeo-endemic fishes than richer basins, which are more likely to harbour neoendemic species (Tedesco *et al.*, 2012).

The Essequibo ecoregion, which includes the Mazaruni River, was previously reported as holding 301 fish species of which 53, around 18%, were endemic (Albert *et al.*, 2011). Our expeditions confirm that the species density and endemicity of fishes in the western Guiana Shield has been underestimated (Albert *et al.*, 2011; Tedesco *et al.*, 2012). Importantly, the high endemism we discovered in this single drainage of the Essequibo also highlights the potential dangers of prioritizing fish conservation by comparisons among units defined at the ecoregional scale. Small areas of high endemism can be overlooked when rates of endemism are calculated at the ecoregional scale, assuming the distribution of endemic species within ecoregions is homogeneous.

Fishes of relatively unexplored isolated basins may have high rates of endemism for several reasons, including hydrogeographic and climatic isolation. This pattern is not limited to the Neotropics. For example, the southern region of the Indian Western Ghats is an area of high fish endemism and uniqueness (Dahanukar *et al.*, 2004). This area is isolated by the Palghat Gap, a barrier to fish dispersal. Unfortunately, the fish fauna of the Western Ghats is threatened by deforestation. The rapidly expanding influence of human industry including forestry and mining in previously inaccessible areas underlies the importance of prioritizing biological explorations of areas like the Western Ghats and the upper Mazaruni river basin.

Gold mining threatens the fishes of the Upper Mazaruni

The unique fish fauna of the upper Mazaruni is seriously threatened by gold mining and associated habitat transformations. With the rising price of gold, small- and medium-scale mining operations, which use mercury amalgamation, have become increasingly common across the Guiana Shield (Fig. 2e–h; Hammond *et al.*, 2007; Howard *et al.*, 2011). In 2010, Guyana produced 9594 kg and exported $346.2 million of gold (Gurmendi, 2011). High mercury concentrations in channels of the lower Mazaruni River have been attributed to mining activity (Miller *et al.*, 2003). In this region, unsafe mercury concentrations (by World Health Organization standards) have been measured in both carnivorous fish and in hair samples from Amerindian communities where fish are frequently consumed (Roopnarine, 2002; Miller *et al.*, 2003; Howard *et al.*, 2011). Small-scale gold mining increases turbidity and suspended sediment concentrations, which leads to accumulations of fine sediments on streambeds, covering structural elements and reducing fish habitat diversity (Mol & Ouboter, 2004). Erosion related to gold mining has been shown to reduce fish diversity and shift fish community composition (Mol & Ouboter, 2004; Brosse *et al.*, 2011).

Siltation is readily observable in the main channel of the upper Mazaruni River, where gold mining is concentrated. There is noticeably higher turbidity on the main channel than in its tributaries, which are typically deep, tea-coloured water with nearly no suspended solids (López-Fernández *et al.*, 2012; illustrated in Fig. 2e). High turbidity is distinctly associated with mining activity in the upper Mazaruni. Analyses of habitat attributes and fish community structure suggest highly altered environments such as the 'tailing' beaches resulting from mining operations are poor habitat for native fishes (E.A. Liverpool & H. López-Fernández unpublished data). This is particularly concerning as some species endemic to the Mazaruni basin appear to be associated with main channel habitats. We did not collect *Mazarunia mazarunii* or *M. pala* anywhere else. Other species, particularly *Apareiodon agmatos*, an undescribed hypopomid knifefish and the catfish genus *Rhamdia*, appear more abundant in undisturbed main channel habitats than in tributaries. Work in other regions of the Guiana Shield has demonstrated fish community composition is affected by even small-scale mining operations, and fish communities are slow to recover after mining activities have ceased (Brosse *et al.*, 2011).

CONCLUSIONS AND RECOMMENDED CONSERVATION MEASURES

The upper Mazaruni River basin in Guyana contains a fish fauna that may represent the highest rate of freshwater fish endemism of any Neotropical ecoregion. The upper Mazaruni drainage appears to house relict evolutionary lineages from several fish families with broader distributions in South America. Although previous work had hinted at the existence of this unique fish assemblage, it remained virtually unknown until our recent field exploration and taxonomic work. Unfortunately, our expeditions also revealed large and increasing habitat transformations in the drainage as a result of gold mining and associated human impacts. As a corollary to our study, we propose that several measures are necessary to ensure the unique fish fauna of the Upper Mazaruni will not rapidly disappear due to anthropogenic impacts. These include: (1) regulating mining practices, which are the primary source of pollution and siltation; (2) protecting the drainage from severe flow alterations including hydroelectric dam development (Park *et al.*, 2003); (3) minimizing deforestation, which is known to threaten endemic fish species through habitat degradation (Dahanukar *et al.*, 2004); and (4) preventing further introductions of non-native fish species (Leprieur *et al.*, 2008). Establishing and properly managing a reserve or national park in the upper Mazaruni River basin would largely address all these recommendations, protecting a region of the Guyana Shield with a disproportionately large potential for biodiversity loss given its highly endemic fish fauna and relatively small geographic area. Additionally, we recommend implementing a standardized population monitoring programme for the rare and highly threatened fishes of the upper Mazaruni. Moreover, expanded exploration of the riverine fauna of the basin should be supported, particularly concentrating on the invertebrate and lower food-web components of the Mazaruni aquatic ecosystem.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix S1 Endemism and taxonomic status of fish species.

Table S1 Fish species in the upper Mazaruni River basin.

Appendix S2 Species accumulation curve.

Appendix S3 Examples of species of fishes from the upper Mazaruni in live coloration.

BIOSKETCHES

Karen M. Alofs is a postdoctoral researcher in the Department of Ecology and Evolutionary Biology at the University of Toronto who is interested in the effects of environmental changes on native and introduced species.

Hernán López-Fernández, Donald C. Taphorn, Calvin. R. Bernard and Elford A. Liverpool are part of a collaborative effort by the Royal Ontario Museum and the University of Guyana to study the diversity, biogeography and evolution of freshwater fishes in Guyana. While most of our research focuses on species discovery, molecular systematics and patterns and rates of phenotype evolution in Neotropical fishes, fieldwork in Guyana also aims at promoting freshwater fish conservation.

Authors contributions: K.M.A. and H.L.F. conceived the ideas. H.L.F, E.A.L., D.C.T, and C.R.B collected the data, K.M.A. and H.L.F. analysed the data and led the writing.

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